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Development of a Risk Control System for the Granulation Process of Ferronickel Skimming Slag Based on HAZOP Analysis Results

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Abstract

***Introduction**: Occupational safety in mining and metallurgical operations continues to be a major concern because these processes involve extreme temperatures, hazardous materials, and complex interactions between workers and equipment, especially in ferronickel smelting where slag handling occurs under high thermal and pressure conditions. **Objective**: This study aims to develop and validate an integrated risk control system for the ferronickel slag skimming granulation process based on Hazard and Operability Study analysis. **Method**: A descriptive qualitative-quantitative case study approach was applied by analyzing three main process nodes using Hazard and Operability Study worksheets, supported by a 5×5 risk matrix to evaluate initial and residual risks, followed by the design and validation of engineering and administrative control systems. **Result and Discussion**: The slag granulation process was identified as a high-risk operation with several critical deviations, where Low Pressure Water showed the highest initial risk value (16) due to its potential to trigger failed granulation, slag agglomeration, and explosions. The main influencing variables included water jet pressure, slag temperature, water flow rate, pump condition, drill gun performance, and nozzle blockage. The developed risk control system integrated engineering and administrative controls, resulting in consistent risk reduction across all process nodes. **Conclusions**: Hazard and Operability Study-based risk control system effectively reduces process risk with an effectiveness range of 40%-75% and an average reduction of 56.62%, enhances process reliability, strengthens process safety management, and supports the development of a proactive safety culture in ferronickel smelter operations.*

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Introduction

Occupational safety remains a major concern in the global mining industry because mining operations involve hazardous materials, extreme temperatures, high-pressure systems, and complex interactions between workers and equipment (Benson *et al*., 2024; Zhang *et al*., 2023). Compared to many other industrial sectors, mining activities are associated with significantly higher occupational risks and fatality rates. According to the International Labour Organization (ILO), although the mining sector represents only around 1% of the global workforce, it contributes nearly 8% of fatal occupational accidents worldwide. This condition shows that mining environments contain substantial hazards requiring systematic risk management approaches. The increasing complexity of mining technology, automation systems, thermal processes, and heavy equipment operations further intensifies operational risk exposure. Therefore, comprehensive process safety management systems are essential to maintain safe, reliable, and sustainable mining operations. The International Council on Mining and Metals (ICMM, 2024) also reported an increase in worker fatalities within major mining companies, showing that occupational risk remains a significant challenge despite ongoing safety improvements.

In Indonesia, occupational safety in the mining sector has become increasingly important due to rapid industrial expansion and the government's downstream mineral processing policy (Haiedar & Kholifah, 2025). The Ministry of Energy and Mineral Resources reported that more than 300,000 workers were employed in the mining sector in 2023, showing the large workforce potentially exposed to occupational hazards. The implementation of good mining practice and the achievement of zero-accident targets require mining companies to prioritize both productivity and operational safety. Regulatory frameworks such as SMKP Minerba, HIRADC, HAZOP, and SMK3 have been widely implemented to strengthen hazard identification and risk management systems (Dinata *et al*., 2025). However, incidents related to exposure to high-temperature materials, high-pressure systems, and human-machine interaction are still frequently reported in Indonesian mining industries.

One of the fastest-growing sectors in Indonesia's mining industry is nickel processing, particularly due to increasing global demand for electric vehicle batteries and critical minerals (Sarmin & Mita, 2026). Indonesia has become the world's largest nickel producer and continues to expand pyrometallurgical and hydrometallurgical smelter development to support downstream industrialization. From a process safety perspective, pyrometallurgical nickel processing introduces significant hazards because the process involves molten materials at temperatures exceeding 1500°C, high-pressure cooling systems, and continuous thermal operations. Failures in controlling these process parameters may lead to severe accidents such as explosions, molten material splashes, equipment damage, and worker injuries (Bai *et al*., 2023). One of the critical operations in ferronickel smelting is slag handling, particularly during the skimming and granulation stages where molten slag directly interacts with high-pressure water. This interaction creates complex thermal-fluid hazards that require strict operational control and reliable safety systems. Consequently, effective process hazard analysis is necessary to identify critical deviations and prevent catastrophic incidents in ferronickel slag granulation systems.

PT Halmahera Jaya Feronikel (HJF) is a ferronickel smelting company operating in Eastern Indonesia using Rotary Kiln Electric Furnace (RKEF) technology for ferronickel production. The company operates eight RKEF production lines with a total production capacity of approximately 780,000 tons of ferronickel annually. Within this process, slag granulation becomes one of the most safety-critical operations because molten slag at temperatures of 1500-1600°C must be rapidly cooled using high-pressure water jets. This process generates direct interaction between extremely hot molten material and pressurized cooling systems, creating the potential for steam explosions, thermal exposure, slag splashes, and operational instability. In addition, failures in water pressure control, nozzle performance, or slag flow stability may significantly increase accident severity and operational disruption.

Occupational safety records at PT Halmahera Jaya Feronikel (HJF) indicate that the slag granulation process still presents substantial operational risks. The company recorded seven near-miss incidents in 2024 and thirteen additional cases up to July 2025. Two major near-miss incidents specifically occurred during slag skimming granulation operations on February 19, 2025, and July 19, 2025. Internal investigation results revealed that these incidents were associated with unstable water pressure and blockage indications in the water jet nozzle system. The resulting pressure instability during interaction between molten slag and cooling water increased the risk of steam explosions, sudden slag splashes, and uncontrolled thermal exposure. These incidents show that failures in process parameter control may escalate rapidly into severe operational accidents if adequate safeguards are not implemented.

Despite the growing number of studies related to process safety and slag handling, important research gaps remain in the context of ferronickel slag granulation systems. Previous studies conducted by Luo *et al.* (2021) primarily focused on slag optimization and energy efficiency improvement rather than process safety risk mitigation. Musyafa *et al.* (2023) integrated HAZOP with RAMS+ and Genetic Algorithms to improve refinery heater safety performance, however, their study did not address metallurgical processes involving molten slag and water interaction hazards. Other researchers such as Suroso and Yanuar (2020) and Durukan *et al.* (2024) successfully applied HAZOP for hazard identification in fabrication and ship systems, yet their studies did not involve extreme thermal environments or high-temperature molten materials. Furthermore, Yi Qi *et al.* (2022) proposed a hierarchical HAZOP-like method for machine learning systems, but the approach focused mainly on cyber-physical systems instead of industrial metallurgical operations. Therefore, studies specifically addressing integrated risk control systems for ferronickel slag granulation processes remain very limited. This study aims to develop and validate a HAZOP-based risk control system capable of reducing operational risk, improving process reliability, supporting evidence-based safety management, and strengthening proactive safety culture implementation in ferronickel smelting operations.

Method

This study employed a descriptive qualitative-quantitative approach using a case study method focused on the ferronickel slag skimming granulation process at PT Halmahera Jaya Feronikel (HJF). The primary objective was to develop and validate an integrated risk control system based on the results of Hazard and Operability Study (HAZOP) analysis. The research was conducted at PT HJF, located on Obi Island, North Maluku, Indonesia, over a period of six months from March to August 2025. The first two months were allocated for preparation, followed by two months for data collection and processing, and the final two months for analysis and comprehensive reporting. The research subjects consisted of individuals directly involved in the HAZOP-based process risk analysis, including the Process Safety Management team responsible for process hazard analysis (PHA), the production department as the process owner, and production operators who perform the skimming process. The research object was the operational system of ferronickel slag granulation.

The variables in this study were categorized into independent and dependent variables. The independent variables included previous HAZOP studies and process parameters of skimming granulation, while the dependent variables consisted of hazard potential analysis using HAZOP and the development of a risk control system. Several research instruments were utilized to support data collection and analysis. These included historical case record data related to the slag skimming granulation process at PT HJF, such as incident reports, near-miss data, investigation results, process parameters during incidents (*e.g.*, water pressure, slag temperature, pump condition), and operator and shift data for human factor analysis. Additionally, HAZOP worksheets were used to systematically identify process deviations, causes, consequences, and mitigation recommendations. A 5×5 risk matrix was applied as a quantitative tool to assess risk levels by combining likelihood and severity. Other instruments included process control forms for the electric furnace to capture real-time process parameters and inspection forms for monitoring skimming activities in the slag pool area. The main parameters analyzed in the HAZOP study are showed in Table 1.

Table 1
Main Parameters of HAZOP Analysis

No.	Parameter	Description
1	Water Jet Pressure	Must remain stable to prevent steam explosion
2	Slag Temperature	Highly critical, ranging from 1500-1600°C
3	Water Flow Rate	Too low flow rate may trigger steam explosion
4	Pump Condition	Affects pressure stability
5	Nozzle Condition	Blockage may cause critical deviations
6	Alarm & Sensors	Early detection system for hazards
7	Interlock System	Automatic shutdown if abnormal parameters are detected

Data analysis in this study was conducted using both qualitative and quantitative approaches to evaluate the effectiveness of the developed risk control system. The qualitative analysis began with examining HAZOP results across three main nodes-Node 1 (Slag Skimming Process), Node 2 (Drill Gun Operation), and Node 3 (Slag Granulation). The analysis focused on identifying deviations, causes, consequences, safeguards, and recommendations. This stage aimed to determine critical deviations with high to catastrophic risk levels, prioritize hazards requiring immediate attention, and understand the relationships between causes, consequences, and existing safeguards. The quantitative analysis involved applying a 5×5 risk matrix to calculate risk levels using the equation risk is likelihood multiplied by severity. Risk values were determined under two conditions: initial risk (before additional controls) and residual risk (after implementing the developed control system). The results were used to classify risks into Low, Medium, High, and Extreme categories and to measure the degree of risk reduction.

A comparative analysis was then performed to evaluate the effectiveness of the risk control system by comparing initial and residual risk values for each critical deviation. The effectiveness was assessed based on the magnitude of risk reduction, the percentage decrease in risk levels, and the system's ability to reduce risks to acceptable levels. The results showd that the developed system significantly reduced risk levels, particularly for high and extreme categories, thereby enhancing process safety and operational reliability in ferronickel slag granulation. The research implementation was carried out systematically in several stages, as showed in Table 2.

Table 2
Research Implementation Stages

No.	Activity Stage	Description	Timeline
1	Literature Study and System Requirement Analysis	Initial stage involving literature review on process safety in metallurgical industries, ISO 31000 and ISO 45001 standards, and previous HAZOP studies, along with system requirement analysis based on actual conditions at PT HJF	March (Week 1-3)
2	Risk Deviation Identification	Analysis of HAZOP results to identify high and extreme risk deviations, including mapping causes, consequences, and evaluation of existing safeguards	March-April (Week 4-5)
3	Risk Control System Design	Development of risk control systems including engineering controls (monitoring pressure and temperature, improving equipment reliability) and administrative controls (SOPs, checklists, inspections, emergency procedures)	April-May (Week 6-8)
4	System Validation and Evaluation	Evaluation of the developed control system through residual risk analysis and comparison between pre- and post-control risk levels	May-June (Week 9-11)
5	Data Analysis and Report Preparation	Final stage involving qualitative and quantitative data processing and preparation of the thesis report, including results, discussion, and conclusions	June-August (Week 12-17)

The study was conducted in accordance with academic and industrial ethical principles, emphasizing integrity, scientific honesty, and professional responsibility. All participants, including operators, technicians, and safety personnel at PT HJF, were informed about the research objectives, methods, and benefits prior to participation, and their involvement was voluntary. Data confidentiality and privacy were strictly maintained, and all collected data were used solely for academic purposes and safety system improvement. The research activities complied with occupational health and safety regulations applicable at PT HJF, including the use of personal protective equipment (PPE) and adherence to operational safety procedures. The researcher maintained objectivity and neutrality throughout the study, ensuring that all findings and conclusions were based on empirical evidence. Furthermore, all references, data sources, and analytical outputs were properly cited in accordance with academic standards, and all results showed in this study are original and free from plagiarism.

Result and Discussion

1. Result

The nickel ore processing plant at PT Halmahera Jaya Feronikel (HJF) consists of eight Rotary Kiln Electric Furnace (RKEF) lines with a total production capacity of 780,000 tons of ferronickel (FeNi) per year, containing 10-12% Ni and 82.99% Fe. The main facilities include eight rotary dryers (RD), eight rotary kilns (RK), eight electric furnaces (EF), and eight ingot casting units, supported by dust handling and slag handling systems. The rotary dryer functions to reduce free moisture content from approximately 35% to around 21%, facilitating material handling and preventing adhesion in conveyors and storage bins. The dried ore is then fed into the rotary kiln along with coal or semi-coke as a reducing agent. Inside the rotary kiln, further moisture removal, decomposition of mineral components, and partial reduction of nickel and iron oxides occur. The resulting calcine, with a temperature of approximately 800°C, is then transferred to the electric furnace for further reduction and smelting, where metal separates from oxides to form slag. The final ferronickel product is cast into ingots.

The smelting process in the electric furnace operates at temperatures between 1400-1500°C. The process aims to reduce NiO and FeO into metallic Ni and Fe, melt both slag and ferronickel, and separate the molten metal from slag. The chemical reactions involved include indirect reduction by CO gas, direct reduction by carbon, and slag-phase reactions near the electrodes. The final reaction produces molten ferronickel (FeNi) at approximately 1450°C. Based (P&ID Furnace), the general specifications of the electric furnace for lines 1-8 at PT HJF are showed in Table 3.

Table 3

General Specifications of Electric Furnace at PT HJF

Parameter	Value
Dimensions	7350 mm × 4050 mm × 2700 mm
Capacity	320-350 tons/day
Furnace Diameter	20,500 mm
Outer Furnace Diameter	23,000 mm
Furnace Height	7,000 mm
Furnace Depth	4,000 mm
Number of Electrodes	3 units
Electrode Diameter	1,500 mm
Electrode Capacity	16,000 KVA
Secondary Voltage	480 Volt
Secondary Current	57.735 kA
Furnace Temperature	1400-1500°C
Slag Temperature	1500-1600°C

The ferronickel slag skimming granulation process consists of three main stages, Node 1 (slag skimming process), Node 2 (drill gun operation), and Node 3 (slag granulation process). These stages are interconnected and play a critical role in maintaining furnace stability and operational safety. The slag skimming process involves removing molten slag from the furnace through the tap hole and directing it to the launder. This stage carries high risk due to the handling of high-temperature molten material, where uncontrolled flow may lead to overflow, equipment damage, or thermal hazards. The drill gun operation supports this process by opening and closing the tap hole using a hydraulic system. Failures in this system, such as inability to open or close the tap hole, may lead to slag accumulation, overpressure, or uncontrolled discharge. The slag granulation process involves rapid cooling of molten slag using high-pressure water jets to produce granular slag. This stage presents significant hazards due to the interaction between high-temperature slag and pressurized water, potentially leading to steam explosions, excessive vapor formation, and reduced visibility.

The HAZOP analysis was conducted to identify process deviations, causes, consequences, safeguards, and required recommendations across the three nodes. The analysis utilized guide words such as no flow, high flow, low flow, high temperature, low pressure, fail to open, and fail to close. The results show that multiple deviations exist across all nodes, with varying levels of risk ranging from low to extreme. The findings from Node 1 (slag skimming process) are in Table 4, the HAZOP results for Node 2 (drill gun operation) are showed in Table 5, and the HAZOP analysis for Node 3 (slag granulation) in Table 6.

Table 4
HAZOP Node 1-Slag Skimming Process

No	Deviation	Possible Causes	Possible Consequences	Safeguards	Consequence Category	S	L	R	Risk Level	Recommendations	S	L	R
1	No Flow	Failure to open tap hole; solid slag blockage	Slag solidification; flow blockage; skimming failure; disruption to furnace smelting	Hole monitoring; routine cleaning; operator training	Production	3	2	6	M6	Standby drill gun procedure; emergency fail open/close procedure	2	2	4
2	High Flow	Large tap hole opening; high fluidity	Launder overflow; slag spillage; thermal hazard to workers	Flow monitoring; temperature sensor	Asset/ Worker	3	3	9	H9	Raise launder height; reduce bend angle; improve supervision	2	2	4
3	Low Flow	Slow flow; high Mg content; viscosity issue	Slag solidification; blockage at tap hole	Flow monitoring; temperature sensor	Production	2	2	4	L4	Temperature sensor calibration	1	2	2
4	High Level	Excess input; large opening	Faster skimming; overflow risk	Flow monitoring; DCS system	Asset	2	2	4	L4	Slag capacity control via DCS	1	2	2
5	High Temperature	Excessive temperature; sensor failure	High flow velocity; launder damage; deformation; leakage risk	Temperature sensor; refractory lining	Asset	4	3	12	H12	Sensor calibration; alarm system; inspection program; response SOP	2	3	6
6	Low Temperature	Low operating temperature	Slag freezing; flow blockage	Temperature sensor	Asset	2	2	4	L4	Sensor calibration	1	2	2
7	Fail to Open	Hard clay; operational error; drill gun failure	Slag buildup; increased furnace pressure; overpressure risk	Drill gun inspection; backup rod; SOP	Production	4	3	12	H12	Emergency SOP for open/close failure	2	3	6
8	Fail to Close	Clay gun failure; drill gun damage; blockage	Continuous slag discharge; FeNi loss; fire/explosion risk	Inspection; cleaning; SOP	Asset	5	3	15	H15	Emergency SOP; drill backup system	3	3	9
9	Leakage	High temperature; launder crack; refractory failure	Slag spill; asset damage; fire; worker injury	Temperature sensor; refractory inspection	Asset	4	2	8	M8	Preventive refractory maintenance; thermal imaging inspection	2	1	2
10	Wrong Composition	Non-homogeneous slag	Reduced granulation efficiency	Lab analysis	Production	2	2	4	L4	Material composition control database	1	2	2
11	Instrument Failure	Sensor failure/inaccuracy	Misinterpretation by operator	Training	Production	3	2	6	M6	Sensor calibration program	2	1	2
12	Slag Spilled	High viscosity; high flow	Launder damage; spill; worker hazard	Visual monitoring; temperature sensor	Asset/Worker	3	2	6	M6	Raise launder; refractory maintenance	2	1	2
13	Launder Erosion	High temperature; high flow; refractory failure	Launder thinning; slag leakage	Inspection; refractory maintenance	Asset	3	3	9	H9	Preventive maintenance; thermal inspection; lifecycle control	2	2	4

Table 5
HAZOP Node 2-Drill Gun Operation

No	Deviation	Possible Causes	Possible Consequences	Safeguards	Category	S	L	R	Level	Recommendations	S	L	R
1	High Pressure	Excess hydraulic pressure; back pressure; oil blockage	Seal damage; hot oil spill; fire risk	Pressure limit; gauge; inspection	Asset	3	2	6	M6	Multi-level pressure alarm; preventive maintenance	2	1	2

2	Low Pressure	Pump wear; clogged filter; low oil volume	Loss of force; incomplete sealing; failure to close	Gauge; inspection; oil level indicator	Production	3	2	6	M6	Pump maintenance; material upgrade	2	1	2
3	High Temperature	Cooling failure; overwork; degraded oil	Oil viscosity loss; leakage; fire risk	Temperature sensor; inspection	Asset	3	2	6	M6	Oil degradation monitoring	2	1	2
4	Gun Jammed	Residue buildup; piston jam; poor cleaning	Drill gun failure; furnace overpressure	Cleaning procedures	Production	3	3	9	H9	Cleaning inspection; emergency SOP	2	2	4
5	No Movement	Hydraulic failure; zero pressure; hose issue	Unsafe position; failure to operate	Inspection; backup tool	Production	2	2	4	L4	Emergency SOP; operator training	1	2	2
6	Oil Leak	Seal wear; fitting wear; hose crack	Oil spill; fire risk; loss of force	Inspection	Production	4	3	12	H12	Absorbent material; hose upgrade; inspection program	3	2	6
7	Human Failure	SOP violation; lack of inspection	Equipment damage; injury risk	SOP; checklist; training	Worker	3	2	6	M6	SOP reinforcement; visual SOP	2	1	2

Table 6
HAZOP Node 3-Slag Granulation

No	Deviation	Possible Causes	Possible Consequences	Safeguards	Category	S	L	R	Level	Recommendations	S	L	R
1	Low Water Level	Pipe leakage; pump blockage; supply issue	Poor granulation; low pressure; slag lumping; explosion risk	Level transmitter; gauge; backup supply	Asset	3	2	6	M6	Emergency shutdown; low-level alarm	2	2	4
2	High Water Level	Excess jet pressure	Water overflow; inefficiency	Level monitoring	Production	2	2	4	L4	High-level alarm; shutdown procedure	1	2	2
3	No Flow	Pump failure; blockage; power failure	Granulation failure; solid slag	Flow meter; pressure gauge	Production	3	1	3	M3	Pump maintenance; nozzle cleaning	2	1	2
4	High Water Temperature	Cooling failure; circulation issue	Poor granulation; equipment damage	Temperature monitoring	Asset	3	3	9	H9	Cooling system maintenance; alarm	2	2	4
5	Low Water Temperature	No temperature control	Thermal shock; explosion risk	Monitoring	Asset	4	2	8	M8	Temperature alarm system	3	2	6
6	Low Pressure Water	Pump failure; leakage; nozzle blockage	Slag lumping; explosion risk	Pressure gauge	Asset	4	4	16	H16	Filtering inspection; pressure monitoring; alarm system	2	2	4
7	High Pressure Water	Overworking pump; sensor failure	Nozzle damage; fine slag	Pressure monitoring	Asset	3	2	6	M6	Pressure control; periodic testing	2	2	4
8	Pump Failure	Mechanical/electrical failure	Loss of pressure; granulation failure	Inspection	Asset	4	2	8	M8	Backup pump system	2	2	4
9	Over Steam	Rapid evaporation	Visibility loss; thermal exposure	PPE; restricted area	Worker	2	4	8	H8	Steam collector installation	1	2	2

2. Discussion

Ferronickel slag is a by product of the nickel smelting process containing various oxide compounds and residual metals. Based on the chemical characteristics shown in Table 2, ferronickel slag is dominated by silica (SiO_2: 48.84%) and magnesium oxide (MgO: 38.98%), while nickel (NiO: 0.02%) and cobalt (Co: 0.00%) contents are relatively low. The presence of alumina (Al_2O_3: 3.02%), iron (Fe: 4.56%), calcium oxide (CaO: 0.42%), and chromium oxide (Cr_2O_3: 1.49%) shows complex viscosity behavior and abrasive properties at high temperatures. The LOI value (0.00%) shows minimal volatile loss, showing thermal stability, yet still allowing exothermic interaction when in contact with high-pressure cooling media such as water jets. These characteristics strongly influence the selection of slag granulation methods. Water jet granulation was chosen due to its capability to rapidly quench and fragment high-viscosity slag into uniform granules while minimizing thermal and mechanical risks. The dominance of silica and MgO increases the tendency of slag to solidify or agglomerate if cooling is not properly controlled, making precise process control essential.

The application of HAZOP is essential for maintaining process safety and product quality. The process is divided into three main nodes which are Node 1 (slag skimming), Node 2 (drill gun operation), and Node 3 (slag granulation). This segmentation allows a detailed and systematic identification of deviations, causes, consequences, and safeguards. Based on the HAZOP results, Node 1 contains the highest number of deviations (13), followed by Node 2 (7 deviations) and Node 3 (9 deviations). Risk classification shows that Node 1 is dominated by flow instability and containment failure, Node 2 by equipment reliability issues, and Node 3 by thermal-fluid interaction risks. Table 7 shows critical deviations in Node 1, where High Flow, High Temperature, Fail to Open, Fail to Close, and Launder Erosion are categorized as high-risk. These deviations show that slag flow rate, temperature, and tap hole operability are key determinants of system safety. Among them, Fail to Close represents the most severe condition due to continuous slag discharge, potential FeNi loss, and fire/explosion hazards.

Table 7

Critical Deviation Identification - Node 1 (Slag Skimming Process)

Node	Critical Deviation	Initial Risk (S×L=R)	Value	Risk Level	Consequences
1	High Flow	3×3=9	H9	B	Slag overflow, exposure risk
1	High Temperature	4×3=12	H12	B	Launder damage, deformation
1	Fail to Open	4×3=12	H12	B	Slag accumulation, overpressure
1	Fail to Close	5×3=15	H15	B	Continuous slag flow, explosion risk
1	Launder Erosion	3×3=9	H9	B	Structural thinning, leakage

Node 2 critical deviations in Table 8, emphasize mechanical reliability, where Gun Jammed and Oil Leak significantly affect operational safety. Oil Leak is particularly critical as it combines fire hazard and functional failure.

Table 8

Critical Deviation Identification - Node 2 (Drill Gun Operation)

Node	Critical Deviation	Initial Risk	Value	Risk Level	Consequences
2	Gun Jammed	3×3=9	H9	B	Operation failure, overpressure
2	Oil Leak	4×3=12	H12	B	Fire risk, loss of hydraulic force

In Node 3 by Table 9, Low Pressure Water emerges as the most critical deviation with Risk Level A (H16), showing the highest priority.

Table 9
Critical Deviation Identification - Node 3 (Slag Granulation Process)

Node	Critical Deviation	Initial Risk	Value	Risk Level	Consequences
3	High Temperature Water	3×3=9	H9	B	Poor granulation, equipment damage
3	Low-Pressure Water	4×4=16	H16	A	Explosion risk, slag agglomeration
3	Over Steam	2×4=8	H8	B	Visibility loss, worker exposure

The design of risk control systems in Table 10-12 shows that effective mitigation requires a combination of engineering and administrative controls.

Table 10
Risk Control Design - Node 1

Node	Deviation	Engineering Control	Administrative Control
1	High Flow	Raise launder height, reduce bends	Flow monitoring
1	High Temperature	Sensor calibration, alarms	Inspection program
1	Fail to Open/Close	Emergency drill availability	Emergency SOP
1	Launder Erosion	Refractory maintenance	Inspection schedule

Table 11
Risk Control Design - Node 2

Node	Deviation	Engineering Control	Administrative Control
2	Gun Jammed	Cleaning monitoring	SOP emergency
2	Oil Leak	Absorbent, hose upgrade	Inspection & housekeeping

Table 12
Risk Control Design - Node 3

Node	Deviation	Engineering Control	Administrative Control
3	High Temperature	Cooling maintenance	Monitoring procedure
3	Low-Pressure Water	Filtering, alarms, indicators	Routine checks
3	Over Steam	Steam collector	Restricted area, SIMOPS

The effectiveness of these controls is validated by comparing initial and residual risks shown in Figure 1.

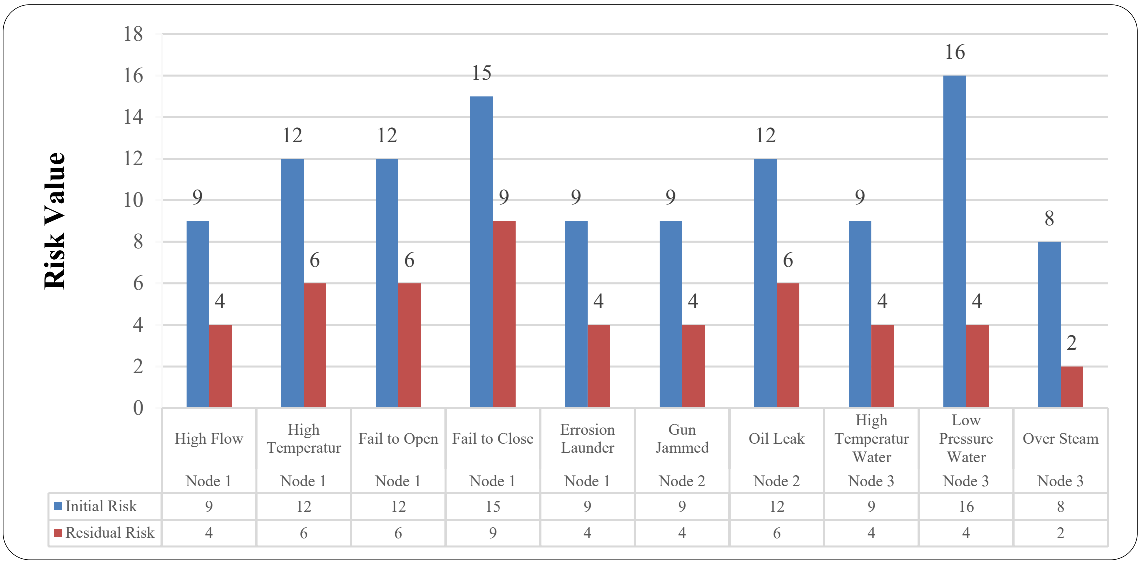


Figure 1. Comparison Graph of Initial Risk and Residual Risk

Results show consistent risk reduction across all nodes. Node 3 shows the highest improvement, particularly Low Pressure Water, which decreases from 16 to 4 (75%).

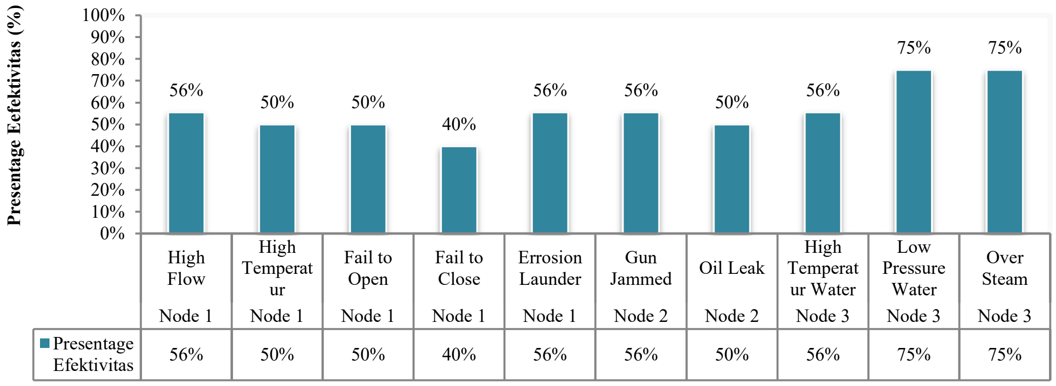
Table 15
Validation of Highest Risk Reduction per Node

Node	Deviation	Initial Risk	Residual Risk	Reduction	Effectiveness
Node 1	Fail to Close	15	9	6	40%
Node 2	Oil Leak	12	6	6	50%
Node 3	Low Pressure Water	16	4	12	75%

Risk reduction is not incidental but achieved through systematic reinforcement of safeguards. The highest effectiveness is observed in Node 3 due to layered engineering controls such as filtration, pressure monitoring, and alarm systems.

The difference in the effectiveness of risk reduction between deviations is strongly influenced by the controllability of the hazard source and the complexity of the operational system. Low-pressure water in Node 3 achieved the highest reduction effectiveness (75%) because the deviation can be directly controlled through layered engineering safeguards, including filtration systems, pressure monitoring instruments, alarms, and preventive maintenance. These controls effectively reduce both the likelihood of failure and the potential for escalation during slag-water interaction. In contrast, Fail to Close in Node 1 only achieved a 40% reduction because the deviation involves more complex mechanical and operational dependencies, including drill gun reliability, hydraulic performance, slag viscosity, refractory conditions, and operator response time. Although emergency SOPs and backup drill systems reduce the likelihood of escalation, the severity consequence remains high due to the potential for continuous molten slag discharge and explosion hazards. This finding shows that deviations involving direct containment of molten material generally require more advanced protective layers and may not be fully mitigated by administrative controls alone. Therefore, residual risks in Fail to Close remain relatively higher compared to process deviations dominated by measurable utility parameters such as water pressure.

The developed risk control system is also aligned with several international process safety standards. The HAZOP implementation in this study follows the principles of IEC 61882, which emphasizes systematic identification of process deviations, causes, consequences, and safeguards within complex industrial operations. The layered engineering controls applied in the granulation system, including alarms, monitoring instruments, interlocks, and preventive maintenance, are consistent with the Process Safety Management (PSM) framework under OSHA 29 CFR 1910.119 and API Recommended Practice 750 regarding hazard analysis, mechanical integrity, and operational control. The integration of administrative controls such as SOPs, inspections, emergency response procedures, and operator training supports the requirements of ISO 45001 concerning occupational health and safety management systems and continuous risk reduction. The combination of engineering and administrative safeguards demonstrates that effective process safety management in ferronickel slag granulation requires both technical reliability and organizational safety commitment.



	High Flow Node 1	High Temperatur Node 1	Fail to Open Node 1	Fail to Close Node 1	Errosion Launder Node 1	Gun Jammed Node 2	Oil Leak Node 2	High Temperatur Water Node 3	Low Pressure Water Node 3	Over Steam Node 3
■ Presentage Efektivitas	56%	50%	50%	40%	56%	56%	50%	56%	75%	75%

Figure 2. Risk Control Effectiveness

Conclusion

The skimming granulation process is confirmed as a high-risk operation due to the interaction between high-temperature molten slag and high-pressure water systems, supported by complex mechanical and hydraulic equipment. The HAZOP analysis identified multiple critical deviations across three nodes, including High Flow, High Temperature, Fail to Open, Fail to Close, Erosion Launder, Gun Jammed, Oil Leak, High Temperature Water, Low Pressure Water, and Over Steam, with Low Pressure Water emerging as the most critical deviation (initial risk value of 16, Level A) due to its potential to cause failed granulation, slag agglomeration, explosions, and severe operational hazards. Process variables such as water jet pressure, slag temperature, water flow rate, pump performance, drill gun condition, and nozzle blockage significantly influence process safety. An integrated risk control system combining engineering controls (*e.g.,* alarms, instrumentation, preventive maintenance, system redesign, and backup equipment) and administrative controls (*e.g.,* SOPs, emergency procedures, inspections, and training) was successfully developed. Validation results show that all critical risks were reduced, with effectiveness ranging from 40% to 75% and an average reduction of 56.62%, where Low Pressure Water and Over Steam showed the highest improvement, while Fail to Close still requires further enhancement.

Reference

Bai, M., Qi, M., Shu, C. M., Reniers, G., Khan, F., Chen, C., & Liu, Y. (2023). Why do major chemical accidents still happen in China: Analysis from a process safety management perspective. *Process safety and environmental protection*, *176*, 411-420.

Benson, C., Obasi, I. C., Akinwande, D. V., & Ile, C. (2024). The impact of interventions on health, safety and environment in the process industry. *Heliyon*, *10*(1).

Dinata, E., Pramayogi, K. S., Asnanning, A. R., & Agustina, R. (2025). Comparative Analysis of HIRARC and HIRADC Methods in Occupational Safety Risk Management for Girder Erection Projects. *Indonesian Journal of Environment and Sustainability Issues*, *2*(1), 20-30.

Durukan, O., Akyuz, E., Destanoğlu, O., Arslanoğlu, Y., & Sezer, S. I. (2024). Quantitive HAZOP and DS evidence theory-fault tree analysis approach to predict fire and explosion risk in inert gas system on-board tanker ship. *Ocean Engineering*, *308*, 118274.

Haiedar, M. H., & Kholifah, S. (2025). The impact of occupational safety, workload, and compensation on employee job satisfaction in the mining industry: a case study of PT BCKA. *Journal of Management and Informatics*, *4*(1), 587-598.

International Labour Organization. (2020). Safety and Health in Mining. Geneva: ILO. (pp. 12-14).

ISO 31000:2018. Risk Management Framework. Clause 6.3-6.5.

Luo, J., Li, G., Rao, M., Peng, Z., Liang, G., Jiang, T., & Guo, X. (2021). Control of slag formation in the electric furnace smelting of ferronickel for an energy-saving production. *Journal of Cleaner Production*, *287*, 125082.

Musyafa, *et al*. (2023). Industrial Safety Optimization. (pp. 90-95).

Qi, Y., Conmy, P. R., Huang, W., Zhao, X., & Huang, X. (2022). A hierarchical HAZOP-like safety analysis for learning-enabled systems. *arXiv preprint arXiv:2206.10216*.

Sarmin, W., & Mita, N. (2026). The Impact of Nickel Downstreaming on Economic Growth in East Luwu Regency for the 2018-2024 Period. *Mustard Journal De Ecobusin*, *3*(1), 12-23.

Suroso, H. C., & Yanuar, K. E. (2020). Analisa Potensi Bahaya pada Perusahaan Fabrikasi Baja menggunakan Metode HAZOP (Hazard and Operability Study). *Journal of Advances in Information and Industrial Technology*, *2*(1), 13-21.

Zhang, *et al*. (2021). Control of Slag Formation in Electric Furnace Smelting of Ferronickel. (pp. 58-60).

Zhang, H., Li, B., Karimi, M., Saydam, S., & Hassan, M. (2023). Recent advancements in IoT implementation for environmental, safety, and production monitoring in underground mines. *IEEE internet of things journal*, *10*(16), 14507-14526.