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Integrated Process Safety Management Framework for Hazard Identification, Risk Assessment and Consequence Analysis in Steel Manufacturing Industries

Raj Dhanyakumar Kale[1], Mohsin Khan[2] and Dr. Neeta Banger[3]

PG Scholar[1] and Professor[2,3]

Shiv Kumar Singh Institute of Technology and Science, Indore, Madhya Pradesh, India

Abstract: *Industrial safety has become a major concern in modern manufacturing industries due to the increasing complexity of industrial processes, the use of hazardous materials, high operating temperatures, combustible gases, pressurized systems, and automated production facilities. Among various manufacturing sectors, steel industries are considered one of the most hazardous because of the presence of fire, explosion, toxic gas release, confined spaces, heavy material handling, molten metal operations, rotating machinery, and high-energy process equipment. Effective Process Safety Management (PSM) is therefore essential to identify potential hazards, assess associated risks, and implement appropriate preventive and protective measures to minimize the likelihood and consequences of major industrial accidents.*

The primary objective of this research is to develop an Integrated Process Safety Management (PSM) Framework for systematic hazard identification, risk assessment, consequence analysis, and risk mitigation in steel manufacturing industries. The proposed framework integrates internationally accepted process safety principles with practical industrial safety methodologies to establish a structured approach for managing process-related hazards. The study emphasizes proactive risk management by identifying hazardous scenarios, evaluating the probability and severity of potential incidents, and recommending suitable engineering, administrative, and operational control measures for improving overall process safety performance.

The research incorporates multiple hazard analysis techniques, including Hazard Identification (HAZID), Process Hazard Analysis (PHA), Hazard Identification and Risk Assessment (HIRA), qualitative risk matrix methodology, consequence analysis, and risk evaluation to investigate various process units and operational activities. Hazards associated with fire, explosion, toxic gas release, confined space entry, work at height, material handling, rotating equipment, electrical systems, pressure vessels, and chemical handling are systematically identified and analyzed. Risk levels are determined by considering both the likelihood of occurrence and the severity of potential consequences, enabling the prioritization of critical hazards requiring immediate attention.

Furthermore, consequence analysis is carried out to evaluate the possible impact of major accident scenarios involving fire, explosion, and toxic releases. The study also proposes appropriate risk reduction strategies based on the hierarchy of controls, engineering modifications, preventive maintenance, standard operating procedures, permit-to-work systems, process monitoring, emergency preparedness, and personnel competency development. A qualitative risk matrix is utilized to classify identified hazards into high, medium, and low-risk categories. High-risk scenarios require immediate corrective actions and implementation of effective control measures, whereas medium-risk activities require continuous monitoring and risk reduction based on the As Low As Reasonably Practicable

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(ALARP) principle. Low-risk activities are considered acceptable under routine operational control and periodic safety review.

In addition to hazard analysis and risk evaluation, the proposed framework highlights the significance of continuous safety improvement through systematic safety audits, incident investigation, process safety performance indicators, emergency response planning, disaster management planning, safety training, and organizational safety culture. The integration of these Process Safety Management elements establishes a comprehensive safety management system capable of reducing process-related incidents, improving regulatory compliance, enhancing operational reliability, and supporting sustainable industrial development. The framework also provides practical guidance for implementing preventive safety measures throughout the operational lifecycle of steel manufacturing processes.

The findings of this study demonstrate that an integrated Process Safety Management approach significantly improves hazard control, strengthens decision-making in risk management, and enhances the effectiveness of consequence-based safety planning. The proposed framework serves as a practical decision-support tool for industrial safety professionals, plant managers, and process engineers in identifying critical hazards, evaluating operational risks, and implementing appropriate mitigation strategies. The methodology developed in this research is generic in nature and can be effectively adapted to other high-risk process industries, thereby contributing to safer industrial operations, improved organizational resilience, and sustainable process safety performance.

Keywords: Process Safety Management (PSM); Hazard Identification (HAZID); Process Hazard Analysis (PHA); Hazard Identification and Risk Assessment (HIRA); Consequence Analysis; Risk Assessment; Risk Evaluation; Risk Matrix; Fire and Explosion Safety; Risk Mitigation; Emergency Preparedness; Industrial Safety; Steel Manufacturing Industries.

I. INTRODUCTION

The Indian steel industry is a major contributor to economic growth, infrastructure development, and employment generation. However, the industry is characterized by the handling of combustible gases, toxic chemicals, molten metal, high-pressure systems, and high-temperature operations, which create significant process safety challenges. Historical incidents such as blast furnace gas leakages, oxygen system explosions, dry pit explosions, and carbon monoxide fires have demonstrated the catastrophic consequences of inadequate process safety management.

Traditional occupational safety programs primarily focus on personal injuries, whereas Process Safety Management (PSM) emphasizes the prevention of major accidents resulting from loss of containment of hazardous energy or substances. Therefore, an integrated framework combining hazard identification, risk assessment, and consequence analysis is essential for improving safety performance in steel manufacturing industries.

Steel is a product of large and technologically complex industry having strong forward and backward linkages in terms of material flows and income generation. It is also one of the most important products of the modern world and of strategic importance to any industrial nation. From construction, industrial machinery to consumer products, steel finds its way into a wide variety of applications. It is also an industry with diverse technologies based on the nature and extent of raw materials used. In India, steel has an output multiplier effect of nearly 1.4X on GDP and employment multiplier factor of 6.8X .

The Indian steel industry has entered into a new development stage from 20024-25, riding high on the increasing after a period of little activity, economy and rising demand for steel. The rapid rise in production has resulted in India becoming the 3rd largest producer of crude steel in 2024 and the country continues to be the largest producer of sponge iron in the world. As per the report of the Working Group on Steel for the 12th Five Year Plan, there exist many factors which carry the potential of raising the per capita steel consumption in the country. These include, an estimated

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infrastructure investment of nearly a trillion dollars, a projected growth of manufacturing from current 8% to 11-12%, increase in urban population to 600 million by 2030 from the current level of 400 million.

At the time of independence in 1947, India had only three steel plants – the Tata Iron & Steel Company, the Indian Iron and Steel Company and Visveswaraya Iron & Steel Ltd and a few electric arc furnace based plants. The period till 1947 thus witnessed a small but viable steel industry in the country, which operated with a capacity of about 1 million tonne and was completely in the private sector. From the fledgling one million tonne capacity status at the time of independence, India has now risen to be the 2nd largest crude steel producer in the world and the largest producer of sponge iron. As per official estimates, the Iron and Steel Industry contributes around 2 per cent of the Gross Domestic Product (GDP) and employs about 25 lakh people directly or indirectly. From a negligible global presence, the Indian steel industry is now globally acknowledged for its product quality. As it traversed its long history since independence, the Indian steel industry has responded to the challenges of the highs and lows of business cycles.

Process Safety- Process safety is a blend of Engineering (Design & Maintenance), operations and management skills focused on preventing catastrophic accidents, particularly structural collapse, explosions, fires and toxic releases associated with loss of containment of energy or dangerous substances such as toxic gases, molten metal, chemicals and petroleum products.

Process Safety Incidents can:

- Kill and injure many people
- Cause massive and long lasting pollution
- Cause major economic disruption
- Severely damage a company's reputation
- Cause companies to become "paralyzed" in the aftermath
- Lead to companies and individuals being prosecuted

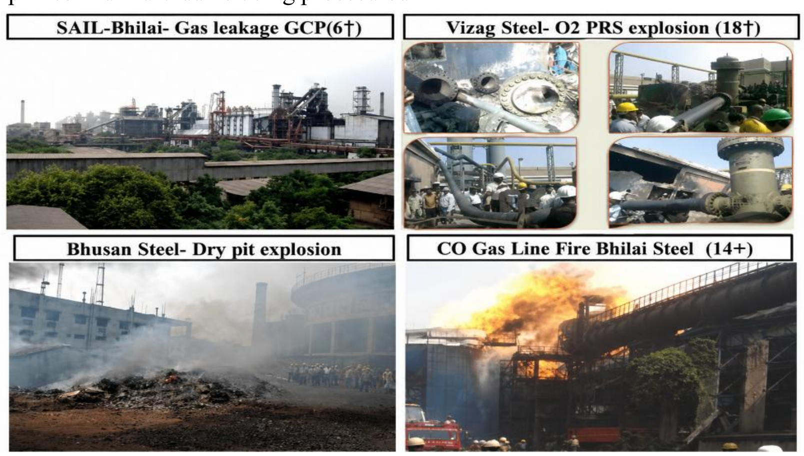

Fig. 1: Process Disasters at Indian Steel Industry

The most important 3 characteristics of safety management system are effort, time and money. In order to achieve a zero accident rate an organization needs to provide these 3 basics. The very next principle of the safety management system is the involvement and commitment towards the assigned work. Since without involvement a work cannot be completed and without commitment the goals and objectives set cannot sustain.

After this then comes the actual responsibility of the organization. It is because an organization needs to set goals, objectives and motivate employees to work for safety. For this management needs to appoint safety officers, provide trainings to the worker class people and try to change their mindset and made them work with all safety measures. Also communication is the most important aspect for safety management system. And for effective communication the

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employees at high position needs to interact with the worker class on a regular interval so that the worker class can put up their views for improving safety standards.

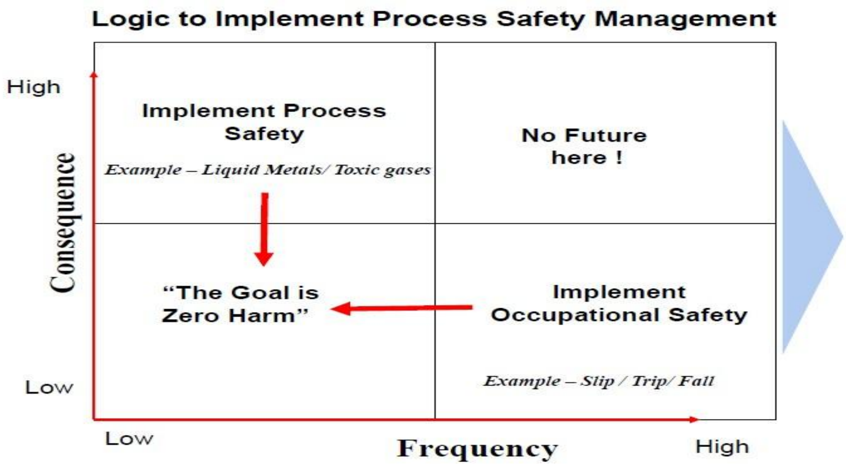

Fig. 2: How process safety is different from occupational safety

II. LITERATURE REVIEW

D V R Seshadri et.al 2024 the case on Tata Steel captures the success story of Tata Steel very effectively as to how a giant corporation, led by a world-class management team, reinvents itself and sets out on a growth path when faced with dramatic challenges from the environment. This analysis is aimed at summarizing some of the issues and the challenges Tata Steel is likely to face in the years ahead.

Firdos Ali et.al 2023 Evolution of industries/companies started in the start of 19th century. Some small and major industries/company established in this century and these company/industries increases day by day throughout the world. Due to this evolution in industries small machinery is replaced with big or powerful machinery, power capacity also increases and system made more complex. Due to this or along with this risk and hazard also increases.

Somnath Kumar 2023 et.al Steel manufacturing is an industry where safe working procedures are important, as workers face many risks due to the nature of the job. The work environment is often hot and noisy, and work tasks regularly heavy and demanding on the body, and there is an always present risk for crushing injuries and burns. Steel companies have significantly improved their safety performance over the last 10 years, but many have reached a plateau where further progress is more difficult to achieve.

Modi Al be et.al 2022 Energy is needed in the wire rod plant processes for any value addition activity to develop the finished product. The increased energy costs and an uncertain steel markets have created the demand for a system in the steel plant, to utilizes the rolling process waste heat, or improve rolling process so that next further processing may be avoided for rolled product.. The process energy optimization is a tool to improve profitability, environment and productivity of an organization

Devdatt P Purohit et.al 2022 in industrial arena, if any industry to be successful, it has to be safe, reliable, and sustainable in its operations. The industry has to identify the hazards and assess the associated risks and to bring the risks to tolerable level. Hazard Identification and Risk Assessment (HIRA) is carried for identification of undesirable events that can lead to a hazard, the analysis of hazard of this undesirable event, that could occur and usually the estimation of its extent, magnitude and likelihood of harmful effects.

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III. AREA OF STUDY

The study focuses on integrated steel manufacturing plants in India, covering major process units such as:

- Coke Oven Plant (COP)
- Sinter Plant
- Blast Furnace (BF)
- Basic Oxygen Furnace (BOF)
- Steel Melting Shop (SMS)
- Continuous Casting Machine (CCM)
- Rolling Mills
- Oxygen Plant and Gas Distribution Network

These units involve toxic gases, explosive atmospheres, molten metal handling, confined space operations, and high-energy systems that require detailed process safety evaluation.

The present research focuses on the integrated implementation of Process Safety Management (PSM) in the steel manufacturing industry, emphasizing systematic Hazard Identification (HAZID), Risk Assessment (RA), and Consequence Analysis (CA) for improving process safety performance. Steel manufacturing is recognized as one of the most hazardous industrial sectors due to the handling of combustible gases, molten metals, high-pressure systems, toxic chemicals, and high-temperature operations. Major process units such as Coke Oven Plant (COP), Sinter Plant, Blast Furnace (BF), Basic Oxygen Furnace (BOF), Steel Melting Shop (SMS), Continuous Casting Machine (CCM), Rolling Mills, Oxygen Plant, Gas Distribution Network, and Utility Systems involve complex interactions between personnel, equipment, materials, and operational procedures, making them vulnerable to major accident hazards.

The study covers the identification of hazards associated with blast furnace gas (BFG), coke oven gas (COG), converter gas (LD gas), oxygen systems, compressed air networks, fuel gas pipelines, pressure vessels, storage tanks, and hot metal handling operations. Historical accident data from Indian steel plants, including gas leakages, explosions, fires, oxygen-related incidents, and confined space accidents, are considered to understand recurring causes and process safety deficiencies.

The research integrates internationally accepted risk assessment methodologies such as HAZOP (Hazard and Operability Study), What-If Analysis, Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Bow-Tie Analysis, Risk Matrix Method, and Layer of Protection Analysis (LOPA) to evaluate process risks. Furthermore, consequence analysis is carried out for credible accident scenarios involving toxic gas dispersion, fire, explosion, and thermal radiation using recognized modelling approaches and consequence assessment tools.

The geographical scope of the study includes integrated steel manufacturing plants in India, with detailed analysis based on representative process units and publicly available accident case studies. The proposed framework aims to establish a comprehensive Process Safety Management model that integrates hazard identification, quantitative and qualitative risk assessment, consequence analysis, engineering controls, administrative controls, emergency preparedness, and continuous safety performance monitoring. The outcome of this research is expected to support steel industries in minimizing major accident risks, strengthening regulatory compliance, enhancing operational reliability, and promoting sustainable and safe industrial operations.

IV. HAZARD IDENTIFICATION AND METHODOLOGY

Hazard identification was performed using HAZID and HAZOP methodologies. Major hazards identified include:

Hazard Category	Major Sources
Toxic Gas Hazard	Blast Furnace Gas, CO-rich gas lines
Explosion Hazard	Oxygen systems, hydrogen and methane rich gases
Thermal Hazard	Molten metal, slag handling, furnaces
Fire Hazard	Fuel gas pipelines, oils, LPG, electrical faults

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Confined Space Hazard	Gas holders, tanks, pits, pipelines
Electrical Hazard	High-voltage equipment and switchyards

Table 1 Major hazards identified

Risk assessment considered both the likelihood of occurrence and the severity of consequences to classify risks into acceptable, tolerable, and unacceptable categories.

Occupational Safety & Working Conditions is relatively neglected area by Indian industry and because of this while India has approximately 3% share of global manufacturing, India has almost 30% share of the industrial fatalities globally. Even Steel industry in India lags its global peers on this parameter and has patchy safety performance with many major incidents involving multiple fatalities. Most of the companies actually do not even have a proper safety management system comparable to global best practices. Though most of large ISPs are OHSAS- 18001 certified, never the less their contribution in workplace fatalities is not insignificant. Contractor workers which accounts for nearly half of the manpower deployed in steel industry are more susceptible to incidents as they are unskilled, not so educated and unaware of the hazardous work environment. However, in-spite of all efforts, their share in fatalities continues to be higher on year to year basis. Safety is still being managed in isolation and not as an essential / integral part of overall business decisions, culture & performance in most of the organizations. Efforts for benchmarking by taking lessons from past failures & good practices from peer industry are limited to few organizations only.

Consequence Analysis

Representative failure scenarios were developed for gas leakage, fire, and explosion events. Consequence analysis evaluated:

- Toxic gas dispersion distances
- Thermal radiation impact zones
- Explosion overpressure effects
- Potential injury and fatality zones
- Damage to adjacent process units

The analysis demonstrated that failure of gas containment systems can produce extensive impact zones affecting both personnel and critical infrastructure.

S. No	Type of Hazard/Risk	Major areas where Hazard is faced
1	Toxic gases (rich in Carbon monoxide)	All over the plant
2	Explosive Gases (Rich in Hydrogen and Methane)	All over the plant
3	Harmful Chemicals	Coal Chemicals plant, CRM
4	Liquid metal/ slag (burn, explosions)	Blast Furnace, SMS, Continuous casting, Foundries
5	Extreme Temperature (-180^0 C to 1700^0 C)	Coke Ovens, Blast Furnace, SMS, Continuous casting, Foundries, Rolling Mills and Cryogenic Oxygen Plant
6	Fire	All over the plant
7	Electric Shock, Electrocution, Flash over	All over the plant and project sites
8	Rail/ Road Traffic Movement	All over the plant and project sites
9	Moving/ Rotating machines (Hit, Caught, pressed etc.)	All over the plant and project sites
10	Working at Height	All over the plant and project sites
11	Dust, noise, heat and Vibration	All over the plant
12	Material Handling	All over the plant and project sites

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13	Confined Space (suffocation/ gas poisoning)	Furnaces, Tanks, Gas Pipelines, Gas holders, Sumps, Pits, Oil cellar, Conveyor/ cable galleries, Silos, etc.

Table 2: Hazard in Steel Plant

As per ILO Code of practice on Safety & Health in the Steel Industry, 2005 Below are the most common causes of injury in the iron and steel industry:

1) Slips, trips and falls on the same level
2) Falls from height
3) Unguarded machinery
4) Falling objects
5) Engulfment
6) Working in confined spaces
7) Moving machinery, on-site transport, forklifts and cranes
8) Exposure to controlled and uncontrolled energy sources
9) Inhalable agents (gases, vapors, dusts and fumes)
10) Contact with hot metal, Reactive substances, hazardous chemicals
11) Fire and explosion
12) Extreme temperatures
13) Radiation (non-ionizing, ionizing)
14) Noise and vibration
15) Electrical burn, Electrical Flash and electric shock
16) Manual handling and repetitive work etc.

Group	Item	Nature of Hazard	Hazard Potential	Remarks
Raw materials Management	Coal for coking	Fire	Moderate	Fire hazard
	Water treatment chemicals like acids/alkalis	Toxic	Major	Bio-corrosive
		Fire	Moderate	Flammable
Production units				
Coke Plant	Dusts and fumes	Asphyxiation	Moderate	Air pollution
	VOC emissions from battery	Toxic	Moderate	Health hazard
	Coke oven gas	Fire & Toxic	Major	Fire and CO hazard
	Tar	Fire & Toxic	Moderate	Flammable
Agglomeration	Dusts	Respiratory	Moderate	Air pollution
Iron making in BF	Release of untreated wastewater	Toxic	Major	Severe pollution of surface water
	BFG handling	Fire	Major	Fire hazard
	Hot metal & slag Handling	Heath	Major	Fire hazard
Steel making in LD shops	Release of untreated wastewater	Toxic	Major	Severe pollution of surface water
	LD gas handling	Fire	Major	Fire and CO hazard
	Hot liquid steel & slag handling	Heath	Major	Fire hazard
Rolling Mills	Gas firing	Fire	Major	Fire hazard
	R e lease of untreated Waste water	Toxic	Major	Severe pollution of

				surface water
Captive Power Plant		Fire	Major	Fire hazard
Utilities				
Fuel gas	Gas leaks	Fire & Toxic	Major	Fire and CO hazard
Electric Power supply	Short circuit	Fire	Major	Fire hazard
Liquid fuel	Fuel handling & storage area	Fire & Toxic	Major	Fire & CO hazard
Hydraulic oil and lubricants	Accidental discharge of hydraulic oil under pressure	Fire & Toxic	Moderate	Fire & personal injury

Table 3: Identification of Hazards

Methodology

Risk analysis (RA) acts as a scrutinizing vehicle for establishing the priority in risk management that concerns human health and environmental quality in general. Though the proposed facilities are not manufacturing, storing or handling any potentially hazardous/toxic chemicals as scheduled in the Manufacture, Storage and Import of Hazardous Chemicals (MSHC) Rules, 1989 and its amendments thereof, the proposed facility would have installations, such as, storage and handling of coal, fuel oil, and fuel gases. An Environmental Qualitative Risk Analysis Flow Chart Procedure is depicted in Figure below

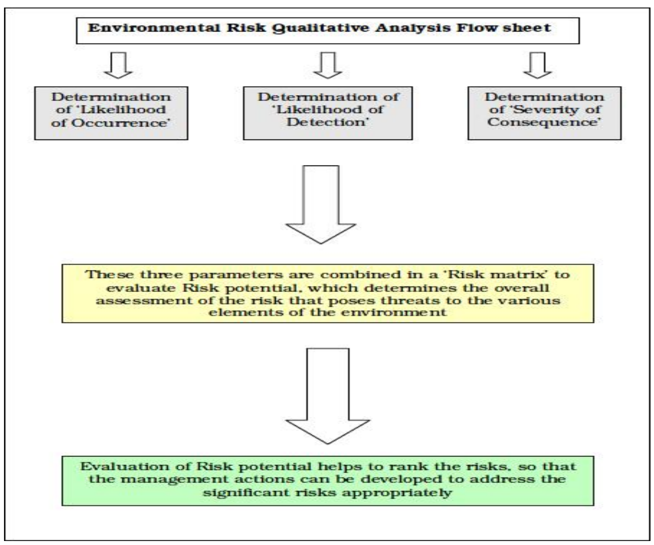

Figure 3 Risk Qualitative Analysis Flow sheet

As revealed in the Figure 3, the relative risk potential analysis is made on the following three factors using a P/I (Probability/Impact) analysis methodology:

- Likelihood of occurrence
- Likelihood of detection
- Severity of consequence

Each of these factors is graded and compiled to determine the risk potential. The factors governing the determination of relative risk potentials are presented in Table 4.1 below

(A)	(B)	(C)
Likelihood of occurrence	Likelihood of detection	Severity of consequence

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Criteria	Rank	Criteria	Rank	Criteria	Rank
Very High	5	Very High	1	Very High	2
High	4	High	2	High	4
Moderate	3	Moderate	3	Moderate	6
Low	2	Low	4	Low	8
Very low	1	Very low	5	Very low	10

Table 4 Determination of Risk Potential

$$\boldsymbol{RISK\ POTENTIAL\ (RP) = (A + B) \times C}$$

Based on the Table for assessing the risk, each probable event will finally been evaluated by addressing several questions on the probability of event occurrence in view of the in-built design features, detection response, operational practice and the likely consequence further in final industry work.

A summarized list of risk potential for the likely events with proper matrix will be prepared in final work.

The Final assessment will be based from the past experience in the operation of an integrated iron and steel plant and best practicable designs for the proposed Project.

The present risk potential evaluation is primarily based on human errors or faulty operation or failure of the control systems. The overall procedure followed by steel plant was discussed here now in the next section we will discuss the actual profile of calculation on the basis.

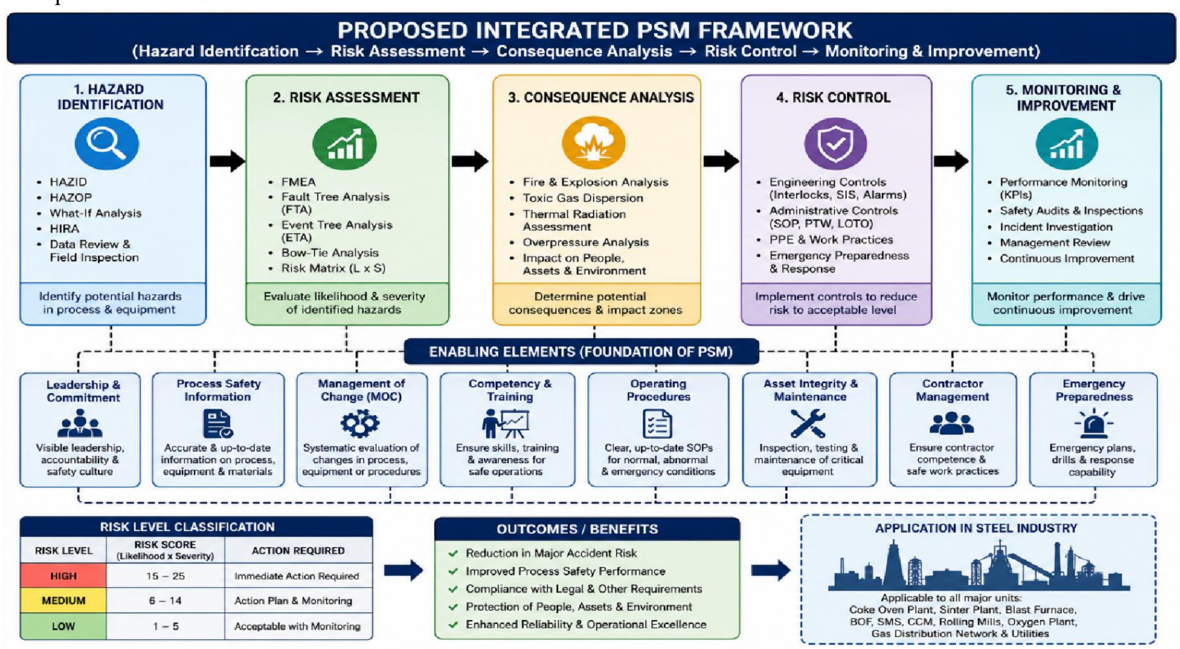

Figure 5 Integrated PSM Framework

V. CALCULATION AND RESULTS

Hazard Identification and it dealing in steel plants with the identification and quantification of risks that are exposed to, due to accidents resulting from the hazards present or handling of hazardous substances in the workplace. This involves Hazard analysis which essentially is identification and quantification of the various hazards that are likely to occur in the industry as well as quantification of the consequences due to a particular hazard. The risk analysis estimates the probability as well as severity of a particular hazard over an exposed group of people, plant equipment or both.

Model assists in identifying the most likely hazards which can have significant impact on workplace safety in an industry. It helps in devising effective management measures as well as engineering measures for both preventive as well as post-disaster management.

The scope of this report includes the study of proposed operations, storage and handling of hazardous materials with respect to Hazard Identification, Risk Assessment and updating of existing Disaster Management plan (DMP). Based on the Hazard Identification and analysis, the major disaster scenarios would be worked out to estimate the consequence of failure. Local based Steel plant already has a comprehensive Disaster Management plan (DMP) and the same would be evolved to also meet the emergency situations due to the proposed expansion-cum-modernization project.

The present report includes hazard identification and consequence analysis for the new projects included in the proposed expansion-cum-modernization of Steel plant as well as ongoing for existing critical units of Steel Plant. The primary potential hazards due to the proposed units are identified based on a detailed Primary Hazard analysis (PHA) along with consequence analysis for the risk assessment.

Proposed Expansion-cum-modernization projects

1) Modernized BOF gas holder in modernized SMS-I
2) New BOF gas holder in SMS-II
3) Revamped propane storages within modernized SMS complex

The process is an ongoing and continual process for existing units and is undertaken on periodical basis for ensuring good workplace safety at Steel plant. It also involves a periodic review of the same as well as dissemination of information to various employees through instruction and along with adequate documentation and record-keeping.

1) Hazard identification
2) Assessment of risks associated with the identified hazards
3) Control measures to manage the exposure to the risks
4) Monitoring and review of the effectiveness of the controls.

Existing Facilities of Steel plant are

1) Energy Management Department (Fuel gases etc.)
2) Blast Furnace
3) Coke Oven and By-product plant
4) Steel making Shop
5) Cold Rolling mill
6) Sinter Plant
7) Raw Material handling plant

A. Gas Mixing Stations

A maximum total of 75,000 m3/hr of mixed gas is proposed to be handled by a new Gas mixing station envisaged at plant Coke Oven complex, wherein BF Gas and Coke Oven gas will be tapped from existing as well as future producing units and will be mixed in suitable proportions to produce Mixed gas of desired calorific value for use at the existing and new coke oven batteries. The results of MCA analysis indicates a maximum fire hazard distance for causing significant damage (@37.5 Kw/m2 thermal radiations) extending up to 38 m in the case of complete failure of the holder and catastrophic release of BOF gas, subsequently being ignited during worst meteorological conditions resulting in a fireball.

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B. BOG Gas Holder

There are two (2) BOF gas holders, i.e. a replaced BOF gas holder of SMS-1 of 50,000 m3 capacities and a new gas holder of 80,000 m3 capacities, both located within the SMS complex of Steel Plant.

The results of MCA analysis indicates a maximum fire hazard distance for causing significant damage (@37.5 Kw/m2 thermal radiations) extending up to 84 m in the case of complete failure of the holder and catastrophic release of BOF gas, subsequently being ignited during worst meteorological conditions resulting in a fireball.

S. No	**Hazardous event**	**Consequence of significant damage**	(A) **Consequence severity*** (1=least severe; 5=most severe)	(B) **Likelihood*** (1=least likely; 5=most likely)	(C) **RISK RANK**
1	Onsite vehicle impact on personnel	Potential for single fatalities, onsite impact only	3	3	9
2	Entrapment/struck by Machinery	Potential for single fatalities, onsite impact only	3	2	6
3	Fall from heights	Potential for single fatalities, onsite impact only	1	3	3
4	Electrocution	Potential for single fatalities, onsite impact only	2	3	6
5	Gas Mixing Station fire & explosion as well as toxic dispersion	Potential for multiple fatalities, onsite impact only	4	1	4
6	BOF gas holder failure and fire & explosion as well as toxic dispersion	Potential for multiple fatalities, onsite impact only	5	1	5
7	Propane Bullet's fire & explosion	Potential for multiple fatalities, onsite impact only	3	1	3
Based on Analysis					

Table 5: Hazardous Events Contributing to Risk and their Risk Ranking

The above risk analysis indicates that although the most severe consequences will be due to rupture of BOF Gas holders followed by Gas Mixing station and Mounded propane bullets, their chances of occurrences are low due to implementation of better safety features in the installations and constant monitoring of vessel / pipe work integrity for regular repair and maintenance, and hence these facilities have low levels of risk in the facility.

C. Mounded Propane Bullet

Plant has envisaged two (2) propane bullets, each of 100Tonne capacity, located within the Steel Plant for heating and cutting purposes. The results of MCA analysis indicates a maximum fire hazard distance for causing significant damage (@12.5 Kw/m2 thermal radiation) extending up to 45 m in the case of complete failure of the pipeline connections on the bullets and release of propane, subsequently being ignited during worst meteorological conditions resulting in a jet fire. Explosion effects having significant potential for damage (@0.21 bar (g) overpressure) is also observed to be up to a distance of 45 m.

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D. Risk Analysis for Proposed Products

The hazardous event scenarios likely to make the significant contribution to the risk of potential fatalities are enlisted in Table 3. The risks to people at plant site are categorized as "On-site" risks while the risks to communities outside the plant premises is categorized as "Off-site" risks.

VI. CONCLUSION, RECOMMENDATION AND FUTURE SCOPE

A. Conclusion

The proposed Integrated Process Safety Management Framework provides a systematic approach for identifying hazards, evaluating risks, and analyzing consequences in steel manufacturing industries. The study demonstrates that comprehensive implementation of PSM elements can significantly reduce the likelihood and severity of major accident events involving toxic gas releases, fires, explosions, and molten metal operations. The framework offers practical guidance for steel plants to strengthen regulatory compliance, improve operational reliability, and achieve sustainable safety performance.

The risk assessment and analysis for steel plant for most severe hazardous events is broadly summarized below: The nearest habitations in the vicinity of the plant

Plant are Local village at distance >4000min NW, Mhow village at distance >3000m in SW, in SE at distance >2500m at distance >2300m in the NE, which are far away from the hazard distances observed for thermal effects (maximum at 127m) as well as toxic effects (maximum at 50m) due to failure of above identified hazardous facilities of plant. Also, these facilities are located in the central part of the steel plant away from each other to prevent multiple hazards, initiated due to fire in one facility and leading to a hazard in another facility, also known as domino effect. So, there will be no significant impact on the local community or damage to property / environment.

The most severe damage effects due to the identified hazardous facilities will be limited to the plant premises and adequate safety controls as well as implementation of recommended control strategies in the design as well as operation stage will ensure effective management of the associated risks.

B. Recommendation.

The following opportunities shall be considered as a potential means of reducing identified risks during the detailed design phase:

1. The zones identified from consequence modeling as affected areas due to thermal radiations greater than 12.5 kW/m2 shall be marked as "Heat Zones" and provisions for firefighting will be made available close to these zones.
2. It is also recommended to provide portable gas detectors within the site in order to facilitate manual gas leak monitoring and regular leakage checks.
3. Constant monitoring of gas leak shall be ensured for immediate identification of leaks and subsequent implementation of action plan to prevent development of any hazardous situation.
4. Further, all major units / equipment shall be provided with the following safety facilities:

- Smoke / fire detection and alarm system
- Water supply
- Fire hydrant and nozzle installation
- Foam system
- Water fog and sprinkler system
- Mobile fire-fighting equipment
- First-aid appliances

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Personal Protective Equipment (PPE) shall be provided for additional protection to workers exposed to workplace hazards in conjunction with other facility controls and safety systems.

a. Restricted access to these areas to have minimum casualties in an event of exposure.
b. The onsite Emergency Plan will be integrated with the Mhow district's Offsite Emergency Plan for comprehensive management of emergencies in minimum response time and maximum rescue results in an event of a disaster

2. /emergency. Co-ordination with nearby industries will also be maintained for creating unified Disaster management resource pool to be utilized in case of any disaster occurrence.
3. The plant structures shall be designed for cyclone floods and seismic events to prevent structural collapse and integrity of weather (water) proofing for storage of dangerous goods.
4. Isolate people from load carrying/mechanical handling systems, vehicle traffic and storage and stacking locations.
5. Security of facility to prevent unauthorized access to plant, introduction of prohibited items and control of onsite traffic; and
6. Development of emergency response management systems commensurate with site specific hazards and risks (fire, explosion, rescue and first aid).
7. Regular safety audits shall be undertaken to ensure that hazards are clearly identified and risk-control measures are maintained within tolerable limits.

Steel plant has a well laid down Onsite-emergency plan for the existing plan. The same will be extended to the proposed modernization and expansion projects also.

C. Future Scope

Safe working procedures for high risk activities:

Highly flammable gases as well as liquid metal are handled during the operations at Steel plant on day-to-day basis. These activities viz. handling of hazardous gases as well as handling of liquid metal are categorized as High risk activities due to their higher damage potential, higher exposure levels despite lower chances of occurrence.

Plant has defined safety procedures to be adhered to while handling hazardous gases as well as liquid metal in plant. These are elaborated in various Inter Plant Standard – Steel Industry (IPSS).

- Steel Manufacturing Industries (Integrated Steel Plants)
- Coke Oven Plant (COP)
- Sinter Plant
- Blast Furnace (BF)
- Basic Oxygen Furnace (BOF)
- Steel Melting Shop (SMS)
- Continuous Casting Machine (CCM)
- Rolling Mills
- Oxygen Plant and Gas Distribution Network
- Utility Systems and Process Pipelines
- Hazard Identification using HAZID & HAZOP
- Risk Assessment using FMEA, FTA, ETA, Bow-Tie, LOPA, and Risk Matrix
- Consequence Analysis for Fire, Explosion, Toxic Gas Dispersion, and Thermal Radiation
- Development of an Integrated Process Safety Management Framework
- Recommendations for Risk Reduction and Process Safety Improvement

Disaster management plan & on-site emergency plan:

The Disaster Management Plan (DMP) is formulated with an aim of taking precautionary measures to control the hazard propagation and to take such action that the damage following a disaster is the minimum.

These hazards and potential causes have already been discussed in the preceding sections. A selective disaster management measures to prevent disaster due to the above mentioned hazards are as follows:

1. Design, manufacture, operation and maintenance of all plant machineries/structures as per applicable national and international standards as laid down by statutory authority.
2. Intelligent formulation of layout to provide 'Assembly Point' and safe access way for personnel in case of a hazardous event/disaster, as can be inferred from Risk & Consequence modeling.
3. Proper emergency (both on site & off-site) preparedness plan, emergency response team, emergency communication, emergency responsibilities, emergency facilities, and emergency actions shall be developed.
4. Proper Alarm system and training the personnel for appropriate response during disastrous situation.
5. Complete fire protection coverage for the entire plant as per regulatory stipulations.
6. Creation and maintenance of Disaster Management cell with adequately trained personnel who can handle all sorts of emergency situation.
7. Provision of funds for prevention of disaster, mitigation, capacity-building and preparedness.

Disaster Management Institute, Bhopal had already carried out a detail DMP for company Works to provide an effective plan for disaster management.

The on-site emergency plan relates to the laid-down and well-practiced procedure after taking care of all design based precautionary measures for risk control. This plan is aimed for tackling any emergency situation, if arises. Both the DMP and the onsite emergency plan for the existing Steel plant have been already prepared by company. The same will be extended to the proposed units also.

Novelty of the Research:

Integration of HAZID, HAZOP, Risk Assessment, and Consequence Analysis into a single framework.

Application of PSM specifically to Indian integrated steel manufacturing plants.

Inclusion of historical steel plant accident case studies for framework validation.

Combination of engineering, administrative, and emergency preparedness controls

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