ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug406

Safety, Security and Process Risk Management in the Chemical Industry: A Review of Risk Assessment, Disaster Preparedness and Emerging Technologies

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Publication Date: 2026/08/17

Abstract: The chemical process industry is indispensable to modern society but involves inherent risks associated with toxic, flammable, reactive and corrosive substances, high pressures and temperatures, complex process interactions and large inventories. Although major accidents are relatively infrequent, their consequences may extend beyond the plant boundary and affect workers, emergency responders, communities, infrastructure and the environment. This review re-examines chemical-industry safety and security from an integrated process-safety and disaster-risk-management perspective, using the author's earlier article as its foundation while substantially rewriting and expanding its content. The review covers hazard identification, HAZOP, What-If analysis, FMEA, fault-tree analysis, Layer of Protection Analysis, quantitative risk assessment, inherently safer design, management of change, safety instrumented systems, mechanical integrity, human factors, emergency planning and community preparedness. It also considers natural-hazard-triggered technological accidents, the Indian regulatory framework and international approaches including OSHA Process Safety Management and ISO 45001. Recent developments in digitalization, sensors, predictive analytics, digital twins and artificial intelligence are examined as opportunities for early warning and decision support, together with their cybersecurity and human-factor implications. The review concludes that effective chemical safety cannot depend on a single safeguard. It requires a continuously verified system integrating safer design, reliable equipment, competent people, strong safety culture, emergency preparedness, physical and cyber security, and organizational learning.

Keywords: *Chemical Process Safety; Disaster Risk Management; HAZOP; LOPA; Inherently Safer Design; Emergency Preparedness; Process Safety Management; Chemical Security.*

How to Cite: Ashok Agarwal (2026) Safety, Security and Process Risk Management in the Chemical Industry: A Review of Risk Assessment, Disaster Preparedness and Emerging Technologies. *International Journal of Innovative Science and Research Technology*, 11(8), 756-761. https://doi.org/10.38124/ijisrt/26aug406

I. INTRODUCTION

Chemical manufacturing supports agriculture, pharmaceuticals, polymers, energy, food processing and numerous downstream industries. At the same time, chemical facilities may contain substances capable of causing toxic exposure, fire, explosion, runaway reaction or environmental contamination. The original manuscript emphasized that vulnerability depends not only on the intrinsic hazard of a chemical but also on inventory, operating conditions, equipment reliability, human performance, plant layout, surrounding population and emergency capability. This remains the foundation of modern process safety.

The Bhopal disaster of December 1984 demonstrated how technical failures can interact with inadequate maintenance, operating practices, management systems and emergency preparedness. Subsequent major accidents worldwide have reinforced the lesson that catastrophic events usually involve multiple failed or degraded barriers rather than one isolated mistake. The 2020 styrene release at Visakhapatnam provided a more recent Indian example in which storage conditions, restart management, emergency response and the surrounding community were central considerations.

Modern process safety therefore seeks to prevent low-frequency, high-consequence events through systematic hazard identification, risk assessment and barrier

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug406

management. OSHA's Process Safety Management framework integrates process safety information, process hazard analysis, operating procedures, training, contractor management, pre-startup review, mechanical integrity, management of change, incident investigation, emergency planning and auditing. ISO 45001 provides a complementary occupational health and safety management framework based on leadership, worker participation, hazard identification, emergency planning and continual improvement.

India has also developed arrangements for chemical-accident preparedness and response. The Chemical Accidents (Emergency Planning, Preparedness and Response) Rules, 1996 establish institutional arrangements, while national disaster-management guidance emphasizes prevention, mitigation, preparedness and coordination among industry, government agencies, emergency services and communities. The continuing challenge is effective implementation at facility level, particularly where hazardous installations coexist with expanding urban areas.

II. OBJECTIVES AND SCOPE

This review aims to summarize the principal hazards of chemical process industries; examine modern hazard-identification and risk-assessment methods; integrate process safety management with disaster risk management; discuss inherently safer design and engineered safeguards; consider human factors, safety culture and emergency preparedness; address natural-hazard-triggered technological accidents; review the Indian regulatory context against international good practice; and assess opportunities and limitations associated with digital technologies and artificial intelligence.

The paper is a technical review rather than a report of new experimental work. The author's original article supplied historical context, Indian accident examples and practical observations. Those ideas have been substantially reorganized and rewritten, while new sections and current authoritative sources have been added.

III. MAJOR HAZARD CATEGORIES

Chemical hazards include toxicity, flammability, reactivity, corrosion and environmental persistence. Process hazards additionally arise from pressure, temperature, vacuum, stored energy, rotating equipment, electrical ignition sources and loss of utility systems. Dust explosions and oxygen-deficient atmospheres may be important in particular operations. The severity of an accident depends on inventory, release rate, physical properties, process conditions, weather, terrain and population distribution.

Risk assessment should therefore proceed beyond listing hazardous substances. It should identify credible initiating events, estimate consequences, identify preventive and mitigative barriers, examine their independence and verify that residual risk is adequately controlled.

IV. PROCESS SAFETY MANAGEMENT

Process Safety Management (PSM) is a systematic approach to preventing catastrophic releases and major process incidents. A mature PSM system begins during design and continues through commissioning, operation, maintenance, modification, shutdown and decommissioning. Core elements include process safety information, process hazard analysis, operating procedures, training and competence, contractor control, pre-startup safety review, mechanical integrity, management of change, permit-to-work and isolation, emergency planning, incident investigation, auditing and management review. [1,9]

The elements must operate as a connected system. A HAZOP recommendation, for example, has little value unless the resulting safeguard is engineered, installed, tested, documented and maintained. Similarly, a safety procedure is ineffective if the equipment condition or control-system configuration no longer matches the procedure.

- *Hazard Identification and Risk Assessment*

Hazard identification should begin during conceptual and basic engineering and be repeated after significant changes. Common techniques include checklists, What-If analysis, HAZOP, FMEA, fault-tree analysis, event-tree analysis, consequence modelling, LOPA, bow-tie analysis and quantitative risk assessment. Each has a different purpose and they should be selected according to the complexity and consequence of the hazard. [1,17,18,19,24]

HAZOP is particularly valuable because a multidisciplinary team examines deviations such as high pressure, low flow, reverse flow, high temperature, contamination and loss of utilities. Its quality depends on accurate P&IDs, process information and competent participation. LOPA provides a semi-quantitative assessment of whether sufficient independent protection layers exist between an initiating event and a defined consequence. Independence is essential; safeguards sharing the same power, instrument, operator action or failure mechanism should not automatically be counted separately.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug406

Table 1 Hazard Identification and Risk Assessment

Technique	Purpose	Typical application
Checklist/What-If	Identify known hazards and deviations	Early design and operating reviews
HAZOP	Systematic process-deviation analysis	P&IDs and operating systems
FMEA	Assess equipment failure modes	Equipment and instrumentation
Fault Tree	Trace combinations causing a top event	Critical scenarios
Event Tree	Follow consequence paths after an initiating event	Barrier analysis
LOPA	Assess independent protection layers	High-consequence scenarios
Bow-Tie	Connect causes, barriers and consequences	Major-accident barrier management
QRA	Estimate frequency and consequence risk	Major-hazard facilities

- *Inherently Safer Design*

The strongest risk-reduction measures reduce the hazard at source. Inherently safer design seeks to minimize, substitute, moderate or simplify hazardous operations. Examples include reducing inventories, substituting less hazardous materials, lowering temperature or pressure where feasible, using smaller vessels, simplifying process arrangements and avoiding unnecessary complexity. [17,18]

Inherently safer design should be considered before detailed design and revisited during debottlenecking, expansion and process optimization. It does not eliminate the need for alarms, trips, relief systems or emergency response; rather, it reduces the severity and likelihood of scenarios that those safeguards must manage.

- *Engineering Safeguards and Safety Instrumented Systems*

Primary containment depends on sound mechanical design, appropriate materials, corrosion control and reliable joints. Secondary protection includes process controls, alarms, interlocks and automatic shutdown. Mitigation includes relief systems, containment, gas detection, firefighting, deluge, emergency ventilation and passive fire protection. Off-site protection includes warning, evacuation or shelter arrangements and coordinated emergency response.

Safety Instrumented Systems should be designed and managed through a defined functional-safety lifecycle. Hazard analysis, allocation of safety functions, integrity requirements, proof testing, bypass control, change management and documentation are all necessary. An automatic trip is not evidence of safety unless the entire lifecycle is maintained.

- *Mechanical Integrity and Reliability*

Loss of containment commonly results from corrosion, erosion, fatigue, brittle fracture, vibration, thermal cycling, gasket failure or unsuitable materials. A mechanical-integrity program should identify safety-critical equipment and establish inspection and test requirements based on credible degradation mechanisms and risk. Continued operation is not by itself evidence of fitness for service. [1,9]

Safety-critical assets include pressure vessels, storage tanks, relief devices, emergency shutdown valves, detectors, firewater systems, critical pumps and compressors, electrical protection and containment systems. Records should be traceable, overdue work visible to management and temporary repairs controlled by formal risk assessment.

- *Management of Change and Human Factors*

Changes to equipment, chemicals, procedures, staffing, software or operating conditions can create hazards that were not present in the original design. Management of Change should therefore cover technical and organizational changes, including temporary modifications. It should address hazards, documentation, training, inspection, control-system effects and emergency implications, followed by a pre-startup safety review where appropriate. [1,22,23]

Human factors include alarm overload, poor interfaces, fatigue, inadequate procedures, conflicting production priorities and insufficient staffing. Procedures should be usable under real conditions, critical tasks should minimize ambiguity, and competence should be demonstrated rather than inferred from attendance at training.

- *Safety Culture and Process Safety Indicators*

Safety culture is expressed through decisions and behaviours. Management commitment is demonstrated when production pressure does not override safety-critical requirements, when workers can report weak signals and when corrective actions are completed. A strong reporting culture is particularly important because near misses may reveal barrier degradation before a major event occurs.

Lagging indicators include fatalities, major releases, fires, explosions and significant process-safety events. Leading indicators include overdue safety-critical inspections, overdue corrective actions, failed proof tests, alarm-management performance, competency assessments, emergency-drill findings and MOC completion. A low occupational-injury rate does not demonstrate control of major-accident risk; process-safety indicators are therefore essential.

- *Emergency Preparedness and Disaster Risk Management*

Emergency preparedness should be based on credible scenarios identified through hazard analysis. Plans should define command structure, alarms, notification, isolation and shutdown, firefighting, medical response, evacuation or sheltering, mutual aid, communication with authorities, environmental monitoring and recovery. [4,8,10]

The disaster-management cycle comprises prevention and mitigation, preparedness, response and recovery. Prevention reduces likelihood or severity; preparedness establishes resources and competence; response controls the

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug406

event; and recovery restores operations and incorporates lessons learned. The cycle should be continuous, with emergency experience feeding back into design, procedures and training.

- *Community Risk and Emergency Communication*

Major chemical incidents can affect people beyond the plant boundary. Toxic clouds, fires, explosions and contaminated water can threaten neighbouring communities. Emergency planning should therefore include local government, hospitals, police, fire services and community representatives. Warning messages should be simple, tested and available in languages understood by the affected population.

Facilities near populated areas should treat off-site consequences as part of risk management rather than as an external responsibility. Community drills can reveal practical problems in siren coverage, evacuation routes, traffic control, medical capacity and public understanding of emergency instructions.

- *Natural Hazards and Natech Events*

Earthquakes, floods, cyclones, lightning and extreme weather can initiate technological accidents. Such events are commonly described as Natech accidents. Examples include tank rupture during earthquakes, loss of cooling during floods, electrical failures during storms and simultaneous releases from multiple units. [13,14]

Natech assessment requires combined hazard analysis. Site selection and design should consider seismic loads, flood levels, wind, drainage, loss of utilities and access for emergency responders. Emergency plans should include multiple simultaneous failures rather than assuming that only one unit will be affected.

- *Lessons from Major Indian Accidents*

The Bhopal disaster remains a central process-safety case study. Its lessons include the importance of minimizing hazardous inventories, maintaining critical safety systems, preventing incompatible conditions, ensuring credible emergency response and providing communities with reliable information and preparedness.

The 2020 Visakhapatnam styrene release provides a more recent example. The event occurred during a period of restricted industrial activity and plant restart. Subsequent reporting and technical analysis highlighted storage-condition control, temperature management, instrumentation, emergency preparedness and atmospheric dispersion. The incident also showed how meteorological conditions can influence the impact of a toxic release.

The value of accident case studies lies in identifying failed or degraded barriers rather than merely assigning blame. Each event should prompt questions about initiating events, prevention, independent protection, equipment condition, procedures, management decisions, emergency communication and recovery.

- *Chemical Security and Cybersecurity*

Safety and security overlap but have different objectives. Safety addresses accidental harm; security addresses deliberate acts, unauthorized access, theft, sabotage and malicious misuse. Security measures should include access control, visitor management, inventory accountability, protection of critical assets, personnel awareness and appropriate cybersecurity.

Industrial control systems are increasingly networked. Remote access, wireless sensors, cloud services and integration with enterprise systems can introduce pathways through which a cyber event affects physical operations. Cybersecurity should therefore be considered part of process safety wherever compromise could change hazardous process conditions. Security controls must nevertheless preserve safe emergency operation.

- *Digital Technologies, AI and Industry 4.0*

Digital control systems, wireless sensors, condition monitoring, predictive analytics and digital twins can improve detection of abnormal conditions and equipment degradation. Digital models can support scenario testing without exposing personnel to hazardous conditions. [1,5]

Artificial intelligence can assist anomaly detection, alarm prioritization, image-based inspection, predictive maintenance and analysis of large historical datasets. However, AI should generally be treated as decision support in safety-critical applications. Models may fail when conditions differ from training data, and opaque recommendations can be difficult to validate.

Safe deployment requires data quality, cybersecurity, validation, human oversight and formal change management. Safety-critical automatic actions should remain under appropriately engineered and verified protection systems rather than relying solely on probabilistic machine-learning predictions.

- *Indian and International Regulatory Framework*

India's hazardous-chemical framework includes environmental, factory, transport and disaster-management provisions. The Chemical Accidents (Emergency Planning, Preparedness and Response) Rules, 1996 establish emergency-planning arrangements. These requirements should be treated as a baseline; responsible operators should also apply recognized process-safety engineering practices.

OSHA Process Safety Management provides an internationally influential model for systematic control of highly hazardous chemical processes. ISO 45001 provides an occupational health and safety management framework emphasizing leadership, worker participation, hazard identification, emergency planning and continual improvement. IEC 61511 provides a lifecycle framework for safety instrumented systems. The standards are complementary and should be integrated rather than implemented as isolated compliance exercises.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug406

➢ *Practical Plant-Wide Risk Reduction*

A practical program can be organized around ten priorities: accurate process safety information; structured hazard analyses; inherently safer design; verification of safety-critical equipment; rigorous MOC; competence and human-factors engineering; leading process-safety indicators; credible emergency response; integrated physical and cyber security; and systematic organizational learning.

Table 2 Practical Plant-Wide Risk Reduction

Priority	Key question	Evidence
Process safety information	Are design and operating limits current?	Approved P&IDs, datasheets and operating envelopes
PHA	Have credible scenarios been examined?	Current HAZOP/LOPA/PHA records
Mechanical integrity	Are critical assets fit for service?	Inspection and test records
MOC	Are changes assessed before implementation?	Approved MOC and PSSR
Competence	Can personnel perform safety-critical tasks?	Competency assessments
Emergency preparedness	Can the plant respond to credible scenarios?	Drills and corrective actions
Security	Are critical assets protected?	Access and cybersecurity assessments
Learning	Are weak signals converted to action?	Incident and near-miss closure

V. DISCUSSION

The central finding is that chemical-plant safety is a systems problem. Individual safeguards are necessary but insufficient. A plant may have modern instrumentation yet remain vulnerable if mechanical integrity is weak; experienced operators cannot indefinitely compensate for inherently hazardous design, degraded equipment or inadequate emergency planning. [1,8,9]

The Indian context presents an additional challenge because industrial development can occur close to residential areas and transport corridors. Prevention of major accidents must therefore include land-use planning, community engagement and coordinated emergency response. Off-site consequences should be part of the design and risk-management basis.

Compliance should not be confused with risk control. A checklist can show that a procedure exists, but field verification is required to show that the barrier works. Audits should test the effectiveness of safeguards and pay particular attention to degraded barriers, temporary modifications, overdue inspections, bypassed alarms and recurring near misses.

VI. RECOMMENDATIONS

Adopt a lifecycle Process Safety Management system covering design, commissioning, operation, maintenance, modification and decommissioning.

- Apply inherently safer design to minimize hazardous inventories and reduce pressure, temperature, complexity and reactivity where practicable.
- Conduct periodic HAZOP/LOPA/PHA reviews and repeat them after significant changes or new information.
- Identify safety-critical elements and establish performance standards, inspection requirements and proof-testing regimes.
- Implement rigorous Management of Change for physical, procedural, software and organizational changes.
- Develop competency programs for operators, engineers, maintenance staff, contractors and emergency responders.
- Use leading process-safety indicators alongside traditional occupational-injury statistics.
- Integrate plant emergency plans with district and state disaster-management arrangements and conduct realistic joint exercises.
- Strengthen community warning, shelter and evacuation arrangements, including multilingual communication where necessary.
- Assess natural hazards and Natech scenarios during site selection, design and emergency planning.
- Integrate physical security and industrial cybersecurity with process-safety management.
- Use AI and digital technologies cautiously, with validation, cybersecurity, human oversight and formal change management.
- Ensure incident investigations identify systemic and organizational causes rather than focusing only on operator error.
- Share lessons from major accidents and near misses across the organization and industry.

Review process-safety performance at senior-management level and ensure production objectives never create incentives to bypass safety-critical controls.

VII. CONCLUSION

Chemical-process safety has evolved from a reactive discipline into an integrated system of hazard prevention, risk management, barrier assurance, emergency preparedness and continual learning. Catastrophic events generally arise from combinations of technical, human and organizational weaknesses. Effective prevention therefore requires a layered approach beginning with inherently safer design and extending through reliable containment, process control, independent protection layers, mechanical integrity, competent personnel, strong management systems and emergency preparedness.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug406

For India, continued industrial development makes chemical-disaster prevention particularly important. National regulations and disaster-management arrangements provide an essential framework, but their effectiveness depends on implementation at individual facilities and coordination with communities and public authorities. Digital technologies, AI and advanced analytics can improve detection and decision support, but they should complement rather than replace fundamental process-safety engineering.

The most sustainable safety strategy is one in which risk is designed out wherever practicable, remaining hazards are protected by independent and verifiable barriers, personnel are competent and empowered to stop unsafe operations, and organizations learn continuously from weak signals as well as major events.

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