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Evaluation of Fire Protection Systems in Cross-Country Natural Gas Pipeline Installations

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Abstract: Cross-country natural gas pipeline systems constitute critical energy infrastructure transporting high-pressure flammable hydrocarbons across geographically diverse and often densely populated regions. Although modern pipeline networks demonstrate strong safety performance, incidents involving gas releases, ignition events, and station-level equipment failures continue to present significant fire and explosion risks. Fire Protection Systems (FPS) installed at compressor stations, intermediate pressure stations, sectionalizing valve stations, and customer gas stations are designed to mitigate such hazards. However, systematic performance-based evaluations of FPS effectiveness relative to statutory and international standards remain limited. This study presents a comprehensive technical evaluation of FPS in cross-country natural gas pipeline installations using a structured field assessment framework. The methodology integrates document review, inspection checklist development, HAZOP analysis, Quantitative Risk Assessment (QRA), fire load estimation, and consequence modeling. Performance benchmarking is conducted against applicable provisions of OISD, PNGRB Technical Standards and Safety Regulations (TSSR), NFPA fire codes, API fire protection guidance, and related statutory frameworks. Results indicate that while most installations satisfy minimum prescriptive compliance requirements, deficiencies are observed in system redundancy, integration of gas detection with emergency shutdown (ESD), reliability of fire water networks under single-failure scenarios, and periodic performance validation. Passive fire protection measures are often under-optimized relative to credible jet fire exposure scenarios. The study identifies critical design and operational gaps and proposes engineering improvements based on reliability modeling and risk-based prioritization.
The findings underscore the necessity of transitioning from checklist-based compliance to performance-driven fire protection validation in pipeline infrastructure. The proposed evaluation model offers a replicable framework for regulators, operators, and safety engineers to enhance resilience and risk mitigation.
Keywords: Cross-country pipelines; Fire protection systems; Quantitative risk assessment; HAZOP; Emergency shutdown systems; Active and passive fire protection; Regulatory compliance.

I. INTRODUCTION

A. Background

Natural gas transmission pipelines operate at high pressures (typically 30–100 bar) to transport methane-rich hydrocarbons over long distances. Unlike process plants, cross-country pipelines are geographically distributed systems comprising discrete nodes such as:

1) Compressor Stations
2) Intermediate Pressure (IP) Stations
3) Sectionalizing Valve Stations
4) Customer Gas Stations (CGS)

These nodes concentrate equipment, instrumentation, and ignition sources, thereby elevating localized fire risk compared to linear pipeline segments.

Global incident databases indicate that while rupture frequencies remain statistically low, consequence severity can be high due to rapid depressurization and formation of large flammable gas clouds. Fire and explosion hazards include:

- High-pressure jet fires
- Vapor cloud explosions (VCE)
- Flash fires
- Secondary equipment fires

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Regulatory bodies such as OISD and PNGRB in India and NFPA/API internationally mandate fire protection provisions; however, most compliance regimes remain prescriptive rather than performance-based.

B. Research Gap

Existing literature predominantly focuses on failure probability modeling and corrosion risk management. Limited peer-reviewed work evaluates the operational performance and reliability of installed FPS against realistic failure scenarios and regulatory benchmarks. Furthermore, integration between active systems (fire water, detection) and process safety systems (ESD, isolation valves) remains insufficiently studied.

This research addresses this gap through:

1) Structured field evaluation of FPS components
2) Reliability and redundancy analysis
3) Risk-based performance benchmarking
4) Gap identification and engineering optimization

II. LITERATURE REVIEW

A. Regulatory and Technical Framework

1) OISD Standards

OISD standards for gas pipeline installations specify requirements for:

- Fire water storage capacity (minimum duration criteria)
- Pump redundancy (electric + diesel-driven)
- Hydrant and monitor spacing
- Fire detection and gas detection interlocks

These standards emphasize availability and operational readiness.

2) PNGRB Technical Standards and Safety Regulations

PNGRB TSSR mandates:

- Risk assessment for pipeline installations
- Emergency response planning
- Periodic safety audits
- Compliance with fire and environmental safeguards

It requires operators to demonstrate safe design and operation rather than mere installation.

3) NFPA and API Standards

NFPA 15, NFPA 20, NFPA 72, and API fire protection guidelines provide internationally accepted methodologies for:

- Water spray system design
- Fire pump sizing
- Alarm and detection reliability
- Hazard classification and protection philosophy

These standards support performance-based engineering approaches.

B. Active vs Passive Fire Protection

Active systems:

- Require activation (manual or automatic)
- Depend on power and maintenance
- Include pumps, hydrants, monitors, detection, clean agents

Passive systems:

- Provide inherent resistance
- Include fireproof coatings, separation distances, blast walls
- Reduce escalation probability

Research indicates optimal safety performance arises from integrated deployment rather than reliance on a single strategy.

III. METHODOLOGY

A. *Study Framework*

The evaluation model consisted of five stages:

1) Document Review – P&IDs, layout drawings, pump curves, detection logic diagrams
2) Field Inspection – Physical verification and functional testing
3) Risk Analysis – HAZOP and QRA
4) Performance Benchmarking – Comparison against OISD, PNGRB, NFPA, API
5) Reliability Modeling – Failure probability assessment

B. *Risk Assessment Techniques*

1) *HAZOP*

Process deviations analyzed:

- High pressure
- Leak scenarios
- Valve failure
- Ignition source presence

2) *Quantitative Risk Assessment (QRA)*

Event trees and fault trees were developed to estimate:

- Individual risk (IR)
- Societal risk (FN curves)
- Thermal radiation contours

Consequence modeling simulated:

- Jet fire length
- Radiation intensity
- Explosion overpressure

3) *Fire Load Calculation*

Fire load density (MJ/m^2) was calculated using combustible inventory and equipment materials.

IV. TECHNICAL EVALUATION OF FIRE PROTECTION SYSTEMS

A. *Fire Water Network Adequacy*

Assessment parameters included:

- Pump redundancy (N+1 configuration)
- Jockey pump pressure stability
- Diesel pump automatic start reliability
- Ring main hydraulic balance
- Hydrant spacing ($<$30–45 m typical industrial guidance)

Finding: In several installations, single pump failure reduced effective discharge below required design density, indicating inadequate redundancy.

B. *Gas and Fire Detection Systems*

Evaluation included:

- Sensor placement relative to prevailing wind
- Detector response time
- Integration with ESD

Critical observation: Gas detectors often functioned as alarm-only systems without automatic isolation logic, reducing mitigation effectiveness.

C. Clean Agent Systems (IG-541 / NOVEC)
Clean agent systems installed in control rooms were evaluated for:
1) Enclosure integrity
2) Discharge time
3) Cylinder hydrotest validity

Observed deficiencies included expired hydrotest dates and inadequate room sealing.

D. Passive Fire Protection
Passive fire protection assessment included:
1) Fireproof coating thickness validation
2) Blast wall adequacy
3) Separation distances

In high-pressure compressor areas, passive measures were sometimes insufficient for credible jet fire exposure durations exceeding 15 minutes.

E. Emergency Shutdown (ESD) Integration
Reliability modeling revealed:
1) Single-point failures in control logic
2) Lack of periodic full-stroke testing of isolation valves

Mean Time Between Failure (MTBF) analysis suggested that detection without automatic isolation increases escalation probability significantly.

V. RESULTS AND DISCUSSION

A. Gap Analysis Summary

Category	Compliance	Performance Reliability	Risk Impact
Fire Water	Compliant	Moderate	High if pump fails
Detection	Compliant	Low Integration	Delayed isolation
Clean Agent	Partially	Maintenance gaps	Limited room protection
Passive Protection	Minimal	Insufficient for jet fire	Escalation risk

B. Critical Observations
1) Compliance does not guarantee performance under worst-case scenarios.
2) Redundancy levels often meet minimum legal criteria but not risk-based adequacy.
3) Preventive maintenance intervals significantly affect FPS reliability.
4) Emergency drills are rarely aligned with modeled scenarios.

VI. CASE STUDY: 180 KM TRANSMISSION SECTION
A representative compressor and valve station network was evaluated.

1) Key Deficiencies
- Inconsistent ring main pressure
- Gas detector drift beyond calibration tolerance
- Diesel pump auto-start delay >10 seconds
- Incomplete fireproof coating in support structures

2) Corrective Actions
- Installation of additional diesel backup pump
- Integration of gas detection with ESD logic
- Passive fire protection retrofit
- Real-time pump performance monitoring

3) *Post-correction QRA indicated*

- 35% reduction in individual risk contour
- 22% reduction in predicted thermal escalation probability

VII. CONCLUSION

This study demonstrates that while cross-country pipeline FPS installations generally comply with prescriptive standards, performance-based assessment reveals systemic weaknesses in redundancy, integration, and reliability. Active systems without robust passive support increase vulnerability under credible worst-case fire scenarios.

A. *Key conclusions*

1) Risk-based fire protection validation should complement statutory compliance.
2) Integration between detection and ESD significantly reduces escalation probability.
3) Redundancy beyond minimum compliance improves resilience.
4) Predictive maintenance enhances FPS reliability.

VIII. POLICY AND OPERATIONAL IMPLICATIONS

A. *Regulators Should*

1) Mandate periodic performance testing beyond visual inspection
2) Encourage QRA-based FPS optimization
3) Introduce reliability validation criteria

B. *Operators Should*

1) Adopt digital monitoring of fire pumps
2) Conduct scenario-based emergency drills
3) Implement asset integrity management for FPS components

IX. SCOPE FOR FUTURE RESEARCH

1) AI-based predictive failure analysis of FPS
2) Digital twin modeling of pipeline stations
3) Real-time gas dispersion simulation integration

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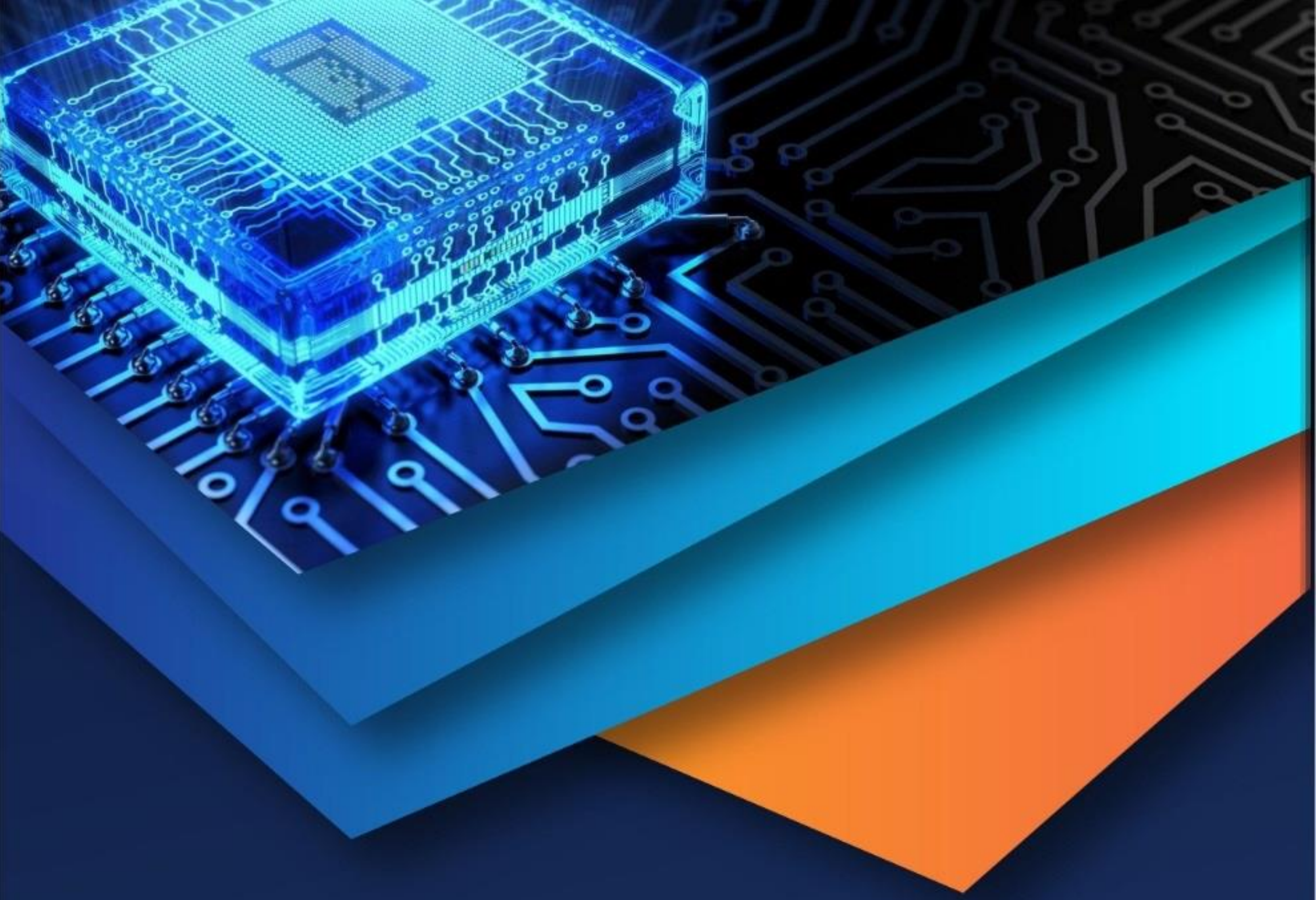

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