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An Integrated EPC-Operational Process Safety Lifecycle Model: Coupling HIRA, FMEA, and Quantitative Risk Assessment for Explosion and Fire Disaster Prevention in Hydrocarbon Facilities

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Abstract: *The Oil and Gas (O&G) and downstream petrochemical industries handle massive volumes of volatile hydrocarbons under extreme thermodynamic conditions, making them exceptionally vulnerable to catastrophic loss-of-containment events. Historically, safety management strategies have operated in silos: occupational safety dominates the Engineering, Procurement, and Construction (EPC) phase, while Process Safety Management (PSM) and Quantitative Risk Assessment (QRA) govern the operational phase. This fragmented paradigm overlooks a critical reality: procedural and mechanical deficiencies during EPC (e.g., inadequate weld fusion, improper flange torqueing, incorrect valve selection, and deficient pre-commissioning testing) represent the latent pathogens that directly trigger major operational disasters. This research presents an integrated, closed-loop process safety lifecycle model that bridges this divide by systematically coupling Hazard Identification and Risk Assessment (HIRA) and Failure Mode and Effects Analysis (FMEA) during EPC execution with QRA thermodynamic and blast consequence modeling. Utilizing rigorous forensic case studies of landmark disasters—including the IOCL Jaipur terminal fire (2009), the ONGC Hazira gas terminal leak (2020), and the IOCL Mathura refinery incident (2020)—we establish direct causal links between construction QA/QC failures and operational vapour cloud explosions (VCE) and boiling liquid expanding vapour explosions (BLEVE). Mathematical consequence modeling utilizing the Roberts fireball formulation for a 3,602,137 kg gasoline inventory yields a maximum fireball diameter (D_max) of 889.09 m, a duration (T_max) of 68.98 s, and an active surface emitting power (SEP_max) of 333.98 kW/m2, producing lethal thermal radiation (>63 kW/m2) even at 500 m standoff distances. TNT-equivalency modeling of a 450,000 kg vapor cloud generates a blast yield of 169,188 kg TNT, establishing peak overpressure contours via Hopkinson-scaled distance (R_bar). Furthermore, a quantitative FMEA framework establishes a strict threshold (RPN > 100) mandating automated safety instrumented systems—specifically Remote Operated Shut Off Valves (ROSOVs) and emergency depressurization interlocks—prior to mechanical completion. The proposed framework provides an empirical, standards-compliant methodology for EPC contractors and plant operators to eliminate latent hazards at the build stage, ensuring inherent process safety across the entire asset lifecycle.*

Keywords: Quantitative Risk Assessment (QRA); Failure Mode and Effects Analysis (FMEA); Hazard Identification and Risk Assessment (HIRA); Vapour Cloud Explosion (VCE); BLEVE Fireball Modeling; EPC Process Safety; Remote Operated Shut Off Valve (ROSOV); Petrochemical Risk Engineering.

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I. INTRODUCTION

The global energy landscape relies heavily on the extraction, processing, refining, and bulk distribution of liquid and gaseous hydrocarbons. Within the Indian subcontinent and across the Middle East, rapid industrialization has catalyzed the construction of mega-petrochemical complexes, such as the Ras Laffan Petrochemicals Project (RLPP) in Qatar and expansive public-sector bulk liquid storage terminals across India operated by entities such as IOCL, BPCL, HPCL, and ONGC. Hydrocarbon facilities represent high-hazard process environments characterized by the continuous containment of Class-A, Class-B, and Class-C flammable liquids, as well as highly volatile liquefied gases under elevated pressures and temperatures. The catastrophic potential of these materials is governed by their low boiling points, narrow explosive limits, high heats of combustion (Delta Hc approx 42-48 MJ/kg), and rapid vaporization kinetics upon atmospheric release.

Conventionally, industrial risk management in process plants is bifurcated into two disconnected domains: (i) Occupational Health and Safety during the Engineering, Procurement, and Construction (EPC) phase, which primarily addresses worker safety during civil, mechanical, structural, and electrical activities; and (ii) Process Safety Management (PSM) during the operational and maintenance phase, which focuses on asset integrity, instrumented protective systems, and emergency consequence mitigation. However, extensive forensic investigations of catastrophic petrochemical disasters reveal that operational failures are rarely spontaneous; rather, they are the deterministic physical manifestations of latent mechanical flaws, substandard procurement quality, flawed pre-commissioning testing, and procedural shortcuts introduced during the EPC lifecycle. For instance, improper bolt torqueing during flange fit-up, undetected lack-of-fusion defects in welded spools, and value-engineering decisions substituting manual blind valves for automated shutdown valves routinely bypass pre-commissioning checks, only to fail catastrophically under continuous operational stresses.

To address this fundamental industry challenge, this research establishes an integrated, closed-loop safety lifecycle architecture. By uniting forward-looking Hazard Identification and Risk Assessment (HIRA) and Failure Mode and Effects Analysis (FMEA) during the construction phase with rigorous Quantitative Risk Assessment (QRA) consequence modeling for operational fire and explosion scenarios, this paper demonstrates how EPC quality verification directly mitigates downstream catastrophic exposure. The specific objectives of this study are: (1) to delineate the physical mechanisms of major hydrocarbon release modes and combustion dynamics; (2) to perform forensic root-cause analysis on benchmark industrial disasters (IOCL Jaipur, ONGC Hazira, and IOCL Mathura); (3) to execute rigorous thermodynamic and gas-dynamic consequence modeling (fireball thermal radiation and TNT-equivalent blast overpressure); and (4) to formalize an EPC FMEA decision framework mandating automated safety barriers prior to plant commissioning.

II. THEORETICAL FOUNDATIONS OF PROCESS HAZARDS AND COMBUSTION DYNAMICS

2.1 Classification of Petroleum Products and Hazardous Area Zoning

Process safety engineering mandates the strict categorization of petroleum fluids based on their closed-cup flash points, as standardized under the Petroleum Act 1934, OISD-STD-118, and API-650 specifications. Fluid classification dictates equipment design, spacing distances, electrical apparatus protection, and firefighting infrastructure:

- **Class-A Petroleum:** Flammable liquids possessing a closed-cup flash point below 23 deg C (e.g., Motor Spirit/Gasoline, Light Naphtha, Hexane). These fluids generate flammable equilibrium vapor concentrations at normal ambient temperatures, requiring comprehensive vapor recovery and explosion-proof containment.
- **Class-B Petroleum:** Flammable liquids with a flash point of 23 deg C and above, but below 65 deg C (e.g., High-Speed Diesel - HSD, Superior Kerosene Oil - SKO, Aviation Turbine Fuel - ATF).
- **Class-C Petroleum & Excluded:** Combustible liquids with flash points between 65 deg C and 93 deg C (e.g., Furnace Oil, Lube Base Oils), and excluded products with flash points exceeding 93 deg C (Bitumen/Asphalt).

In conjunction with product classification, industrial facilities are segregated into hazardous area zones according to the temporal probability of explosive gas-air mixtures (IEC 60079 / IS 5572): Zone 0 (continuous presence > 1000 hrs/yr,

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such as inside storage tank vapor spaces), Zone 1 (likely to occur under normal operational cycles, 10-1000 hrs/yr, such as loading gantries and pump seals), and Zone 2 (unlikely to occur during normal operation, and persisting for short durations only, < 10 hrs/yr, such as pipe racks and dyke retention areas).

2.2 Loss of Containment Phenomena and Consequence Event Trees

When primary hydrocarbon containment is breached, the ultimate disaster mode is governed by thermodynamic phase, release pressure, environmental confinement, atmospheric stability, and ignition timing. Figure 1 illustrates the comprehensive petrochemical process event tree mapping the physical propagation from initial Loss of Primary Containment (LOPC) to catastrophic consequence states.

Figure 1: Petrochemical Process Event Tree & Failure Progression Pathway

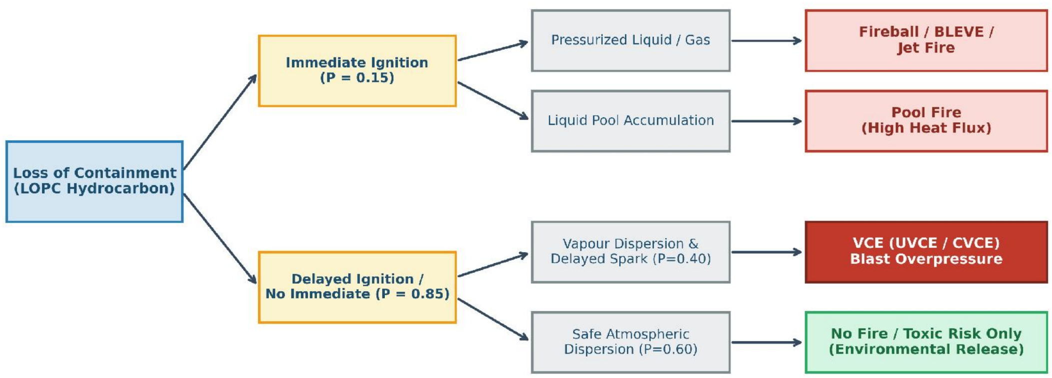

Figure 1: Comprehensive Event Tree Flowchart for Hydrocarbon Loss of Primary Containment (LOPC).

As detailed in Figure 1, an unignited release of high-pressure gas or volatile liquid leads either to immediate thermal events (Jet Fire or Fireball) upon rapid contact with an ignition source, or to delayed atmospheric dispersion. In delayed scenarios, if the dispersing cloud encounters delayed ignition in an unconfined terrain, an Unconfined Vapour Cloud Explosion (UVCE) or Flash Fire ensues. If the cloud migrates into congested structures, process modules, or buildings, turbulent flame acceleration drives a Confined Vapour Cloud Explosion (CVCE), dramatically amplifying destructive blast overpressures.

2.3 Combustion Wave Physics: Deflagration vs. Detonation

Combustion wave propagation through a flammable hydrocarbon-air mixture occurs via two fundamentally distinct regimes: (1) Deflagration, where the reaction front is propagated by molecular and turbulent diffusive transport of heat and mass into the unburned gas, advancing at subsonic velocities relative to the unburned medium (flame speeds typically 5-100 m/s); and (2) Detonation, where the combustion front is driven by a leading supersonic shock wave that compresses and auto-ignites the mixture via shock heating, advancing at velocities between 1,800 m/s and 2,800 m/s. In congested petrochemical geometries (dense pipe racks, offshore modules), flame front interactions with obstacles create violent wake turbulence, causing rapid Deflagration-to-Detonation Transition (DDT) and generating catastrophic blast loads.

Figure 2 illustrates the classical idealized pressure-time history (P-t) of an unconfined chemical blast wave exhibiting a discontinuous shock front followed by exponential decay.

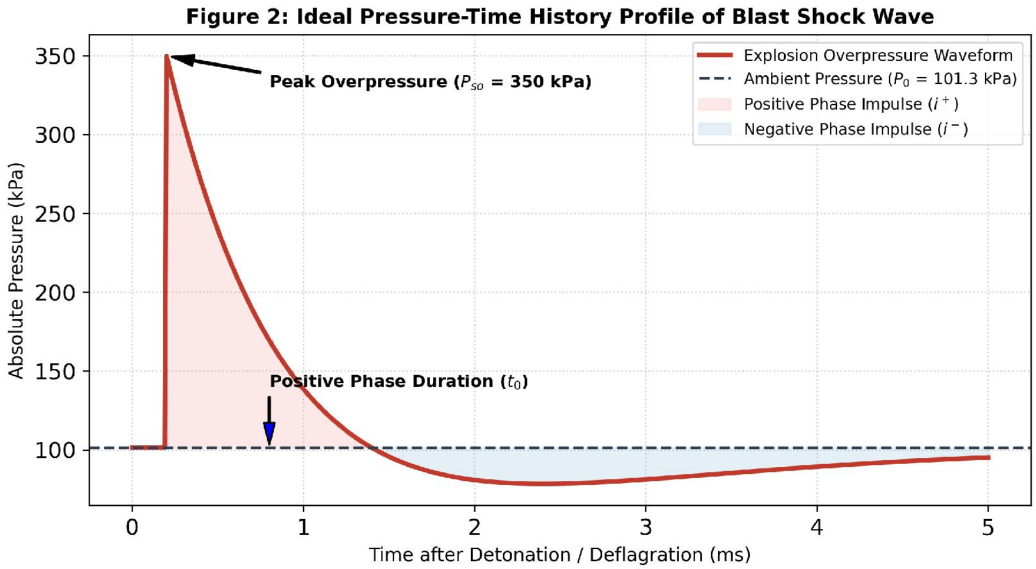

Figure 2: Theoretical Pressure-Time History Profile of Blast Shock Wave showing Positive and Negative Phases.

The primary destructive parameters governing blast damage are the peak side-on overpressure (P_so) and the positive phase specific impulse (i+), defined as the integral of overpressure over the positive phase duration (t0):

$$i^+ = \int [P(t) - P_0] \, dt = \int P_{so} (1 - t / t_0) \exp(- b t / t_0) \, dt$$

Where b represents the waveform decay parameter. Following the positive phase, the rapid outflow of expanding gases creates a partial vacuum below atmospheric pressure (P_0), generating a negative phase duration (t-) and suction forces capable of pulling structural cladding inward.

III. FORENSIC ACCIDENT INVESTIGATIONS AND EPC ROOT-CAUSE DECONSTRUCTION

To establish the empirical foundation linking EPC deficiencies to operational catastrophes, this study deconstructs three benchmark industrial disasters in the Indian hydrocarbon sector, investigating the precise sequence of mechanical failure and procedural breakdown.

3.1 Case Study 1: IOCL Jaipur Bulk Storage Terminal Explosion (2009)

On October 29, 2009, a catastrophic explosion and multi-tank fire engulfed the Indian Oil Corporation Limited (IOCL) Bulk Storage Terminal at Sitapura, Jaipur. The incident claimed 12 lives, injured over 300 individuals, destroyed 11 storage tanks containing over 60,000 kL of petroleum products, and registered a seismic shock of 2.3 on the Richter scale, audible over a 30 km radius. The terminal had been constructed in compliance with API 650 and OISD-118, storing Class-A Motor Spirit (MS) and Class-B High-Speed Diesel (HSD).

Sequence of Failure: During a routine line-clearing and product changeover operation between MS Tank 401-A and the pipeline receipt manifold, operators attempted to operate a manual 'Hammer Blind Valve' on the tank delivery line. The valve mechanism seized and suffered catastrophic mechanical failure, discharging a high-velocity jet of liquid gasoline under a static liquid head of ~15 meters. The facility lacked Remote Operated Shut Off Valves (ROSOVs) at the tank nozzle. The manual shut-off valve was engulfed by the rapidly growing liquid and vapor cloud, preventing human intervention. Over 1,000 tons of MS escaped uncontrolled over 75 minutes, forming a massive ground-hugging vapor cloud across the entire terminal. Upon encountering an electrical or vehicular spark at the boundary gantry, the cloud detonated, initiating an unconfined vapor cloud explosion equivalent to ~20 tons of TNT and igniting all adjacent storage tanks in an unstoppable 11-day multi-tank domino disaster.

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3.2 Case Study 2: ONGC Hazira Gas Processing Plant Terminal Disaster (2020)

On September 24, 2020, a major fire and vapor cloud deflagration occurred at the Gas Terminal of ONGC's Hazira Processing Plant near Surat, Gujarat. The facility processes sour gas and condensate received via 36-inch subsea and overland trunklines. At 02:15 hrs, a massive leak developed in the condensate metering skid on a 6-inch high-pressure condensate line operating at ~35 bar. The expanding hydrocarbon mist and vapor cloud accumulated in the congested process unit. At 03:08 hrs (53 minutes post-leakage), the cloud ignited, triggering massive blast overpressures followed by intense jet and pool fires.

Root Cause Analysis: Forensic engineering revealed that all stud bolts securing the 6-inch metering skid flange had suffered sudden mechanical failure. Investigations identified that during previous EPC modification and maintenance turnarounds, improper bolt torqueing, lack of torque-wrench calibration records, and the installation of non-certified carbon steel fasteners in a corrosive sour condensate environment led to stress corrosion cracking (SCC) and thread stripping. Furthermore, operational isolation was delayed by over 40 minutes due to the absence of automated emergency isolation valves on the skid boundary, allowing thousands of cubic meters of condensate to vaporize.

3.3 Case Study 3: IOCL Mathura Refinery Hot Work Flash Fire (2020)

On January 7, 2020, a fatal explosion and flash fire erupted near the Effluent Treatment Plant (ETP) at the IOCL Mathura Refinery during construction and maintenance modifications on a spent caustic line. Six contract construction personnel suffered severe third-degree burns, resulting in one fatality. During the execution of piping replacement, contractor welders were fitting up a newly prefabricated pipe spool to an existing line. Hydrocarbon residues trapped in the poorly purged line were mobilized by atmospheric temperature rises. The open flame of the welding torch ignited the escaping hydrocarbon vapors, triggering an instantaneous flash fire within the confined trench excavation.

Root Cause Analysis: The disaster was driven entirely by EPC execution failures: (1) flawed Job Safety Analysis (JSA) failing to recognize simultaneous operations (SIMOPS); (2) inadequate positive isolation (absence of physical spade blinding); (3) failure to execute continuous LEL explosive gas testing prior to issuing the Hot Work Permit; and (4) absence of fire-resistant spark containment habitat screens in the trench.

Disaster Case Study	Primary Physical Failure	EPC / Construction Root Cause	Delayed Control Failure	Consequence Severity	Mandated Safety Barrier
IOCL Jaipur Terminal (2009)	Hammer Blind Valve Seizure & Gasket Blowout	EPC valve selection substituting manual blind for automated valve; layout congestion	Manual valve unreachable due to dense vapor cloud (75 min release)	12 Fatalities; 11 Tanks Destroyed; 20t TNT Eqv Blast; 11-day fire	Remote Operated Shut Off Valves (ROSOV); OISD-244 compliance
ONGC Hazira Gas Terminal (2020)	Flange Stud Bolt Failure on 6-inch Metering Skid	Substandard fastener metallurgy; improper EPC torqueing; lack of bolt QA/QC	40-minute delay in manual trunkline block valve closure	Severe Process Unit Destruction; Multi-hectare Vapour Cloud Fire	Flange Integrity Management System (FIMS); SIL-3 Emergency Shutdown Valves
IOCL Mathura Refinery (2020)	Trapped Hydrocarbon Flash Ignition in Trench	Deficient JSA; lack of positive spade isolation during piping tie-in; poor gas monitoring	Immediate flash ignition upon arc strike; no fire watcher intervention	1 Fatality; 5 Critical Burn Injuries; Unit Shutdown	Strict PTW/LOTO Framework; Continuous Gas Detection;

					Habitation Barrier

Table 1: Forensic Deconstruction of Landmark Petrochemical Disasters Linking EPC Deficiencies to Operational Loss.

IV. QUANTITATIVE RISK ASSESSMENT (QRA) AND DISASTER MODELING

To establish the quantitative consequence magnitude of loss-of-containment disasters in bulk hydrocarbon storage terminals, this section formulates rigorous mathematical models for two catastrophic operational scenarios: (1) Scenario I: Fireball and Boiling Liquid Expanding Vapour Explosion (BLEVE) thermal radiation dynamics; and (2) Scenario II: Vapour Cloud Explosion (VCE) blast overpressure using the TNT-Equivalency and Hopkinson-Cranz scaling methodologies.

4.1 Scenario I: Thermal Radiation Modeling for BLEVE and Fireball (Roberts Method)

When a large atmospheric storage tank or pressurized vessel undergoes catastrophic shell failure under external fire engulfment, the instantaneous depressurization of superheated liquid results in a massive spherical fireball. Consequence modeling is performed based on the standard empirical formulations established by Roberts and the Center for Chemical Process Safety (CCPS).

Model Input Data: Consider an API-650 atmospheric floating roof storage tank conforming to the Jaipur Terminal inventory parameters:

- Tank Gross Capacity: 7,389 m3
- Operating Fill Level: 65%
- Stored Product: Motor Spirit (Gasoline, Class-A)
- Fluid Density: 750 kg/m3
- Total Flammable Mass Released (M): M = 0.65 x 7,389 m3 x 750 kg/m3 = 3,602,137.5 kg (~3,602 metric tons)
- Heat of Combustion of Gasoline (Delta Hc): 47,300 kJ/kg = 47.3 MJ/kg

The maximum fireball diameter (D_max) and total combustion duration (T_max) are governed by the power-law empirical scaling laws:

$$D_{max} = 5.8 \times M^{(1/3)} = 5.8 \times (3{,}602{,}137.5)^{(1/3)} = 889.09 \text{ meters}$$

$$T_{max} = 0.45 \times M^{(1/3)} = 0.45 \times (3{,}602{,}137.5)^{(1/3)} = 68.98 \text{ seconds}$$

The height of the fireball center above grade (H) is taken as H = D_max = 889.09 m. The specific burning rate per unit surface area (m') is calculated by dividing total fuel mass by effective surface area and duration:

$$m' = M / (0.888 \times \pi \times D_{max}^2 \times T_{max}) = 3{,}602{,}137.5 / (0.888 \times \pi \times (889.09)^2 \times 68.98) = 0.0238 \text{ kg/(m}^2\cdot\text{s)}$$

The maximum Surface Emitting Power (SEP_max) at the fireball surface is a function of the radiative heat fraction (Fs = 0.307) and combustion enthalpy:

$$SEP_{max} = F_s \times m' \times \Delta H_c = 0.307 \times 0.0238 \text{ kg/(m}^2\cdot\text{s)} \times 47{,}300 \text{ kJ/kg} = 345.59 \text{ kW/m}^2$$

The thermal radiation heat flux (q') incident upon a terrestrial target located at a horizontal distance a from the ground zero epicenter is expressed via the geometric view factor (F_view) and atmospheric transmissivity (tau_a approx 1.0 for conservative near-field estimation):

$$q' = SEP_{max} \times F_{view} \times \tau_a = SEP_{max} \times (R / X)^2 \times \tau_a$$

$$\text{where } R = D_{max} / 2 = 444.55 \text{ m}, \quad X = \sqrt{H^2 + a^2} = \sqrt{(889.09)^2 + a^2}$$

Distance a (m)	Slant Dist. X (m)	View Factor (F_view)	Heat Flux q' (kW/m²)	Human Exposure Effect	Structural / Facility Damage
50	890.49	0.2490	86.05	100% Lethality in < 5 seconds	Total structural collapse; instantaneous auto-ignition of

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					storage tanks
100	894.69	0.2467	85.25	100% Lethality in < 5 seconds	Heavy steel distortion; immediate boiling of adjacent tank inventories
200	911.30	0.2377	82.15	100% Lethality in < 8 seconds	Rapid failure of process piping supports and electrical cable trays
500	1020.03	0.1898	65.60	100% Fatal in < 15 seconds	Severe blistering of painted surfaces; secondary tank seal ignition
750	1163.17	0.1460	50.45	3rd Degree Burns in 10s; High Fatal	Melting of PVC/insulation; collapse of wooden/light structures
1000	1337.38	0.1105	38.18	Threshold of 100% Lethality (37.5 kW/m²)	Blistering of heavy industrial coatings; critical radiation limit

Table 2: Fireball Thermal Radiation and Consequence Distances for 3,602 Metric Ton Hydrocarbon BLEVE.

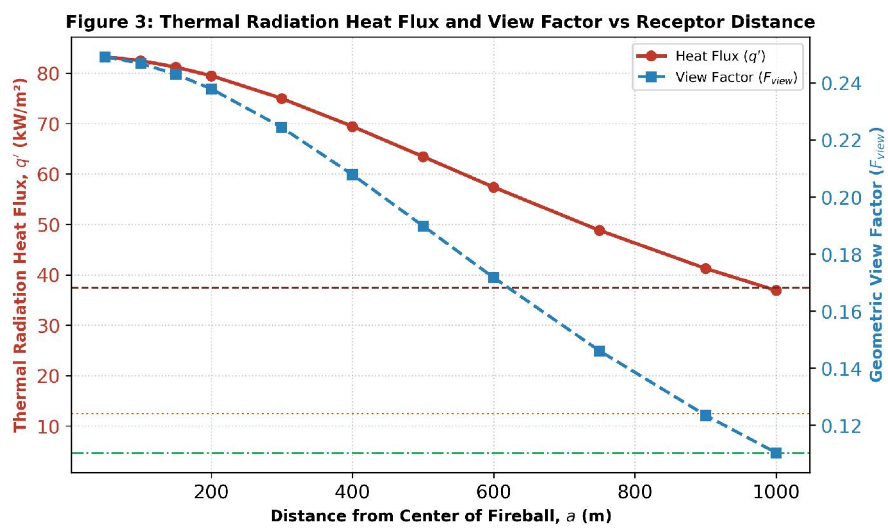

Figure 3: Attenuation of Thermal Radiation Heat Flux and View Factor as a Function of Receptor Distance.

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Discussion of Thermal Radiation Data: The mathematical results plotted in Figure 3 prove that the thermal radiation footprint of a large-scale gasoline fireball is devastating. The universally recognized 100% lethality threshold of 37.5 kW/m2 extends beyond a 1,000-meter radius from the tank epicenter. This quantitative finding proves that manual emergency intervention (such as dispatching operators to manually isolate valves in adjacent dykes) is physically impossible during a major release, providing undeniable mathematical justification for fully automated, remotely actuated shut-off valves (ROSOVs) located outside the primary hazard zone.

4.2 Scenario II: Vapour Cloud Explosion (VCE) Blast Overpressure Modeling

In the event of an uncontrolled Class-A liquid spill (such as the 1,000-ton MS release at Jaipur), intense vaporization generates a massive flammable cloud. The blast overpressure produced upon delayed ignition is modeled using the TNT-Equivalency method combined with Hopkinson-Cranz blast scaling.

Thermodynamic Parameter Calculation:

• Stored Gasoline Mass Escaped: M_total = 1,000,000 kg
• Flashing and Evaporation Mass in Vapor Cloud (M_vap): Conservatively estimated at 450,000 kg (45% of total spill over 75 min duration)
• Flammable Mass Yield Fraction (F): Calculated from thermodynamic flash fraction and atmospheric entrainment (F = 0.62)
• Effective Combustible Vapor Mass in Cloud (W_f): W_f = 2 x F x M_vap = 2 x 0.62 x 450,000 = 558,000 kg
• Explosion Blast Efficiency Factor (alpha_e): Standard CCPS value for moderately congested unconfined hydrocarbon clouds (alpha_e = 0.03 = 3%)
• Heat of Combustion of Gasoline (H_f): 47,300 kJ/kg
• Standard Heat of Detonation of TNT (H_TNT): 4,680 kJ/kg

The equivalent mass of TNT (W_TNT) is computed as:

$$W_{TNT} = \alpha_e \times (W_f \times H_f) / H_{TNT} = 0.03 \times (558{,}000 \text{ kg} \times 47{,}300 \text{ kJ/kg}) / 4{,}680 \text{ kJ/kg} = 169{,}188.46 \text{ kg TNT } (\sim 169.2 \text{ Metric Tons TNT})$$

To determine the peak side-on blast overpressure (P_so) at any radial distance R, we compute the Hopkinson-Scaled Distance (R_bar):

$$\bar{R} = R / (W_{TNT})^{(1/3)} = R / (169{,}188.46)^{(1/3)} = R / 55.31 \text{ (m / kg}^{(1/3)} \text{)}$$

Actual Distance R (m)	Hopkinson Scaled Dist. R_bar	Peak Blast Overpressure (kPa)	Observed Structural Damage Category	Human Fatality / Injury Risk
100	1.808	285.4	Total demolition of reinforced concrete structures; heavy machinery sheared from foundations	100% Lethality via whole-body displacement and lung rupture
150	2.712	142.1	Heavy structural collapse of steel frames; complete rupture of atmospheric tanks	> 80% Lethality from severe blast trauma and collapse
200	3.616	78.6	Heavy damage to steel frame buildings; collapse of brick walls and pipe racks	50% Eardrum rupture; critical blunt force projectile injuries

300	5.424	36.2	Distortion of steel columns; failure of storage tank roof-to-shell seams	10% Eardrum rupture; severe injuries from flying debris
500	9.040	14.8	Moderate damage; non-structural walls crack; heavy window frames sheared	Minor injuries from glass fragments; fall injuries
750	13.560	7.4	Partial glass breakage; light roofing sheet displacement; minor cracking	Threshold of glass shrapnel lacerations

Table 3: Blast Overpressure and Scaled Distance Effects for 169.2 Metric Ton TNT Equivalent Explosion.

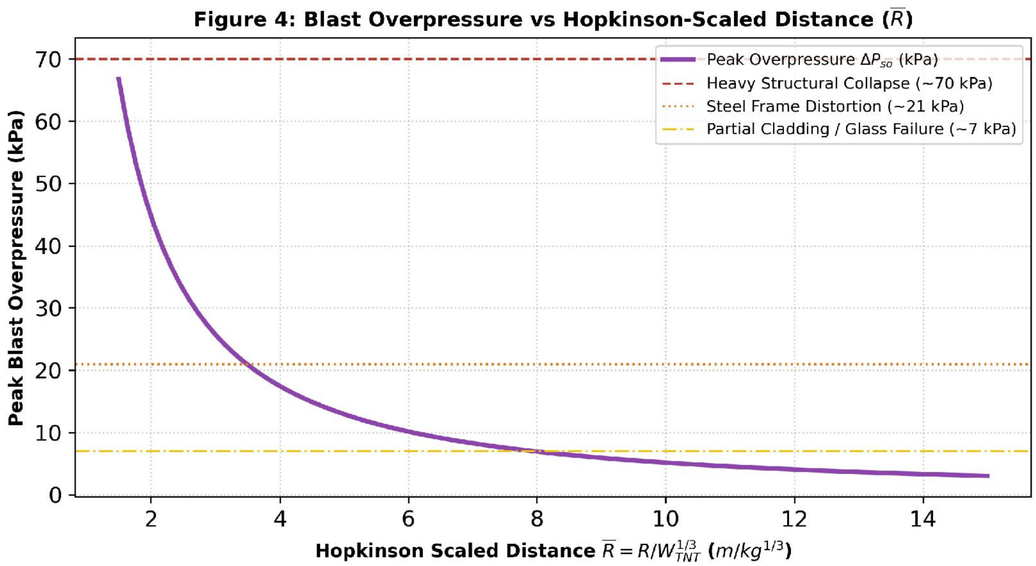

Figure 4: Peak Side-on Blast Overpressure (P_so) as a Function of Hopkinson-Scaled Distance (R_bar).

V. THE INTEGRATED EPC PROCESS SAFETY ARCHITECTURE: HIRA AND FMEA

The consequence modeling in Section 4 demonstrates the catastrophic irreversibility of operational hydrocarbon releases. Consequently, the primary engineering strategy must shift from downstream emergency response to upstream latent defect elimination during the Engineering, Procurement, and Construction (EPC) phase. This section formalizes the integration of Hazard Identification and Risk Assessment (HIRA) with Failure Mode and Effects Analysis (FMEA).

5.1 HIRA Implementation across Mega-Petrochemical Construction Modules

Based on project HSE frameworks utilized at the Tecnimont Qatar RLPP Polyethylene Plant, Table 4 presents the comprehensive HIRA matrix identifying occupational and latent process hazards across 8 major construction fronts, mapping initial risk to residual risk post-barrier implementation.

EPC Activity / Front	Main Construction & Latent Hazards	Initial Risk	Engineered Mitigative Controls (PTW / Standards)	Residual Risk
Excavation & Trenching	Trench wall collapse; striking underground utility lines; toxic gas ingress.	HIGH	Excavation permit, underground scanning/trial pits, shoring/benching, gas testing.	LOW
Steel Structure Erection	Crane rigging failure; dropped structural beams; working at height falls.	HIGH	Critical lift plan (>20t), certified riggers, dual taglines, 100% tie-off harness.	LOW
Piping Fabrication & Welding	Hot work fire; toxic welding fumes; weld root lack of fusion / porosity.	HIGH	Hot work permit, fire watcher, welding habitats, 100% NDT (RT/UT) QA hold points.	MEDIUM
Hydrotesting & Flushing	High-pressure line rupture; manifold whip; sudden water discharge.	MEDIUM	Calibrated test manifolds, calibrated gauges, physical exclusion barricading.	LOW
Pneumatic Pressure Testing	Massive stored pneumatic energy blast; projectile missile generation.	EXTREME	Specific engineering calculation of safe standoff radius, acoustic emission testing.	MEDIUM
Confined Space Entry	Atmospheric oxygen deficiency; toxic gas exposure; trapped personnel.	EXTREME	Confined space permit, continuous forced ventilation, standby rescuer, gas logging.	LOW
Electrical Commissioning	Arc flash blast; electric shock; premature line energization.	HIGH	Comprehensive LOTO/LTT system, calibrated insulated tools, arc-flash NFPA PPE.	LOW
Flange Fit-up & Torqueing	Gasket pinching; uneven bolt stress; latent operational hydrocarbon leak.	HIGH	Hydraulic torque tightening, calibrated wrenches, digital joint tag log.	LOW

Table 4: Comprehensive Hazard Identification and Risk Assessment (HIRA) Matrix for Petrochemical EPC Phases.

5.2 Failure Mode and Effects Analysis (FMEA) and RPN Mandate Framework

To quantitatively connect EPC mechanical quality with operational disaster prevention, Failure Mode and Effects Analysis (FMEA) is applied. The Risk Priority Number (RPN) is calculated for each failure mode as the product of Severity (S), Occurrence (O), and Detection (D):

$$\textbf{RPN} = \textbf{Severity (S)} \times \textbf{Occurrence (O)} \times \textbf{Detection (D)}$$

Where S, O, D are scored on standard 1-10 engineering rating scales. In our proposed lifecycle framework, a strict critical threshold (RPN > 100) is established. Any construction or procurement failure mode generating an RPN > 100 cannot be mitigated by administrative controls alone; it mandates the implementation of automated, safety-instrumented engineering barriers (e.g., ROSOVs, SIL-2/3 trips, and automatic deluge) prior to mechanical completion.

EPC Construction Front	Specific Mechanical Failure Mode	Downstream Operational Consequence	S	O	D	RPN Score
Valve Selection & Procurement (Jaipur Baseline)	Installation of manual Hammer Blind valve instead of fail-safe ROSOV	Unstoppable hydrocarbon release during line switch; multi-tank BLEVE/VCE disaster	10	3	4	**120 (MANDATE AUTOMATED ROSOV)**
Flange Management & Bolting (Hazira Baseline)	Inadequate bolt torqueing; non-certified fastener metallurgy in sour service	High-pressure gasket blowout; massive condensate vapor cloud explosion	9	4	3	**108 (MANDATE FLANGE INTEGRITY QA)**
Hot Work & Tie-in Operations (Mathura Baseline)	Failure of physical isolation / spade blinding during spool replacement	Flash fire and localized vapor ignition burning maintenance personnel	8	5	2	80 (QA/QC HOLD POINT REQUIRED)
Piping Prefabrication & Welding	Root lack of fusion / undetected slag inclusions in process spools	Piping fatigue rupture under operational vibration; continuous jet fire	10	3	2	**60 (MANDATE 100% RADIOGRAPHY NDT)**
Pneumatic Pressure Testing	Over-pressurization beyond design envelope / relief valve sizing error	Catastrophic pipeline fragmentation; missile generation during test	10	2	2	40 (SAFE DISTANCE BARRICADING)

Table 5: Failure Mode and Effects Analysis (FMEA) for Critical Petrochemical EPC Operations.

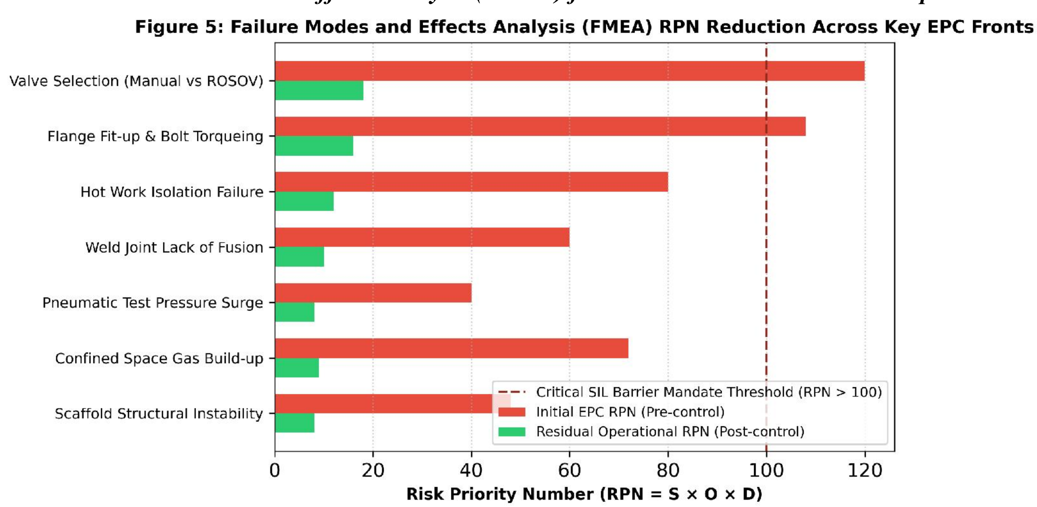

Figure 5: Pareto Comparison of Risk Priority Numbers (RPN) Pre- and Post-Engineered Barrier Implementation.

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VI. CONCLUSION AND PRACTICAL RECOMMENDATIONS

This research has developed and validated an integrated EPC-Operational process safety lifecycle model, addressing the critical vulnerability gap between construction quality assurance and catastrophic operational risk. The key findings and conclusions of this study are summarized below:

- **Forensic Disaster Validation:** Forensic deconstruction of the IOCL Jaipur (2009), ONGC Hazira (2020), and IOCL Mathura (2020) disasters proves that major operational losses are the direct consequence of latent EPC procedural failures (manual valve selection, substandard bolt torqueing, and defective hot work isolation).
- **Consequence Modeling Proof:** Thermodynamic fireball modeling for a 3,602-metric-ton gasoline inventory establishes that lethal thermal radiation (>37.5 kW/m2) extends beyond 1,000 meters, mathematically disproving the viability of manual emergency isolation and establishing the necessity of remote automated barriers.
- **FMEA Quantitative Threshold Mandate:** The established FMEA framework demonstrates that failure modes with RPN > 100 mandate automated Safety Instrumented Systems (such as ROSOVs and SIL-rated shut-off logic) before mechanical completion sign-off.

6.1 Standard Operating Recommendations for EPC Contractors and Operators

6.1.1 Mandatory ROSOV Installation: All bulk atmospheric storage tanks containing Class-A and Class-B petroleum products must be equipped with Remote Operated Shut Off Valves (ROSOVs) directly at the tank nozzle, interlocked with control room ESD panels and dyke-perimeter LEL hydrocarbon gas detectors (in compliance with OISD-STD-244).

6.1.2 Flange Integrity Management System (FIMS): Implement 100% digital torque logging and calibrated hydraulic wrenching for all ASME Class 300+ and sour service flanges during EPC prefabrication and erection, eliminating bolt failure pathogens.

6.1.3 100% Radiography Testing (RT) on Critical Spools: Enforce 100% volumetric non-destructive examination (RT or Phased Array UT) on all critical process lines, tie-ins, and manifold welds prior to hydrotesting.

6.1.4 Fire Water and Foam Deluge Redundancy: Ensure dedicated on-site fire water storage capable of sustaining 4 hours of maximum terminal demand, coupled with FM-approved Aqueous Film Forming Foam (AFFF) supply for 65 minutes of continuous high-expansion foam blanket generation (OISD-STD-117).

6.1.5 Dynamic HIRA/PTW Verification: Enforce continuous multi-gas atmospheric testing (LEL %, O_2 %, H_2S ppm) and physical positive spade isolation for all hot work and tie-in modifications in operating refinery zones.

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