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# QRA and Reliability Optimization in Gas Pipeline Construction using Fault Tree Analysis A Scenario-Based Construction-Phase Risk Assessment Framework

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**Abstract:** *Gas pipeline construction comprises route preparation, excavation or horizontal directional drilling (HDD), pipe transportation and stringing, lifting, welding, non-destructive testing, coating, lowering-in, backfilling, testing and tie-in activities. These operations may interact with existing buried utilities and live hydrocarbon systems, creating pathways to pipeline damage, loss of containment, fire, explosion and struck-by injury. This study develops a construction-phase risk assessment framework that integrates task-based hazard identification and risk assessment (HIRARC), Fault Tree Analysis (FTA), data-screened Quantitative Risk Assessment (QRA), and reliability improvement. Four top-event scenarios are formulated: (i) mechanical damage to an existing buried gas pipeline during excavation; (ii) fire or explosion during hot work; (iii) unexpected hydrocarbon release during construction or tie-in; and (iv) a dropped pipe or load striking a person during lifting. Preliminary fault trees separate initiating mechanisms, failed safeguards and exposure conditions, thereby clarifying the AND/OR relationships that must be validated. Documentary triangulation uses the supplied project report, relevant accident-investigation records, and technical guidance on FTA, excavation and hot-work controls. The industrial visit to Oil Terminal is treated only as contextual familiarisation; the visit photographs do not demonstrate the occurrence of any modelled event. The analysis identifies utility-location assurance, permit-to-dig, positive isolation, gas testing, hot-work control, lifting integrity, exclusion zones and communication as critical barrier themes. Since task-specific failure rates, exposure denominators and consequence parameters were not supplied, numerical probabilities, risk contours and risk-reduction percentages are intentionally not reported. The principal contribution is a transparent, auditable framework for validating construction-related fault trees and populating a QRA when reliable project data become available.*

**Key Words:** Gas pipeline construction; Fault Tree Analysis; Quantitative Risk Assessment; reliability improvement; excavation damage; permit to work; hydrocarbon release

## 1. INTRODUCTION

Natural gas transmission and distribution networks support industrial, commercial and domestic energy supply. Expansion and maintenance of pipeline infrastructure require construction activities across variable terrain, land uses and operating environments. Typical onshore work packages include route survey, right-of-way preparation, excavation or HDD, pipe transportation, stringing, bending, alignment, welding, non-destructive testing (NDT), coating, lowering-

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in, backfilling, pressure testing and tie-in preparation. Each work package combines equipment, people, temporary works and management controls; the risk profile changes as the work front moves.

A central safety challenge occurs when construction teams work near existing live pipelines, terminal piping, electrical cables or other buried services. A new pipeline may be uncommissioned during much of installation, yet nearby operating infrastructure may contain pressurised flammable inventory. Inaccurate utility drawings, ineffective detection and marking, uncontrolled excavation, inadequate isolation, poor gas testing, hot-work ignition sources, lifting failures and weak communication can interact. NTSB investigations document third-party excavation damage followed by natural-gas release and ignition, demonstrating the plausibility of this mechanism in other locations [5], [6]. These cases are not evidence of incidents at the industrial-visit location considered in this study.

Task-based HIRARC is useful for identifying hazards, estimating risk and assigning controls. However, a risk register may not explicitly reveal the combinations of failures that produce a major event. FTA provides a deductive, top-down representation of the causal structure, while QRA can combine event frequency with consequence analysis when defensible input data exist [1], [2]. The present work therefore positions HIRARC as the task-screening layer, FTA as the causal-modelling layer, and QRA as a data-dependent quantification layer.

### 1.1 Research gap and contribution

The project material identifies excavation, HDD, welding/hot work and lifting as important construction activities and discusses human, procedural and equipment-related contributors. The gap addressed here is the need to connect these work activities to explicitly defined top events and barrier failures, rather than treating all hazards as independent entries in a risk register. The contribution is a scenario-based framework with four preliminary fault trees, a transparent statement of data requirements, and a barrier-oriented reliability-improvement plan. The manuscript is a framework study, not a completed probabilistic validation.

### 1.2 Research questions

- Which construction-stage activities and interfaces can credibly lead to serious injury, pipeline damage or loss of containment?
- How should human, equipment, procedural, isolation and communication failures be represented in FTA?
- What event combinations are necessary for each defined top event under the proposed logic?
- What traceable data are required before a numerical QRA can be performed?
- Which preventive and mitigative barriers can interrupt the identified causal pathways?

### 1.3 Highlights

- Four construction-phase top events are defined and represented using preliminary fault-tree logic.
- Pipeline damage, hydrocarbon release and ignition are treated as distinct event stages.
- Minimal cut-set logic is discussed without assigning unsupported basic-event probabilities.
- Critical preventive barriers are mapped to the failure mechanisms they are intended to interrupt.
- QRA is made conditional on traceable frequency, exposure and consequence data.

## II. LITERATURE REVIEW

### 2.1 Task-based risk assessment and construction safety

The supplied Minor Project report builds on a HIRARC-oriented base study of onshore gas pipeline installation. It emphasises work-step identification, site observation, consultation and consideration of excavation, HDD, welding and lifting. It also describes the hierarchy of controls, from elimination and substitution through engineering and administrative controls to personal protective equipment. This is consistent with construction-safety research that stresses tracing accidents beyond immediate unsafe acts to management decisions, site conditions and underlying causal factors [3], [4].

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Human and organisational factors should be expressed as observable failures wherever possible. Examples include an unverified permit, incorrect line identification, missing spotter, incomplete toolbox briefing, failure to respect a marked tolerance zone, or a change in scope not communicated to operations. Treating all such contributors as a single generic 'human error' event weakens the usefulness of the fault tree.

### 2.2 Fault Tree Analysis and QRA

FTA begins with a clearly bounded undesired top event and decomposes it into intermediate and basic events through logical gates. An OR gate represents an output that can occur when one or more input events occur; an AND gate represents an output requiring all specified inputs. Minimal cut sets are the smallest combinations of basic events sufficient to produce the top event under the model assumptions. IEC 61025 provides guidance on FTA principles, event definitions, assumptions, symbols and quantitative aspects [1].

For statistically independent input events, the probability of an OR combination is $P(OR)=1-\prod(1-P_i)$, while the probability of an AND combination is $P(AND)=\prod P_i$. These expressions are not appropriate without qualification where common-cause failures, conditional dependencies or shared management weaknesses exist. Event frequencies must also use a consistent exposure basis (for example, per excavation, per lift, per operating hour or per project-year).

QRA extends the analysis by combining scenario frequency with consequence modelling. Depending on the objective, consequences may include thermal radiation, overpressure, gas dispersion, fatality probability, asset damage or environmental impact. Scenario-specific inventory, pressure, release geometry, isolation time, weather, ignition conditions and occupancy are required before such outputs can be estimated. In their absence, numerical risk contours or individual-risk values would be speculative.

### 2.3 Accident learning and management systems

NTSB's investigation of the 2010 Enterprise Products incident describes a power auger puncturing an unmarked 36-inch natural-gas transmission pipeline during utility-pole installation, followed by ignition and fatal and non-fatal injuries [5]. The 2019 San Francisco investigation describes a mini-excavator striking a gas-service branch connection during conduit excavation, resulting in gas release and fire [6]. These investigations support the plausibility of the excavation-damage pathway and highlight the importance of utility locating, marking, tolerance-zone practices and operator/spotter coordination.

API Recommended Practice 1173 describes a pipeline safety management system built around leadership, stakeholder engagement, risk management, operational controls, incident learning, safety assurance, emergency preparedness, competence and documentation [7]. Although its primary focus is pipeline operators, its management-system principles are relevant to contractor interfaces and lifecycle safety. OSHA excavation requirements likewise call for determining underground installation locations before excavation, contacting utility owners and determining exact locations by safe means as work approaches them [8]. OSHA hot-work guidance identifies welding, cutting and other spark-producing work as ignition sources and recommends permits, isolation, removal of combustibles and fire-watch arrangements where applicable [9].

### 2.4 Synthesis

The literature and incident records support a barrier-based analysis rather than a simple list of hazards. The four scenarios selected in this paper span the main causal pathways represented in the project report: utility strike, release and ignition, loss of containment during intrusive work, and dropped-load injury. External case records are used only to establish mechanism plausibility; they are not transferred as failure probabilities for the present study.

## III. AIM, OBJECTIVES AND STUDY BOUNDARY

The aim is to develop a construction-phase risk assessment and reliability-improvement framework for onshore gas pipeline construction using FTA and, where reliable data are available, QRA.

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- Identify hazards associated with excavation, HDD, lifting, welding, tie-in, testing and interfaces with existing live hydrocarbon infrastructure.
- Define four critical construction-related top events and develop preliminary AND/OR fault trees.
- Separate initiating mechanisms, failed safeguards and exposure conditions.
- Identify candidate minimal cut-set logic and the data needed for probability estimation.
- Recommend engineering, administrative and emergency barriers that target the identified contributors.

### 3.1 Scope

The study boundary extends from site and route preparation through excavation/HDD, pipe handling, welding, NDT, coating, lowering-in, backfilling, construction testing and tie-in preparation. Routine gas transportation after commissioning, long-term corrosion and ageing, unrelated operational leaks, and post-handover maintenance are outside the present scope. Existing live pipelines are included only where construction can interact with them or where they form the hazardous inventory in a construction-stage scenario.

| Work package / interface | Potential hazard or failure source |
|---|---|
| Site preparation and route marking | Incorrect route information, unidentified utilities, poor work-area demarcation |
| Excavation and trenching | Mechanical contact with buried line, trench collapse, struck-by exposure |
| HDD and pipe pulling | Bore-path uncertainty, equipment malfunction, excessive or uncontrolled pulling load |
| Transportation, stringing and lifting | Dropped load, rigging failure, equipment instability, pipe displacement |
| Welding, cutting and tie-in | Ignition source, flammable atmosphere, inadequate isolation or gas testing |
| NDT, coating and lowering-in | Chemical exposure, suspended pipe, equipment-person interface |
| Backfilling and testing | Stored energy, temporary connections, pressure-related hazards |

### 3.2 Industrial visit context

The supplied report documents an industrial familiarization visit to Oil Terminal. The photographs on pages 21–23 of the source PDF show visitor-entry documentation, the terminal identification sign and the entrance/access-control area. They do not show pipeline excavation, welding, tie-in, lifting or a specific unsafe condition. Accordingly, the terminal is identified only as the industrial-visit context; no modelled incident or unsafe practice is attributed to Oil Terminal.

## IV. RESEARCH METHODOLOGY

A documentary and scenario-modelling methodology was adopted from the supplied project report. It comprises: (i) review of the project material and relevant technical literature; (ii) mapping of the construction workflow; (iii) task-based hazard identification; (iv) definition of top events; (v) preliminary FTA development; (vi) documentary plausibility checks against accident investigations and technical guidance; and (vii) preparation of a data register and barrier-improvement recommendations.

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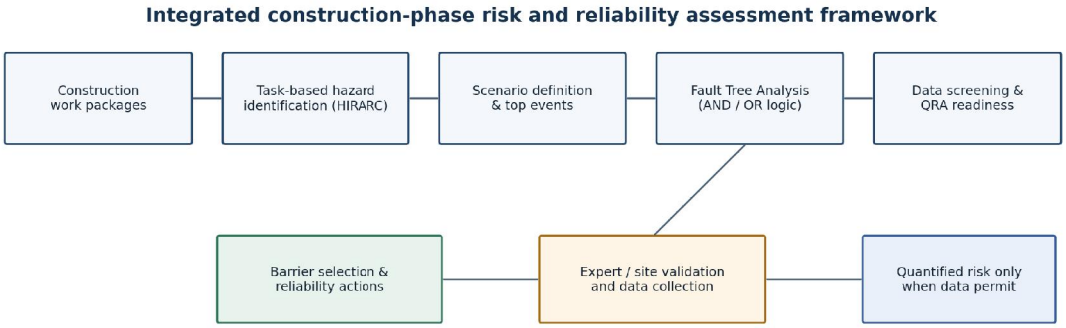



*Figure 1. Integrated workflow linking HIRARC, scenario definition, FTA, data validation, QRA readiness and reliability improvement.*

### 4.1 Fault-tree modelling rules

| Term | Operational meaning in this study |
|---|---|
| Top event | The undesired system-level outcome selected for analysis. |
| Intermediate event | A contributing event further decomposed into causes or barriers. |
| Basic event | A lowest-level event not further developed in the current conceptual model. |
| OR gate | Output occurs if one or more input events occur. |
| AND gate | Output requires all specified input events to occur together. |
| Minimal cut set | Smallest combination of basic events sufficient to produce the top event. |

The four trees are preliminary models. Before publication as validated FTA, the project team should review gate logic with the project guide and competent pipeline construction/operations personnel. The review should check scenario boundaries, causal direction, duplicated events, missing barriers, common-cause failures and whether a listed item is an initiating event, safeguard failure or consequence.

### 4.2 QRA readiness and data quality

For each basic event, the data register should record the source, time period, exposure denominator, event definition, population, uncertainty and applicability. A frequency per lift cannot be directly combined with a frequency per operating year without a consistent exposure conversion. Where only ordinal likelihood categories are available, the result should remain qualitative or semi-quantitative rather than being converted into unsupported probabilities.

## V. PRELIMINARY FAULT TREE MODELS

### 5.1 TE-1: Mechanical damage to an existing buried pipeline

The first top event is mechanical damage to an existing buried gas pipeline during excavation. The proposed structure requires excavation to enter the pipeline corridor together with ineffective location or work-execution controls. Candidate basic events include outdated utility drawings, failure to consult the utility owner, ineffective detection or marking, absence of trial holes where required, permit-to-dig deficiencies, failure to maintain an exclusion/tolerance zone, ineffective spotter communication and inadequate supervision.

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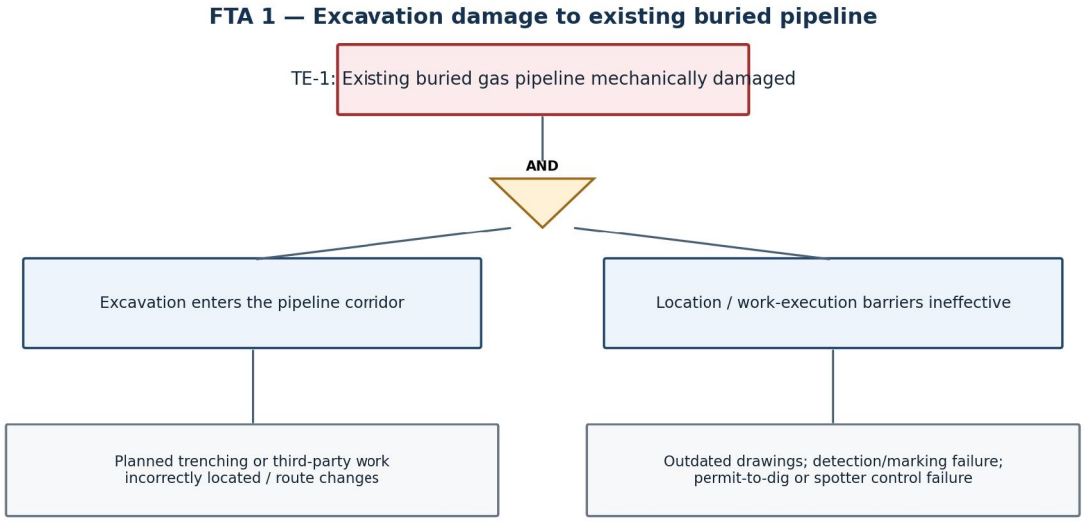



*Figure 2. Preliminary conceptual FTA for excavation damage. Gate logic requires validation against the actual work method and barrier dependencies.*

The candidate cut-set logic is expressed at a high level as: [excavation enters the pipeline corridor] AND [location/work-execution barriers are ineffective]. This is not yet a mathematically reduced minimal cut set because the internal branch logic and dependence among utility marking, permit-to-dig and spotter controls have not been validated. OSHA's excavation provisions provide a relevant control benchmark for locating underground installations before work and determining their exact location as excavation approaches [8].

### 5.2 TE-2: Fire or explosion during hot work

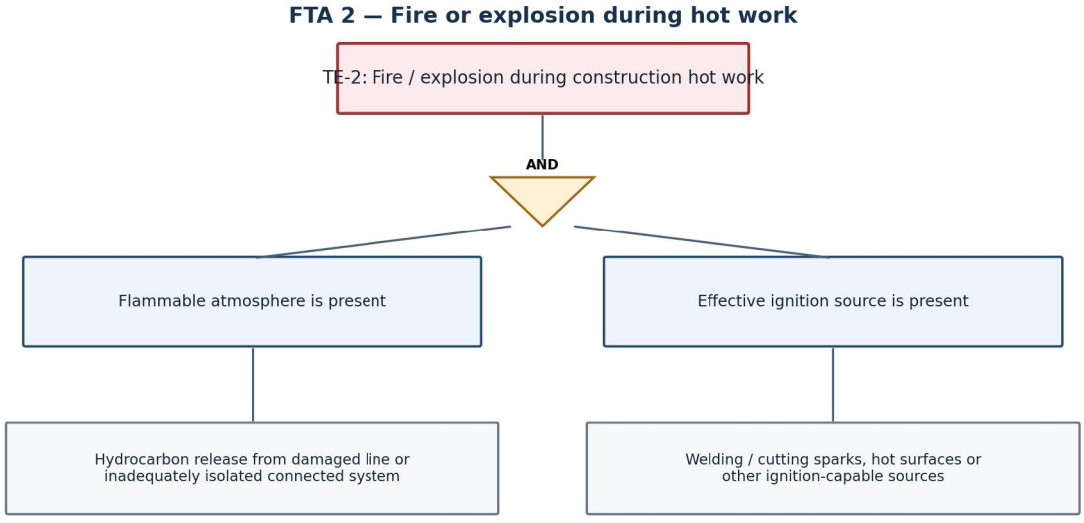



*Figure 3. Preliminary conceptual FTA for fire or explosion during hot work.*

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The second top event is fire or explosion during welding, cutting or other hot work in the construction area. The fundamental physical logic requires both a flammable atmosphere and an effective ignition source. A flammable atmosphere may arise from damage to an existing live line or intrusive work on an inadequately isolated connected system. Welding sparks, cutting operations, hot surfaces or other ignition-capable sources may supply ignition.

The top-level logic is [flammable atmosphere present] AND [effective ignition source present]. Permit-to-work failure, inadequate gas testing and failed isolation are safeguards or contributors to the flammable-atmosphere branch; they are not themselves the physical ignition mechanism. The model should specify gas-test locations, test frequency, retest triggers and stop-work criteria. OSHA's hot-work guidance supports the use of permits, isolation/LOTO, control of combustibles and fire-watch arrangements as applicable [9].

### 5.3 TE-3: Unexpected hydrocarbon release during construction or tie-in

The third top event is an unplanned hydrocarbon release during construction, tie-in or isolation work. The proposed logic separates creation of a loss-of-containment pathway from the continued availability of hazardous inventory or pressure. Potential pathways include mechanical damage to a connected line, opening the wrong line, intrusive work before positive isolation, valve leakage or failure of a temporary connection/tie-in.

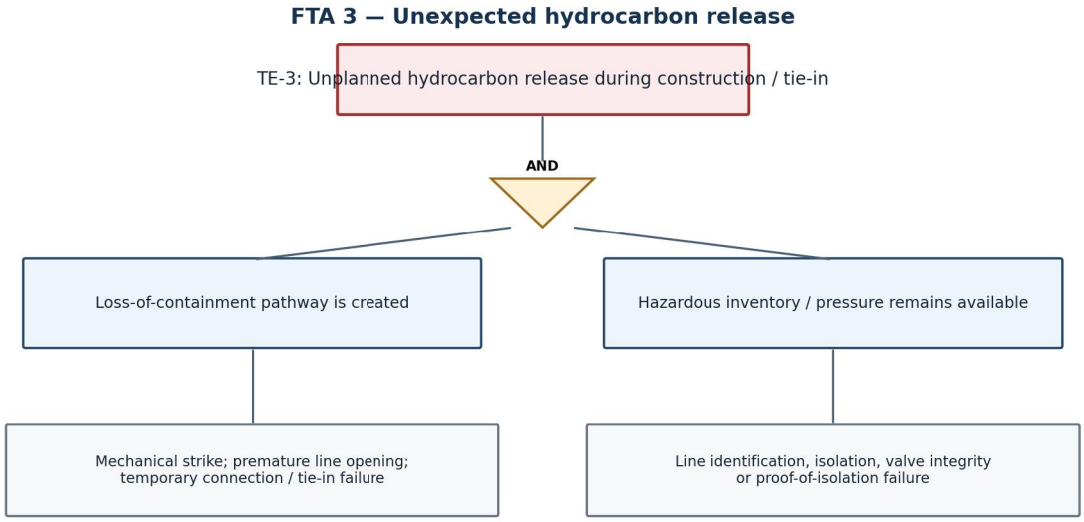



*Figure 4. Preliminary conceptual FTA for unexpected hydrocarbon release.*

The candidate top-level relationship is [loss-of-containment pathway created] AND [hazardous inventory/pressure remains available]. The final tree should explicitly distinguish line-identification errors, isolation-boundary errors, valve integrity, proof-of-isolation, depressurisation and temporary-connection integrity. Isolation should be verified using the approved site procedure; a permit alone does not physically prevent release.

### 5.4 TE-4: Dropped pipe or load during lifting

The fourth top event is a suspended pipe or load falling and striking a person. For the selected injury outcome, both an uncontrolled load and a person within the impact zone are required. Candidate causes of load loss include unsuitable or defective lifting accessories, incorrect rigging, unverified load weight or centre of gravity, equipment instability, ground-bearing failure, poor lift planning and communication failure. Exposure contributors include an absent or ineffective exclusion zone and personnel entering beneath a suspended load.

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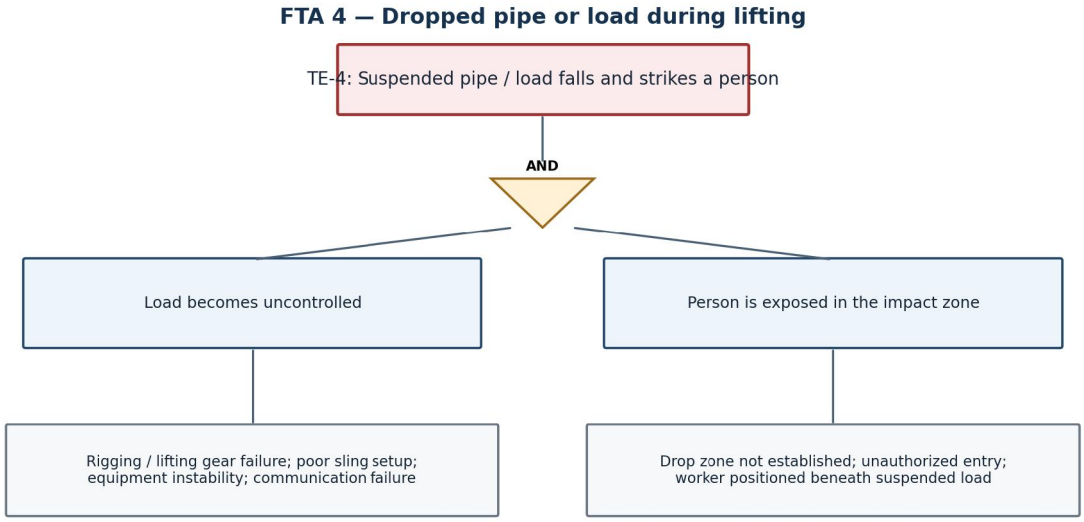



*Figure 5. Preliminary conceptual FTA for dropped-load injury during lifting and handling.*

The top-level relationship is [load becomes uncontrolled] AND [person is exposed to the impact zone]. A dropped load without a person in the impact zone may still cause asset damage or a near miss and can be modelled as a separate top event. OSHA excavation requirements also prohibit employees from working beneath loads handled by lifting or digging equipment [8].

## VI. RESULTS AND DISCUSSION

The results are structural and documentary rather than probabilistic. Four construction-phase top events were defined, their principal causal branches were mapped, and the key barriers requiring validation were identified. No field survey dataset, company failure-rate dataset, equipment reliability record or validated expert probability estimate was available in the supplied project material. Accordingly, the analysis does not report numerical event probabilities, annual frequencies, individual fatality risk, societal-risk contours or quantitative before/after reductions.

| Top event | Necessary high-level conditions | Key barrier themes | Evidence status |
|---|---|---|---|
| TE-1 Excavation damage | Excavation enters pipeline corridor AND location/work controls fail | Utility drawings; locating/marking; trial holes; permit-to-dig; spotter | Conceptual; requires site/expert validation |
| TE-2 Hot-work fire/explosion | Flammable atmosphere AND effective ignition source | Isolation; gas testing; hot-work permit; ignition control; fire watch | Conceptual; release/ignition data absent |
| TE-3 Hydrocarbon release | Loss-of-containment path AND hazardous inventory/pressure available | Line identification; positive isolation; proof of isolation; tie-in control | Conceptual; equipment/site data absent |
| TE-4 Dropped-load injury | Uncontrolled load AND person in impact zone | Lift plan; certified gear; equipment stability; exclusion zone; signalling | Conceptual; lifting records absent |

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### 6.1 Cross-scenario findings

- Utility-location assurance is a critical upstream barrier: an error in drawings or marking can undermine permit-to-dig and operator controls simultaneously.
- Pipeline damage, hydrocarbon release and ignition are separate event stages. A pipeline strike does not automatically imply fire; release and ignition conditions must also be present.
- Permit-to-work and gas testing are administrative/monitoring barriers. They should be represented as failed safeguards, not substituted for the physical release or ignition mechanism.
- Human and organisational contributors should be decomposed into observable failures and role-specific controls rather than grouped under a broad human-error label.
- For dropped-load injury, load control and personnel exposure are distinct branches. Exclusion-zone discipline can prevent injury even where a load-control failure occurs.

### 6.2 Documentary plausibility checks

The Enterprise Products investigation records a buried pipeline puncture by a power auger during utility-pole installation, followed by natural-gas ignition, one fatality and six injuries [5]. The San Francisco investigation records a mini-excavator strike on a gas branch connection during conduit installation, followed by release and fire [6]. These cases support the plausibility of the TE-1 to TE-3 causal chain and illustrate why utility locating, marking, operator/spotter coordination and emergency isolation are important. They do not provide a probability that can be transferred to the present project.

### 6.3 Data required to complete quantitative analysis

| Required input | Purpose | Potential source |
|---|---|---|
| Excavation-strike frequency | Estimate initiating-event frequency per excavation exposure | Project/contractor incident and near-miss logs; verified industry datasets |
| Utility detection / marking failure | Estimate location-control barrier reliability | Utility-owner records; detection logs; audits and permit reviews |
| Isolation failure on demand | Estimate probability of ineffective isolation | Isolation test records; valve maintenance and incident records |
| Gas-test failure / missed detection | Estimate probability of unsafe atmosphere not being detected | Detector calibration/bump-test records; gas-test logs |
| Hot-work ignition probability | Estimate ignition conditional on flammable atmosphere | Scenario-specific technical literature and expert review |
| Lifting / rigging failure frequency | Estimate dropped-load initiating frequency | Lifting inspection logs; equipment records; incident databases |
| Consequence parameters | Estimate injury, fatality, asset and environmental outcomes | Inventory, pressure, release geometry, weather, occupancy and response data |

## VII. RELIABILITY IMPROVEMENT AND CONTROL STRATEGY

Reliability improvement should target the basic events and barrier weaknesses that are both credible and controllable. In the absence of validated probability estimates, the recommendations below are qualitative. They are not assigned percentage reductions or numerical importance rankings.

| Scenario | Preventive / reliability measures | Mitigative measures and verification |
|---|---|---|
| Excavation damage | Current utility drawings; utility-owner consultation; suitable detection; trial holes; marked tolerance zone; permit-to-dig; competent spotter; controlled | Stop work and raise alarm; isolate damaged line through authorised personnel; evacuate; emergency response. Verify permits, |

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| | | |
|---|---|---|
| | excavation | detection records and field marking. |
| Hot-work fire / explosion | Positive isolation where required; gas-free verification; valid hot-work PTW; calibrated detector; retesting triggers; remove/control combustibles; fire watch | Stop work; alarm and evacuation; emergency shutdown/isolation; firefighting and medical response. Audit gas-test records and permit conditions. |
| Unexpected release | Line identification; isolation plan; LOTO; proof of isolation; depressurisation and gas testing; approved tie-in procedure; temporary connection inspection | Emergency isolation; gas detection/alarm; exclusion and evacuation; ignition control; emergency response. Verify isolation certificates and line-opening checklists. |
| Dropped load | Task-specific lift plan; load assessment; certified/inspected lifting gear; competent operator/riggers; equipment stability; clear signals; enforced exclusion zone | Stop work; rescue/first aid; emergency medical response; preserve scene and investigate. Audit lifting plans, gear registers and exclusion-zone compliance. |

### 7.1 Management-system integration

The proposed controls should be embedded in a repeatable management cycle. API RP 1173 identifies leadership commitment, stakeholder engagement, risk management, operational controls, incident learning, safety assurance, management review, emergency preparedness, competence and documentation as pipeline safety management system elements [7]. For construction projects, this supports stronger coordination between the operator, principal contractor, subcontractors, utility owners and site safety personnel.

### 7.2 Performance indicators for follow-up

- Percentage of excavation permits supported by current utility drawings and documented detection results.
- Percentage of intrusive-work permits with verified isolation evidence where isolation is required.
- Gas detector calibration and functional-test compliance; percentage of hot-work permits with defined retest triggers.
- Percentage of lifts supported by approved lift plans and current lifting-gear inspection records.
- Number of near misses, utility strikes, dropped-load events and stop-work interventions per defined exposure unit.
- Closure time and recurrence rate for corrective actions arising from audits and incident investigations.

## VIII. LIMITATIONS AND VALIDATION REQUIREMENTS

This manuscript is based on the supplied Minor Project-I PDF and documentary sources. The project report describes an industrial visit but does not provide a structured set of field observations about pipeline construction activities at Oil Terminal. The visit photographs establish the visit context only. The underlying HIRARC base paper is referenced in the supplied report as an unpublished academic document; its raw respondent-level data and detailed scoring definitions were not supplied in the present PDF. Therefore, any survey-derived risk scores from that base study have not been imported.

The four fault trees are preliminary conceptual models. Their logic has not yet been formally reviewed by a panel of pipeline construction, operations and safety experts. Common-cause dependencies may affect permit verification, gas testing, supervision and operator compliance. Numerical probabilities, failure rates, consequence distances, risk contours and risk-reduction percentages are not available and have not been invented. The manuscript should not be represented as a completed quantitative risk study until those data and validation steps are completed.

| Validation level | Required action | Current status |
|---|---|---|
| Scenario validation | Check each top event against task scope, project drawings, procedures and documented accident mechanisms | Preliminary documentary support |

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| | | |
|---|---|---|
| Logic validation | Expert review of event definitions, AND/OR gates, dependencies and common-cause failures | Pending |
| Data validation | Traceable failure rates/probabilities with exposure denominator, period and uncertainty | Not available in supplied PDF |
| Consequence validation | Verified inventory, pressure, release geometry, isolation time, weather and occupancy | Not available |
| Control effectiveness | Before/after evidence or documented expert elicitation | Not validated |

## IX. CONCLUSIONS

This study presents a scenario-based framework for analysing construction-phase hazards in onshore gas pipeline projects through the integration of task-based HIRARC, FTA, data-screened QRA and reliability improvement. Four top events were formulated: excavation damage to an existing buried pipeline, hot-work fire or explosion, unexpected hydrocarbon release during construction or tie-in, and dropped-load injury during lifting.

The preliminary fault trees clarify that major outcomes arise through combinations of initiating mechanisms, failed safeguards and exposure conditions. In particular, fire or explosion requires both a flammable atmosphere and an effective ignition source; unexpected release requires a loss-of-containment pathway while hazardous inventory or pressure remains available; and dropped-load injury requires both loss of load control and a person in the impact zone. These distinctions improve the transparency of risk communication and the targeting of preventive barriers.

The most important practical recommendations are to strengthen utility-location assurance and permit-to-dig controls; apply positive isolation and documented proof of isolation for intrusive work; implement competent gas testing and controlled hot-work permits; and ensure engineered lifting plans, inspected equipment and effective exclusion zones. The study does not provide numerical risk estimates because the necessary site-specific failure, exposure and consequence data were not supplied. Its value is therefore a transparent and auditable analytical foundation that can be validated and quantified in a subsequent field study.

## X. FUTURE SCOPE

- Conduct structured interviews and a questionnaire survey with pipeline construction, operations, maintenance and safety personnel, subject to organisational permission and informed consent.
- Obtain anonymised project and contractor records to estimate task-specific initiating-event frequencies and barrier-failure data.
- Validate the four fault trees with competent experts and calculate minimal cut sets, importance measures and sensitivity rankings.
- Undertake consequence modelling for credible gas-release scenarios using verified inventory, pressure, release geometry, isolation time, meteorological data and occupancy.
- Extend the framework to HDD crossings, hot tapping, road/rail crossings, pressure testing, purging, commissioning and handover as separately bounded scenarios.
- Compare baseline and improved performance using audit results, near-miss trends, permit compliance, utility-damage records and lifting-event data.

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