SPRING26 +22ND GCPS

A Joint AIChE and CCPS Meeting

April 12 – 16, 2026
Houston, TX

Where Chemical Engineering Meets Innovation

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Beyond a PHA: Using QRA, ETA, and FTA to Evaluate Complex Hazards

Where Chemical Engineering
Meets Innovation

Presenter

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AcuTech Group, Inc.
Senior Engineer

15+ years of experience in process safety consulting and risk engineering

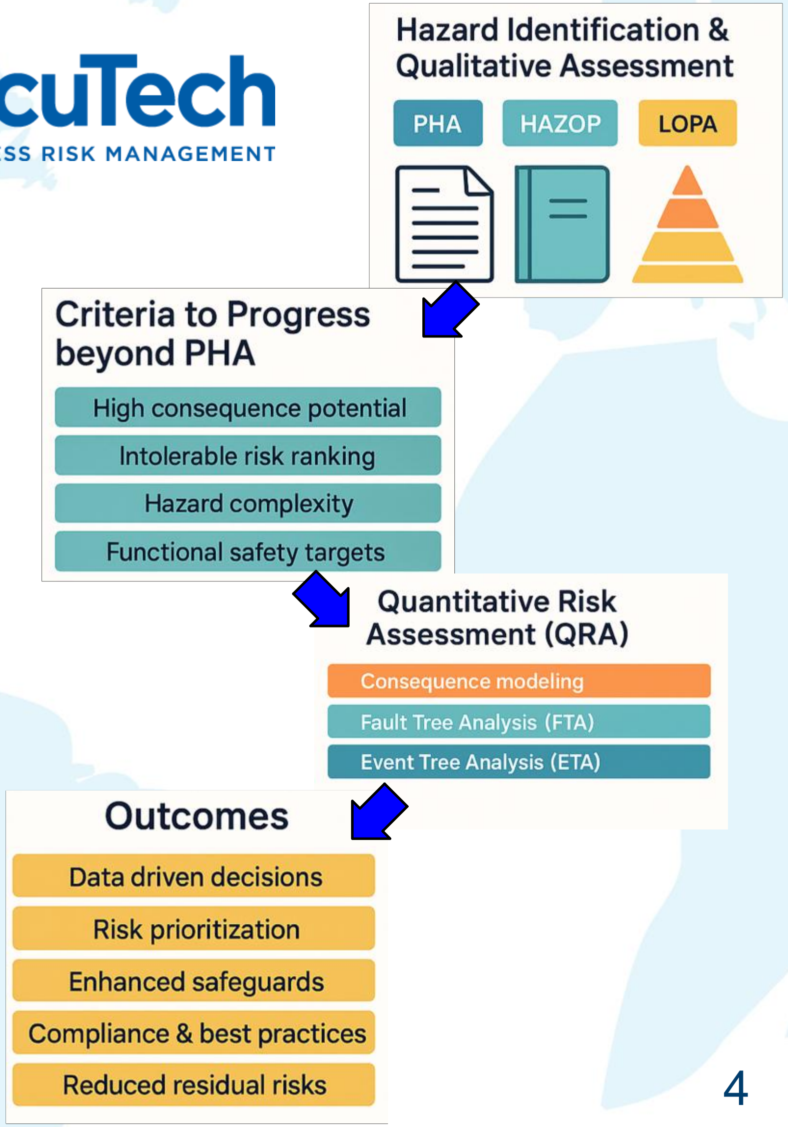
Areas of Expertise

- Quantitative Risk Assessment & Facility Siting
- Risk model development
- PHA/HAZOP/HAZID/LOPA Facilitator
- OSHA PSM/ EPA RMP Program Development

Overview

AcuTech
PROCESS RISK MANAGEMENT

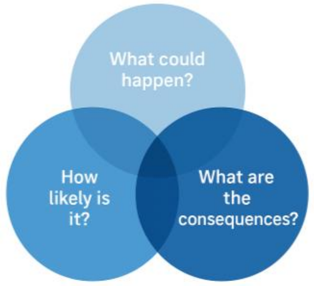
- Limitations of traditional Process Hazard Analysis (PHA) for complex hazards and scenarios.
- Quantitative Risk Assessment (QRA), Event Tree Analysis (ETA), and Fault Tree Analysis (FTA) as advanced risk assessment tools.
- Decision framework and criteria for determining when QRA is warranted
- Case studies based on AcuTech's global consulting experience where the risk assessment progressed from PHA to quantitative analysis



Foundational Safety: PHA and HAZOP

PHA and HAZOP

- Fundamental for process safety management & regulatory compliance.
- Structured, team-based approach for qualitative identification of common industrial hazards.
- Effective for a wide range of hazards, forming the basis of many safety protocols.
- Methods are regularly revalidated to ensure current and effective hazard information.



Limitations of PHA/HAZOP

- Traditional qualitative methods present inherent limitations for assessing complex hazards and often screen out rare events as “not credible.”
- Rare and high-consequence events, intricate process interactions, human factors, cascading failures, and extreme external events may not be adequately addressed
- Cognitive biases (e.g., confirmation, availability, anchoring, groupthink) can influence team-based PHA studies.

High-consequence

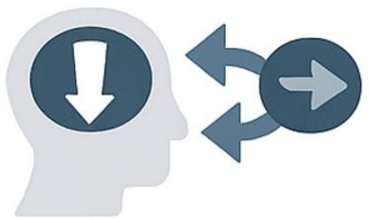
Cascading Failures

Human Factors Uncertainty

Intricate Processes and Interactions

New & Emerging Technologies

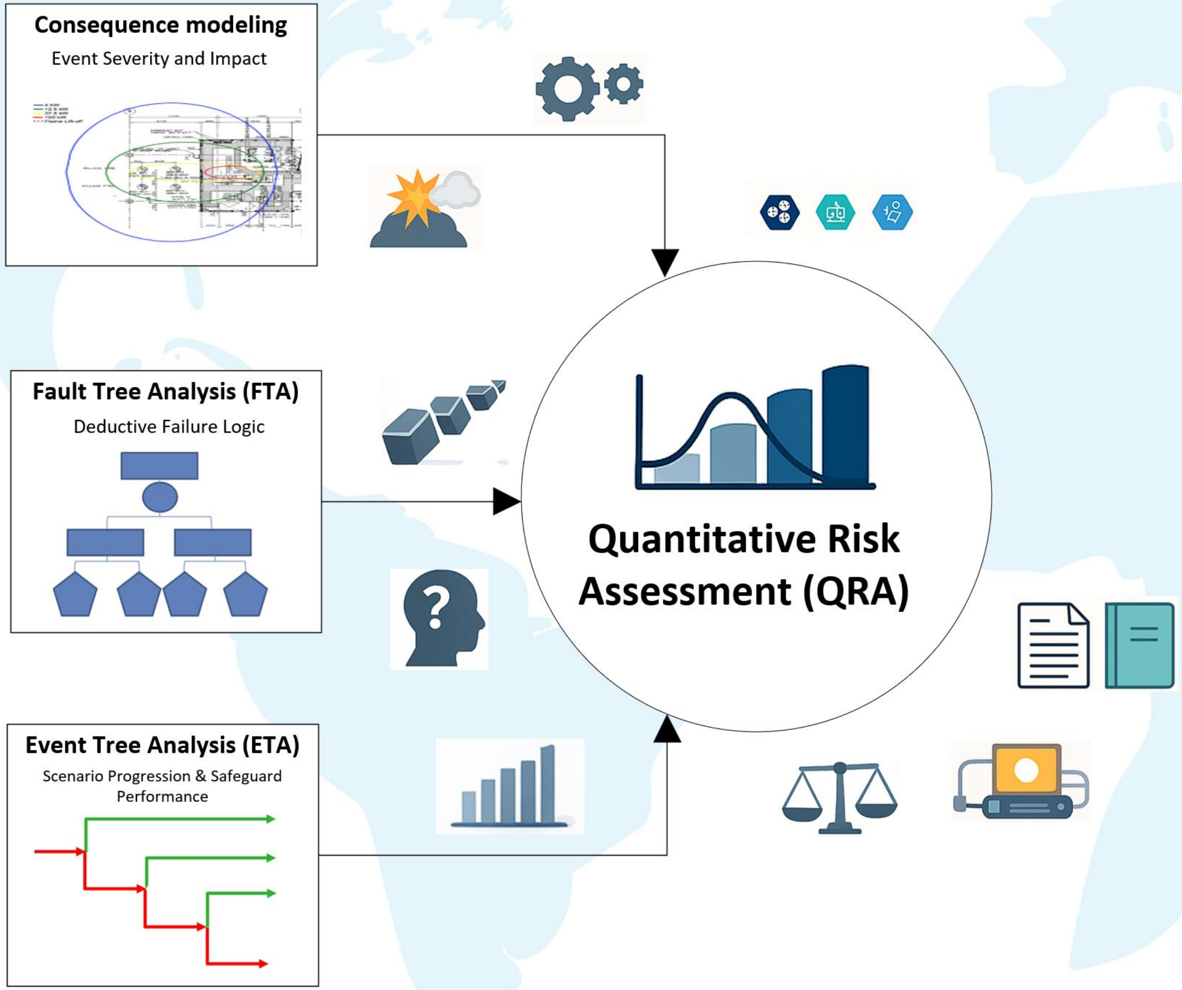
Cognitive Biases



Advanced Quantitative Approaches

QRA, FTA, and ETA

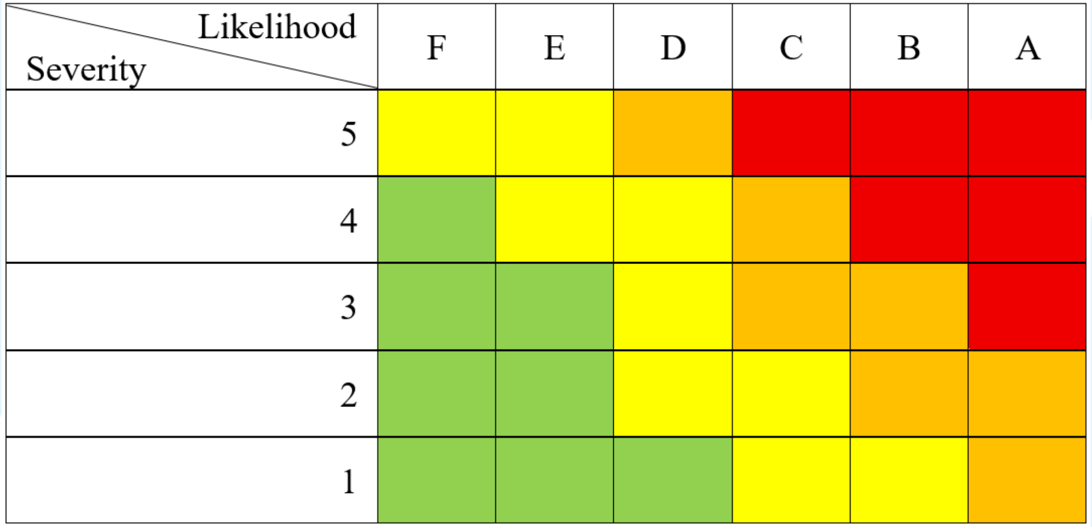
- QRA offers a comprehensive, quantitative approach to address complex hazards.
- Consequence modeling to quantify severity and impacts
- FTA applies deductive logic to identify combinations of basic failures leading to a top event.
- ETA models post-initiating-event progressions and safeguard performance.
- These methods mitigate subjective bias through structured probability logic and documented assumptions.



When to Progress to Quantitative Analysis

Decision to progress to a QRA is guided by risk-tolerability criteria and several supporting factors. Situations in which a QRA should be considered include:

- When potential consequences are severe, including the possibility of multiple fatalities, significant environmental harm, or major financial impacts.
- When a more detailed understanding of risk is required based on qualitative risk ranking and criteria, such as evaluating the effectiveness of safeguards.
- When system complexity exceeds the capability of qualitative tools, including intricate designs, multiple interdependencies, or operational scenarios that require quantitative assessment.



Category	Frequency/ year
A	>1
B	0.1 - 1
C	0.01 - 0.1
D	1E-4 - 1E-2
E	1E-6 - 1E-4
F	1E-7 - 1E-6

Category	Severity
5	Extensive; >5 on site fatalities; >$50M
4	Major; 1-5 on site fatalities; loss ~$10M
3	Significant; major injuries; loss ~$1M
2	Measurable; minor injuries; loss ~$100K
1	Minor; first-aid injuries; loss ~5K

Guidelines for Criteria and Decision Points

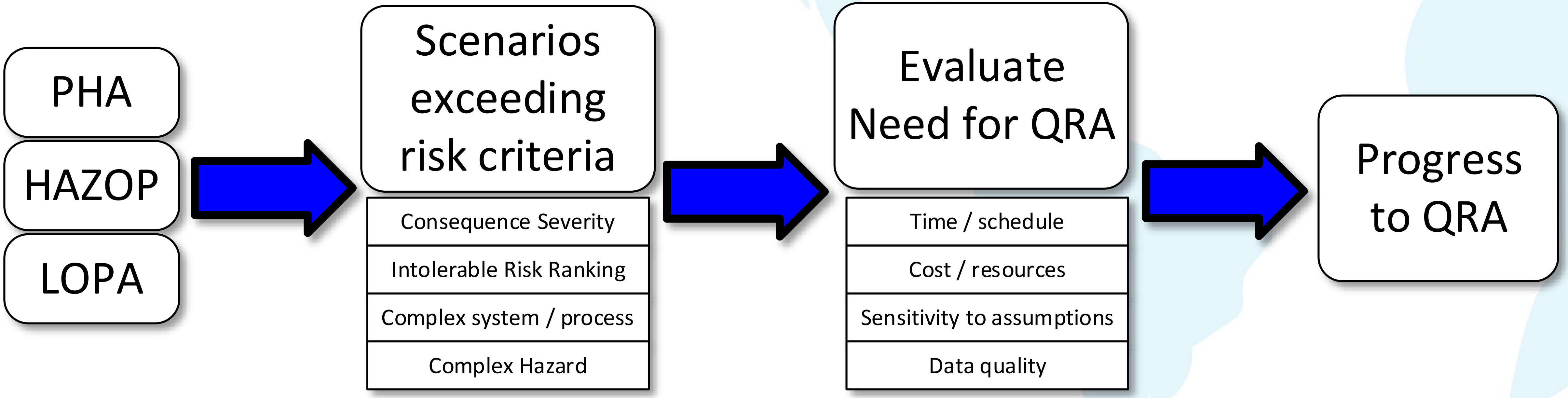
Risk tolerability criteria are central to effective process safety management and can be used to determine when QRA is warranted.

- High-consequence potential or public exposure with credible multiple-fatality impacts considering safeguards.
- Risk matrix placement is intolerable or near the tolerability boundary.
- Functional safety or integrity targets must be set or justified.
- Hazard complexity, such as escalation, intricate dependencies, time-dependent exposure, and sparse failure data as with novel technologies, not fully addressed by qualitative assessment.

Severity \ Likelihood	F	E	D	C	B	A
5						
4						
3						
2						
1						

QRA Limitations and Caveats

Organizations must evaluate whether QRA will deliver value relative to opportunity costs, resource demands, and data quality before progressing beyond PHA.



QRA Limitations and Caveats

Time and Schedule Impacts

- **Extended Duration Requirements:** QRA spans months rather than days or weeks, like PHA, and involves multiple analysis phases requiring specialized staff and coordination
- **Project Timeline Alignment:** Late initiation may miss decision windows or delay regulatory approvals
- **Critical Success Factor:** Plan QRA initiation sufficiently early in project lifecycle to meaningfully inform design decisions without creating schedule bottlenecks

Cost and Resource Requirements

- **Direct Costs**: Specialized personnel, licensed modeling software, and dedicated engineering support
- **Opportunity Costs:** Internal staff diverted from other process safety activities; extended engagement required from site personnel
- **Impact:** May reduce capacity for concurrent safety initiatives, especially in resource-limited organizations

QRA Limitations and Caveats

Data Availability and Limitations

- **Generic Failure Rate Data:** Industry failure rate data may not reflect site-specific conditions and results may not be representative without careful adjustment and justification
- **Site-Specific Data Challenges:** Incomplete incident data leads to uncertainty, which may limit accuracy improvements over generic data
- **Human Reliability Analysis (HRA) Uncertainty:** Analyst judgment required for evaluation of performance shaping factors and dependencies, leading to potentially large variability in estimated human error contributions
- **Risk of False Precision:** Precise numerical outputs may exceed confidence supported by input data quality, requiring transparent communication of uncertainty and confidence bounds

Model Complexity and Transparency

- **Technical Complexity Barriers**: Fault trees, event trees, and consequence models are technically complex and non-intuitive, and can hinder understanding and acceptance by non-specialist stakeholders
- **Stakeholder Comprehension Challenges:** Risk estimates are sensitive to independence, ignition probabilities, and common-cause assumptions, with small changes in assumptions capable of producing order-of-magnitude differences in results
- **Mitigation Strategies:** Clear, comprehensive documentation, simplified representations of complex logic, focused sensitivity analyses. identification of key risk drivers increase overall resource requirements but are essential for stakeholder alignment and trust

QRA Limitations and Caveats

Sensitivity to Scope and Assumptions

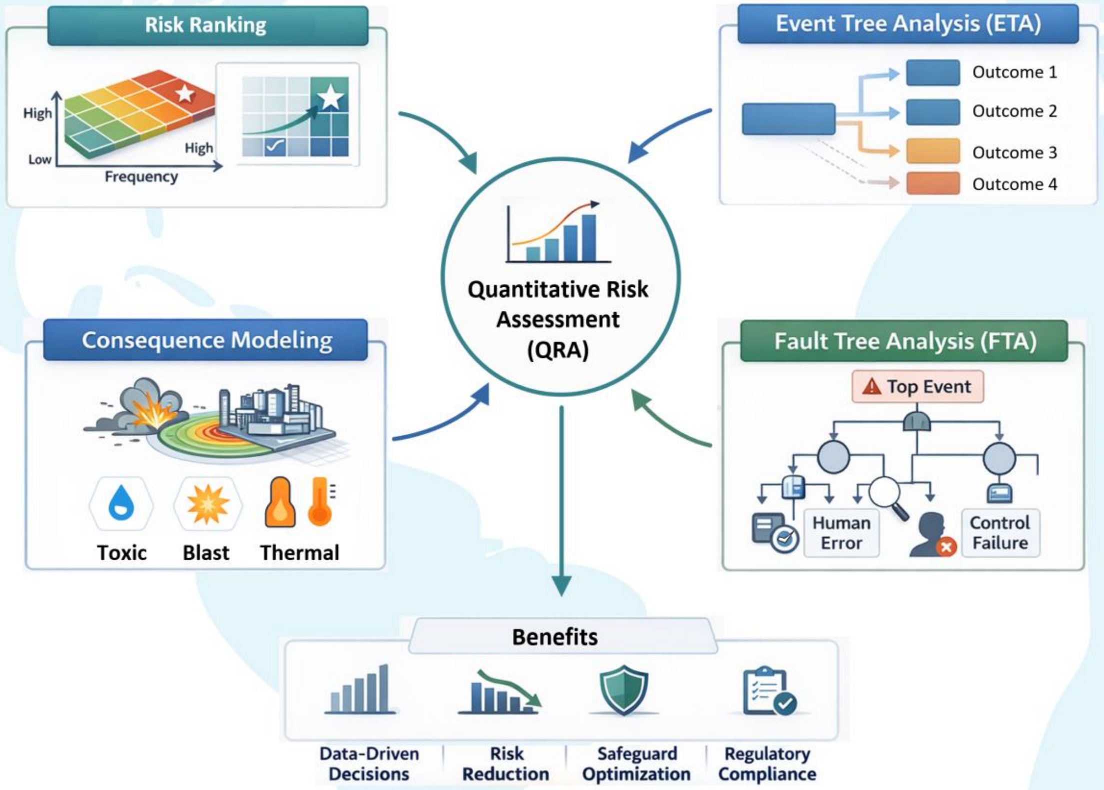
- **Assumption Sensitivity:** Risk estimates are sensitive to assumptions, where small changes can produce order-of-magnitude differences in results
- **Analytical Variability:** Different practitioners may produce materially different results using defensible methods, emphasizing the need for sensitivity analysis and assumption transparency
- **Requirements for Robust Analysis**: Clear scope definition, sensitivity analysis, and documentation of assumptions will allow decision-makers to understand outcome ranges, not just point estimates

Integrated Framework

- **When QRA Delivers Value**: QRA excels at evaluating high-consequence hazard and complex interactions when qualitative methods cannot resolve risk questions
- **Keys to Success**: Early integration, sufficient resources, transparent communication, and focused scope ensures QRA supports meaningful, defensible risk management decisions

Integrated PHA to QRA Workflow

- Begin with qualitative evaluation using PHA, HAZOP, or LOPA and determine whether to progress to QRA
- Define QRA structure and utilize consequence modeling, fault trees analysis, and event tree analysis, where appropriate.
- Calibrate with human reliability, equipment failures, and safeguard performance specific to scope.
- Quantify risk by integrating calibrated frequencies with consequence modeling.
- Risk assessment outputs provide data for informed decision-making regarding risk reduction, safeguard optimization, and regulatory compliance.



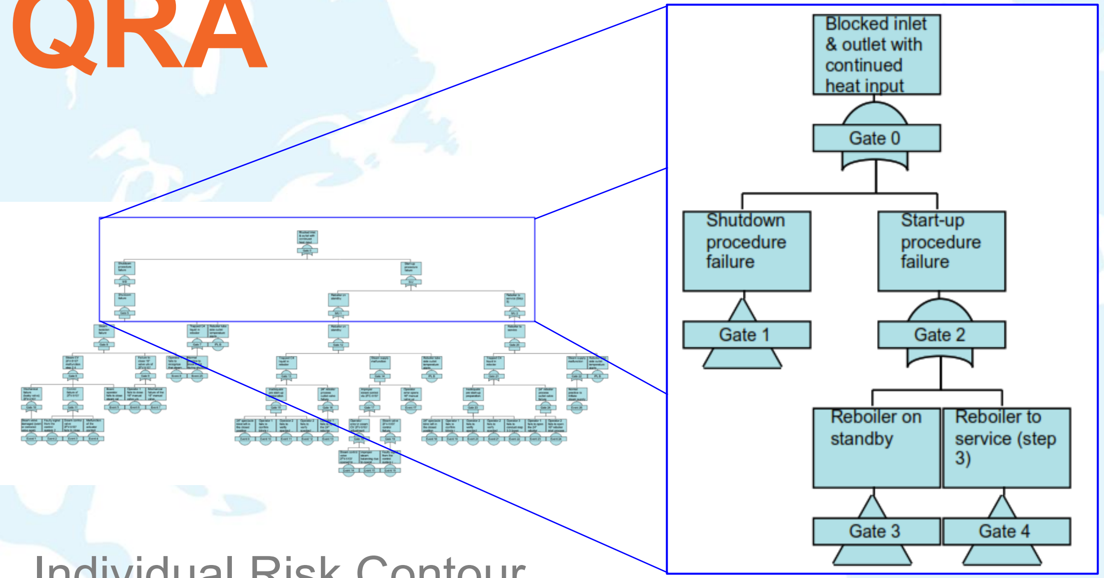
Case Study 1: Reboiler QRA

Refining Risk with FTA

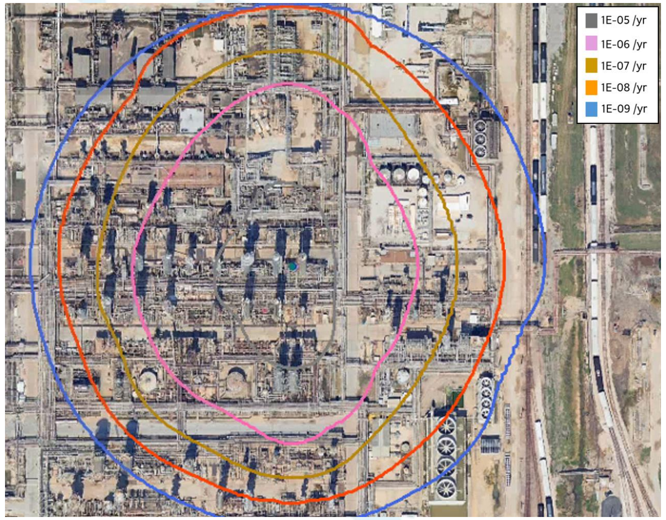
- HAZOP identified a high-risk scenario: "Blocked inlet & outlet with continued heat input," potentially leading to loss of containment.
- FTA was used to quantify the frequency of this top event, breaking it down into human errors and equipment failures.
- Human error probabilities estimated using SPAR-H method; equipment failures based on dangerous undetected failure rates.
- Integrated with consequence modeling to determine risk (LSIR, IRPA) to personnel, leading to actionable reduction strategies.

Case Study 1: Reboiler QRA
Refining Risk with FTA

- FTA used failure probabilities and Boolean logic to estimate frequency of Top Event: Blocked inlet/outlet with continued heat input
- Consequence modeling & ETA used to determine fire & explosion outcomes and severities
- Individual risk to personnel quantified
- Outcome: risk ranking revised based on QRA results and recommendations developed to implement safeguards and improve operating procedures consistent with risk ranking.

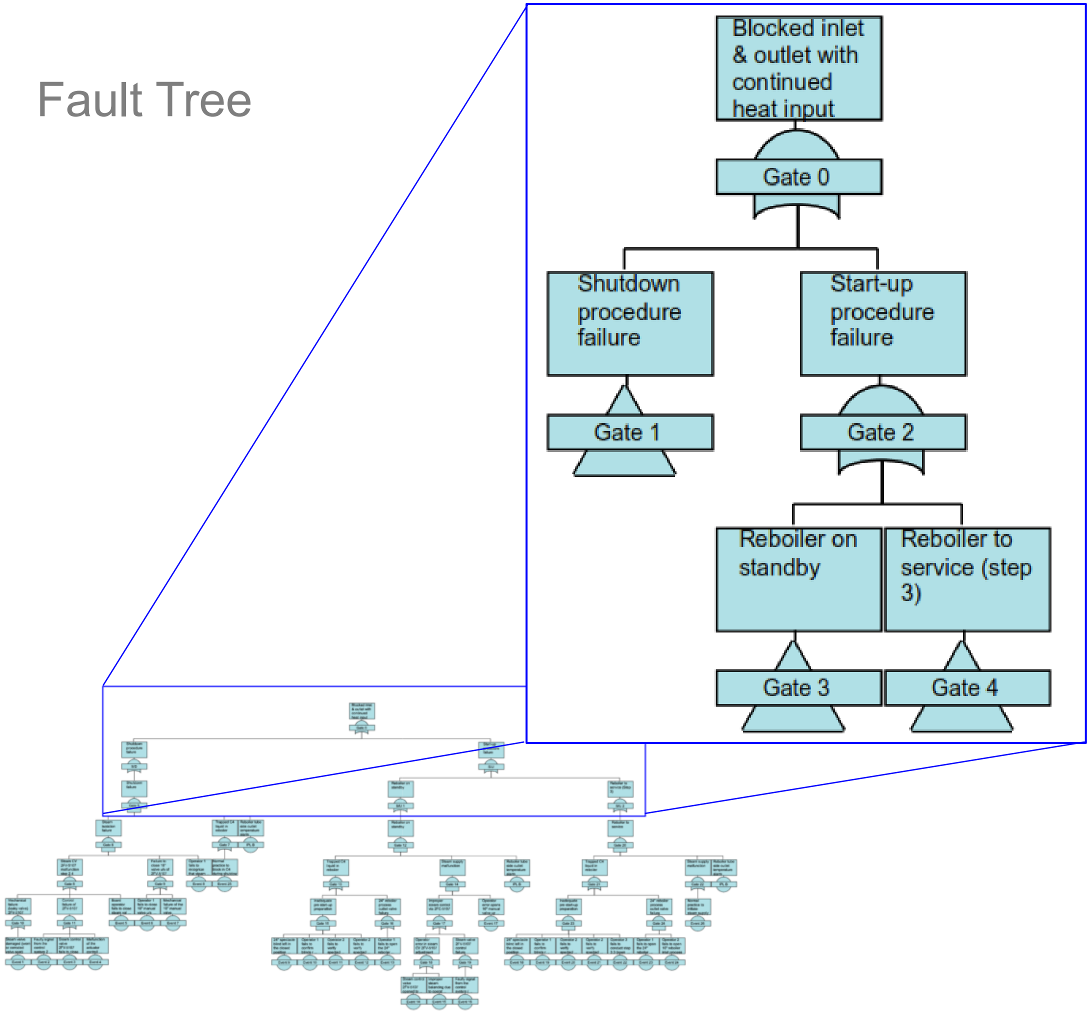


Individual Risk Contour

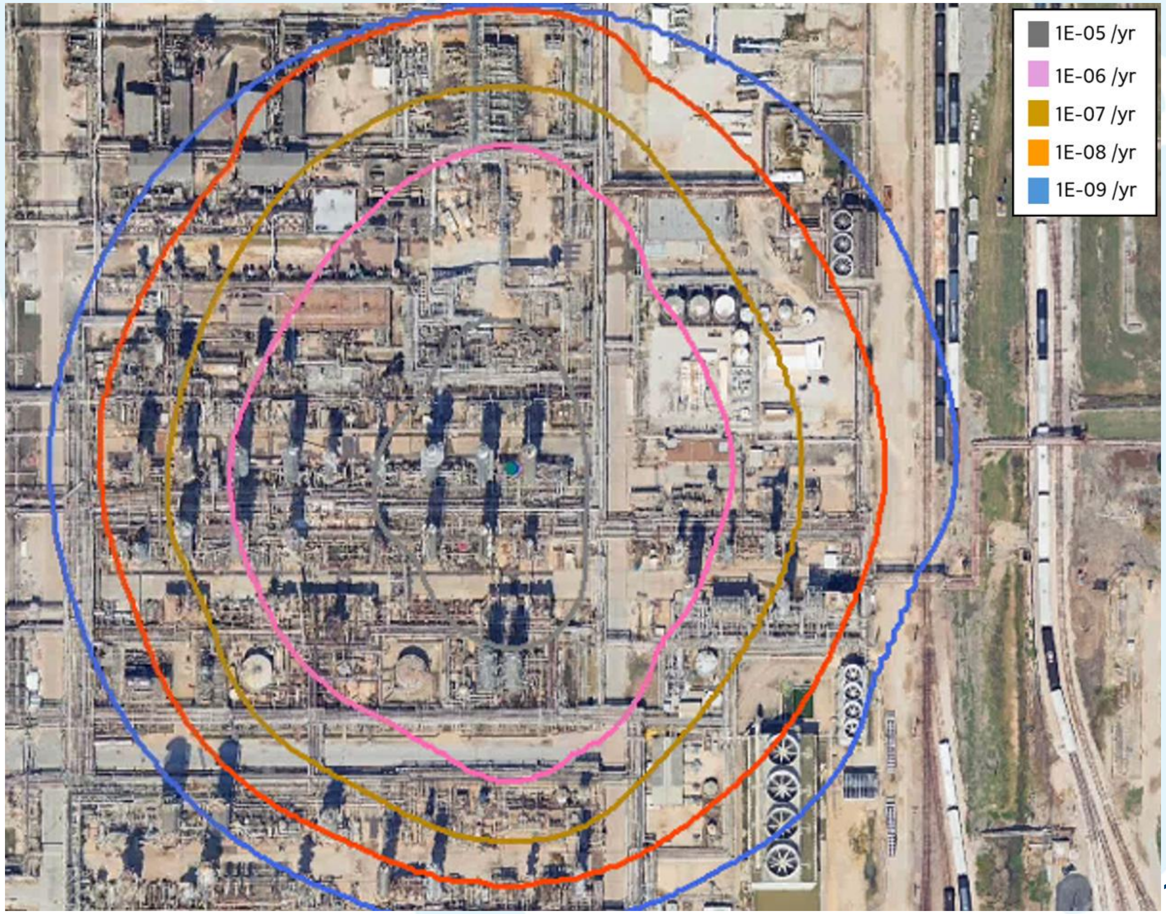


Case Study 1: Reboiler QRA

Fault Tree



Individual Risk Contour

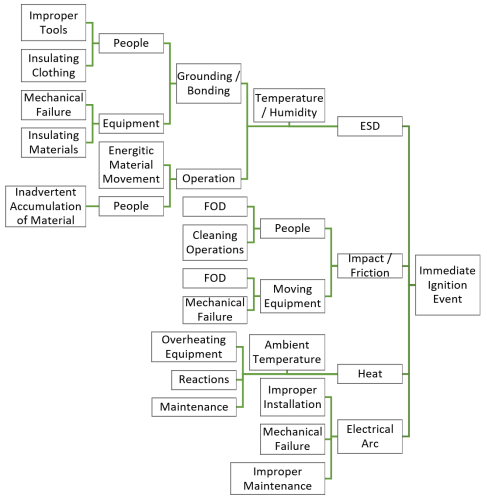


Case Study 2: Energetic Material QRA

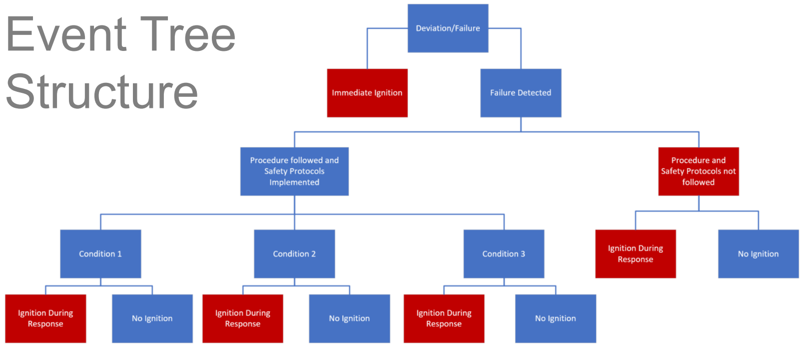
Prioritizing Risk with ETA/FTA

- Facility manufacturing energetic materials sought QRA for processes with high ignition/injury risk.
- HAZOP, LOPA, and FMEA identified scenarios, IPLs, and potential impact severities.
- ETA modeled scenario progressions and conditional ignition probabilities; FTA structured ignition mechanisms.
- Provided insights for high-severity risks and ignition mechanisms, and guided targeted mitigations to address asset integrity, electrostatic discharge, and control of foreign object debris.

Fault Tree Structure

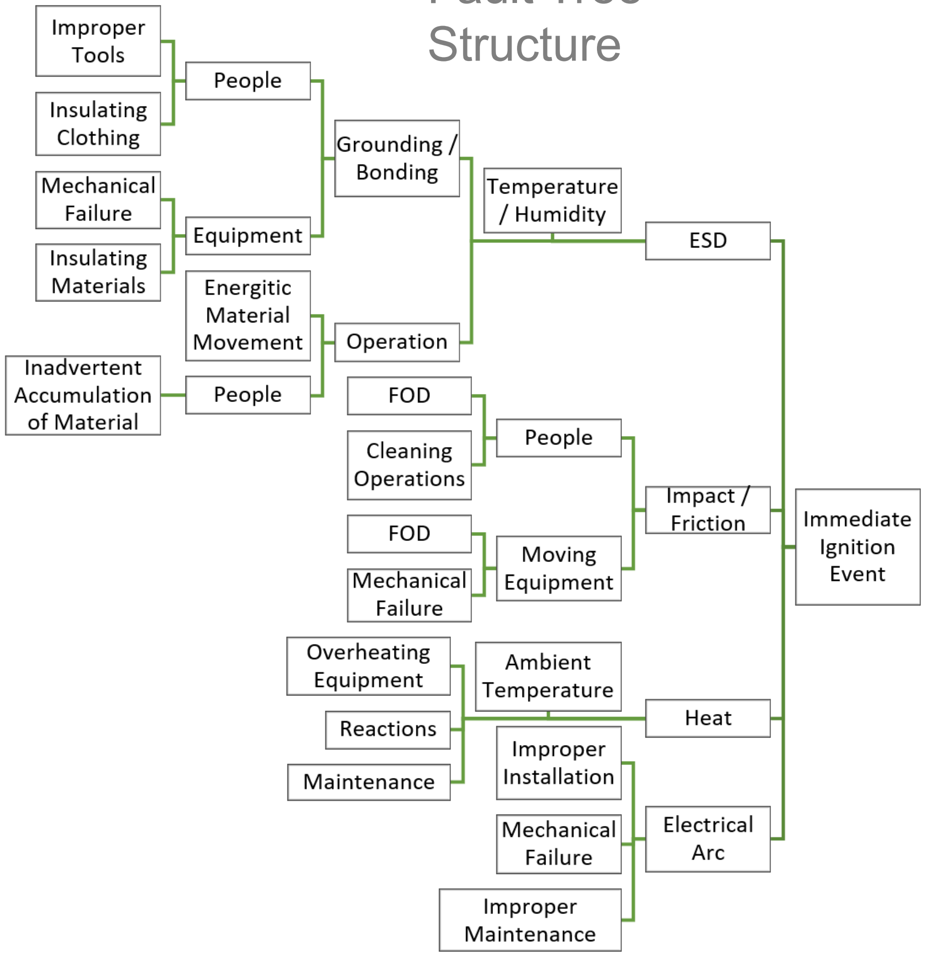


Event Tree Structure



Case Study 2: Energetic Material QRA

Fault Tree Structure



Event Tree Structure

Case Study 2: Energetic Material QRA

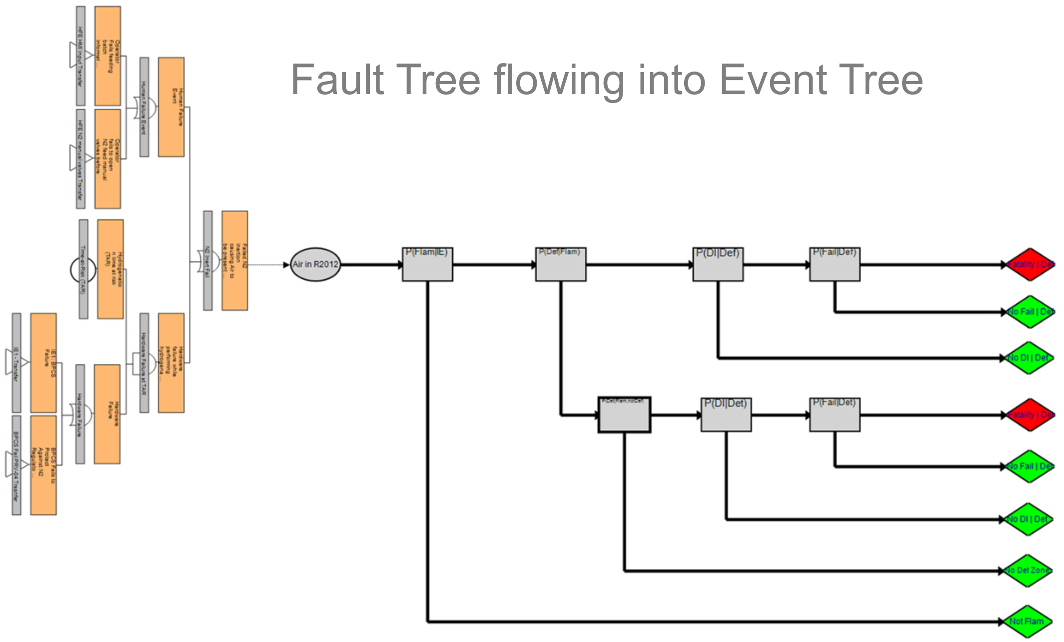
Former site of an Accurate Energetic Systems facility (not assessed by AcuTech) following explosion that occurred on October 10, 2025

Case Study 3: Hydrogenation Reactor QRA

Quantifying Inerting Failure

Likelihood → Severity ↓	H	G	F	E	D	C	B	A
5	5H	5G	5F	5E	5D	5C	5B	5A
4	4H	4G	4F	4E	4D	4C	4B	4A
3	3H	3G	3F	3E	3D	3C	3B	3A
2	2H	2G	2F	2E	2D	2C	2B	2A
1	1H	1G	1F	1E	1D	1C	1B	1A

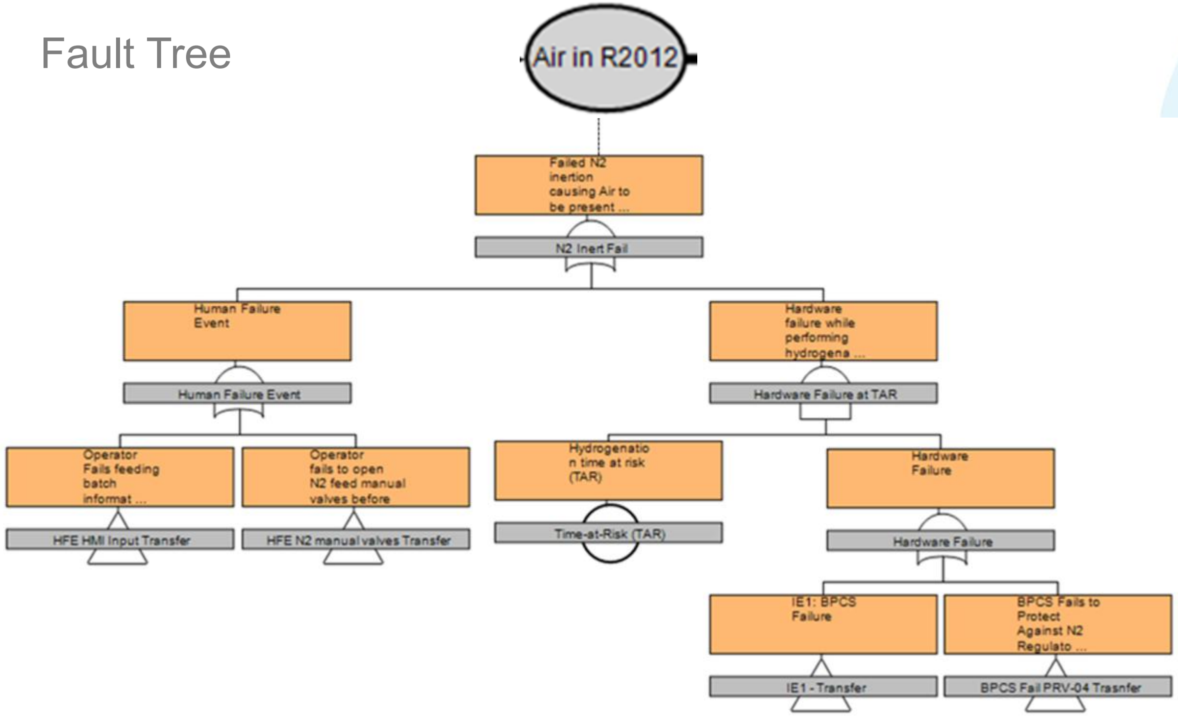
- HAZOP/LOPA identified critical scenario: inadequate nitrogen inerting leading to internal explosion.
- FTA estimated the likelihood of nitrogen inertion, the Top Event, and broke it down to basic events associated with human factors and hardware/software failures.
- ETA captured post-top-event progression, including deflagration-to-detonation potential.
- Quantified site-specific fatality frequency, leading to the conclusion that a SIL 2 safety instrumented function was required.



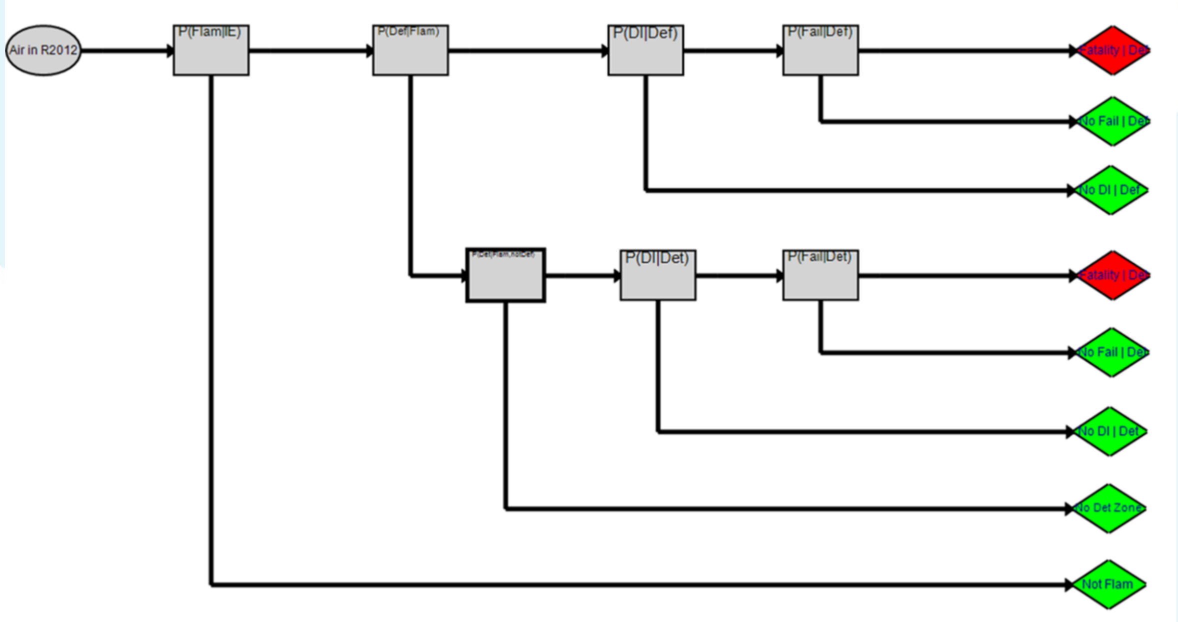
Fault Tree flowing into Event Tree

Case Study 3: Hydrogenation Reactor QRA

Fault Tree



Event Tree



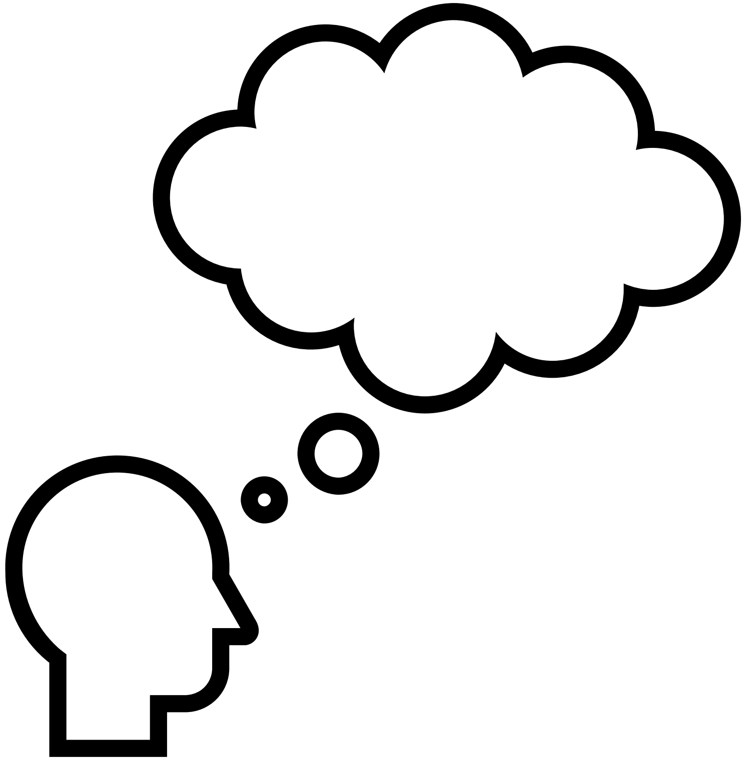
Benefits of QRA paired with PHA

- Enhanced quantification of complex risks to better understand interdependencies and uncertainties.
- Improved data to support decisions for prioritizing risk reduction and safety investments.
- More objective basis for allocating resources effectively where they will have the greatest impact.
- Effective for evaluating rare, high-consequence events that qualitative methods may underestimate.

Shaping Industry Best Practices

- The paper establishes guidance for advancing to quantitative techniques when qualitative methods reach their limits.
- Promotes a comprehensive approach to process safety and risk management.
- Case studies provide practical insights and models for industry application.
- Emphasis on data-driven decision-making and quantification of complex hazards contributes to evolving RAGAGEP.

Questions & Discussion



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