Risk Assessment & Mitigations Based on Dispersion for a Hazardous Pipeline with Example of a CO_2 Pipeline

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Challenges with Gas Pipelines

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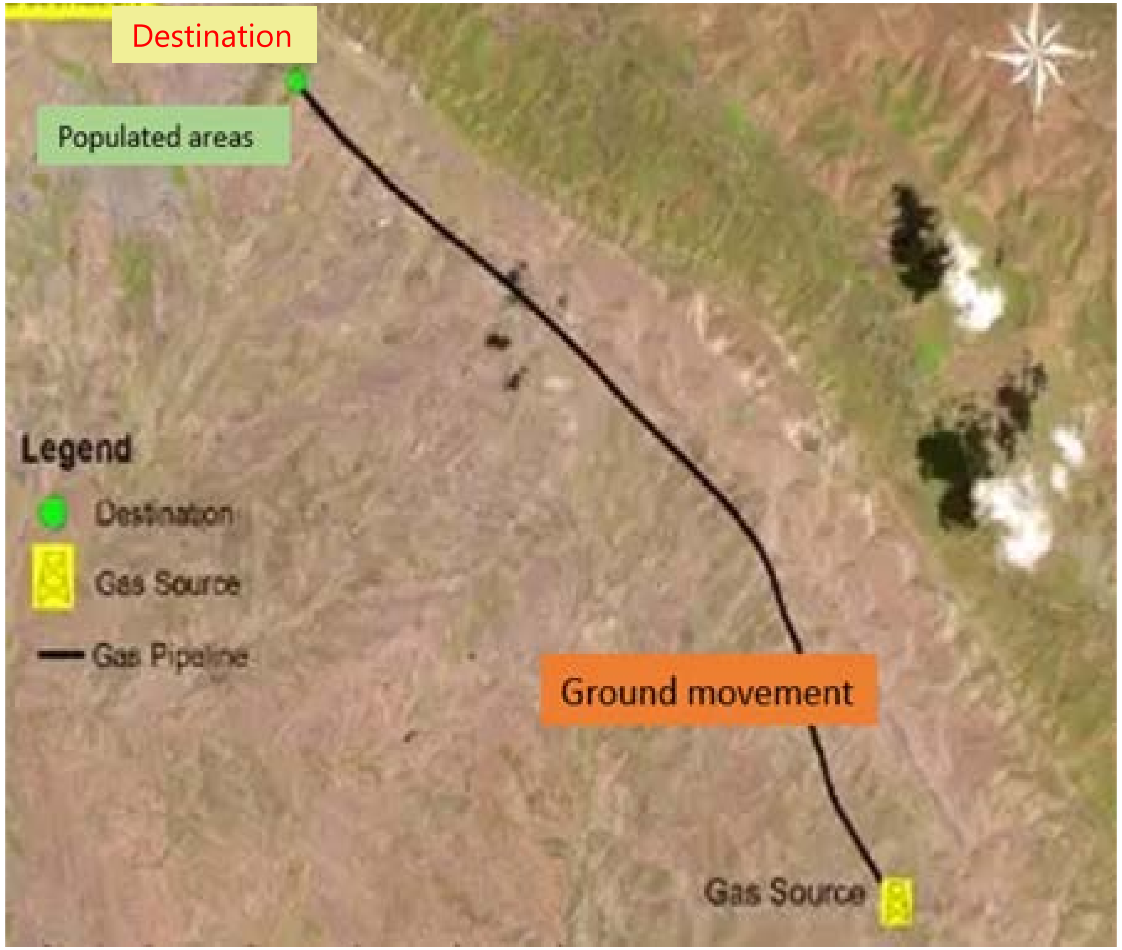
- Long routes and large dispersion radius of gas around pipelines
  - Dangerous if hazardous gases, passing through highly populated areas
- Properties of the gas being transported and their effects
  - Flammable (e.g. natural gas), toxic (e.g. H_2S), asphyxiating (e.g. CO_2 which is heavier than air and displaces O_2)
- Impacts on human safety is becoming a part of impact assessment procedures for major projects and therefore risk assessment consequently becoming an integral part
- When building a pipeline, community consultations and stakeholder engagements are critical
- Routing is important in eliminating the risk;
  - Routes should ideally be selected to avoid populated, geotechnical, and environmentally sensitive areas, if possible
  - A totally risk-free route may not be possible or practicable
  - Is re-routing to avoid high population and sensitive areas within the dispersion radius possible or feasible?



Quantitative Risk Analysis (QRA)

An overview

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- A Quantitative Risk Assessment (QRA) is a tool to quantify the risk generated by an activity, industrial site or area compromised by industrial sites (example pipelines and installations)
  - It can focus on "internal" on-site or "external" off-site risks
  - The latter includes the risk to which the surrounding population is exposed
- After performing a QRA, risk values can be evaluated to determine whether the risk can be considered acceptable
  - The risk acceptance criterion is usually classified as "As Low As Reasonably Practicable" (ALARP)
- Individual Risk (IR) and Societal Risk (SR) are very commonly used to quantify risk
- QRA followed by Geographical Information System (GIS) mapping of hazard zones and setbacks
- QRA is included in regulatory requirements, municipal plans, public consultation processes

Questions for Risk Assessment

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- Risk Assessments are an integral part of project approval, and the following are some important questions that we need to ask to carry out this assessment:
  - What is the dispersion radius of the gas and what are the concentrations at different distances?
  - What will be the concentration of leaked gas at vulnerable establishments?
    - Is it enough to cause fatalities?
  - Will the concentration at sensitive locations stay below Immediately Dangerous to Life or Health (IDLH)?
  - How long will the gas take to disperse to safe levels?
    - 5 minutes? 30 minutes? more?
  - When applying the risk-based land use planning contours in GIS, such as the Major Industrial Accidents Council of Canada (MIACC) guidelines, how should existing establishments be represented?
    - What are the establishments that do not conform to MIACC?
    - Do all existing establishments comply to the MIACC guidelines?
    - Are the MIACC guidelines enough consideration?
  - In such cases, mitigations will need to be in place, to reach ALARP level of risk
    - How does the pipeline fare with corporate risk matrix?
  - What urban developments could happen in future around the pipeline?

Quantitative Risk Analysis (QRA)

Breakdown of QRA calculation results

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QRA calculation results are categorized into various formats, including but not limited to the definition of potential accident scenarios, such as:

- **Initiating events**
  - External interference
  - Corrosion
  - Construction defect / material failure
  - Hot tap made by error
  - Ground movement
  - Other / unknown
- **Dispersion modes**
  - Horizontal, vertical, or horizontal with obstruction
- **Types of leak**
  - Pinhole / crack: the effective diameter of the hole is smaller than or equal to 2 cm
  - Hole: the effective diameter of the hole is larger than 2 cm and smaller than the diameter of the pipe
  - Rupture: the effective diameter of the hole is larger than the pipeline diameter
- **Model-Buried / above ground**
  - For buried CO_2 pipeline crater model as used by Safeti™ by DNV
  - Phast or more detailed CFD (Computation Fluid Dynamics) model

Quantitative Risk Analysis (QRA)

Assessment procedure

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- Evaluate the consequences of the event
  - Dispersion radius, concentrations and durations at sensitive areas
- Estimate potential accident frequencies
  - Leverage statistical data sources—e.g., European Gas Pipeline Incident Data Group (EGIG)
- Estimate the impact of the events
  - Possible fatalities, health concerns, emergency action plan implementation, and evacuations
- Estimate the risk
  - IR / LSIR (Location-Specific Individual Risk)—by means of iso-risk contours
  - Consequence—by means of iso-risk contours
  - SR (Societal Risk)—by means of a Farmer's diagram (F-N curve) and SR maps
- Evaluate the risk
  - Any Potential Loss of Life (PLL), perform risk ranking
- Identify and prioritize the risk mitigation or risk reducing measures

Dispersion Cloud Footprint

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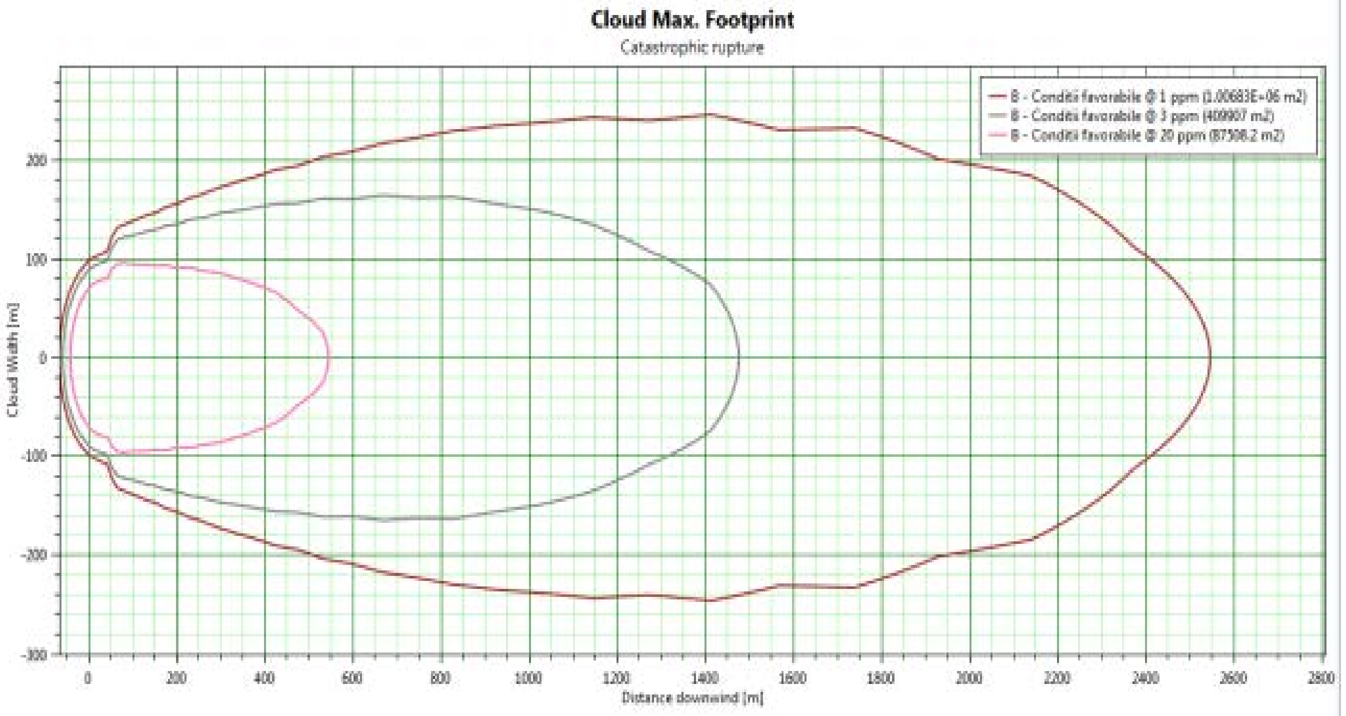
- In the case of CO_2, we could have clouds showing higher ppm's: 40000 ppm , 70000 ppm, 100000 ppm, 150000 ppm and 220000 ppm (picture below of CO_2 cloud)

Example of dispersion graph



Location-Specific Individual Risk (LSIR)

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- Location-Specific Individual Risk (LSIR) is expressed as a likelihood per year that a person without protection at that location is killed due to an event leading to the release of hazardous gas, (e.g., CO_2)
  - Inputs—terrain, wind direction, being protected or not, being able to escape
  - The summation of all the failure frequencies
  - Probability of an effect (e.g., probability that a mitigating measure fails, probability of ignition, probability of explosion, etc.)
  - Statistical data used to calculate individual risks—EGIG
  - The EGIG database offers an overview of the failure frequencies in relation to one pipeline parameter (e.g., diameter, pressure, wall thickness)

Pipeline Incident Rates

2013—2022, data from the 12th EGIG report

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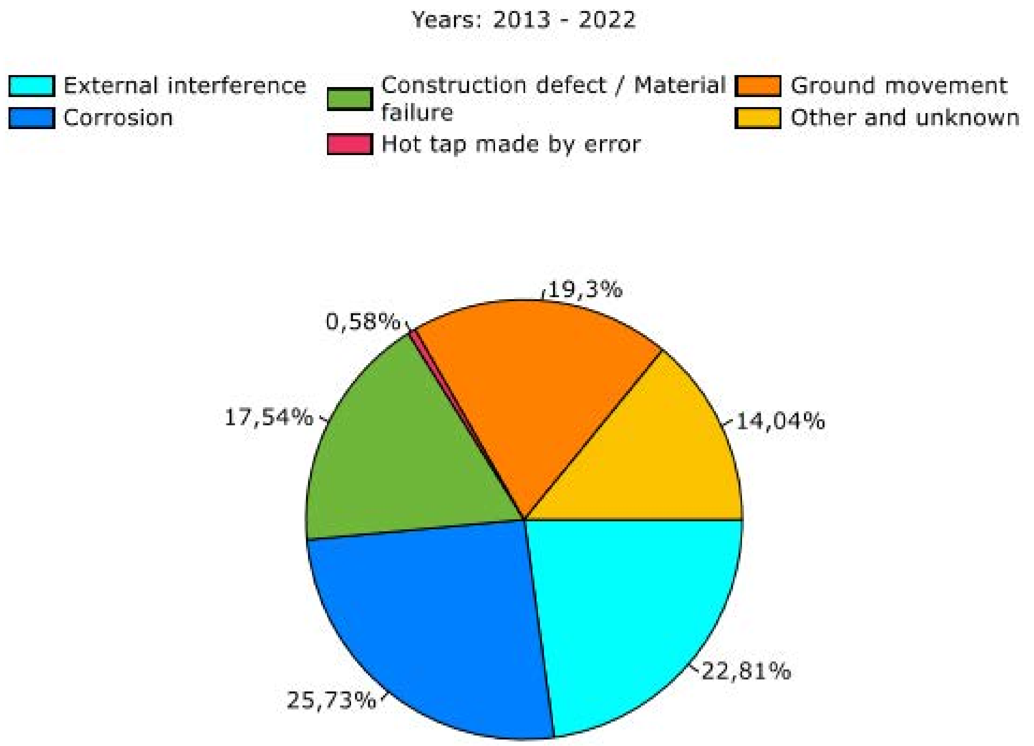
- Pipeline incidents reported between 2013—2022
  - Corrosion: **25.7%,**
  - External interference: **22.8%**
  - Ground movement: **19.3%**
  - Construction defects: **17.5%**
- Corrosion and external interference account for nearly half of all incidents



Primary Failure Frequencies per Leak Size

1970—2022, data from the 12th EGIG report

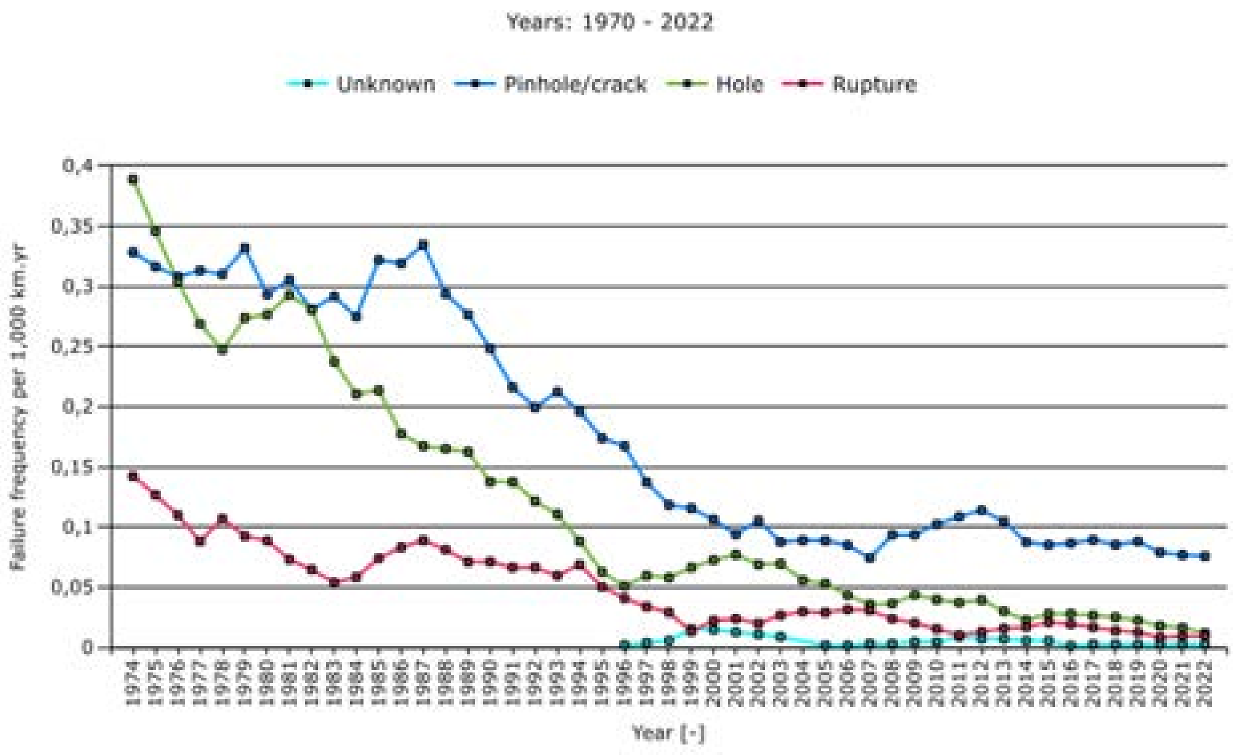


Figure 16: Primary failure frequency (five year moving average) per leak size

Number of Incidents per Cause

2013—2022, data from the 12th EGIG report

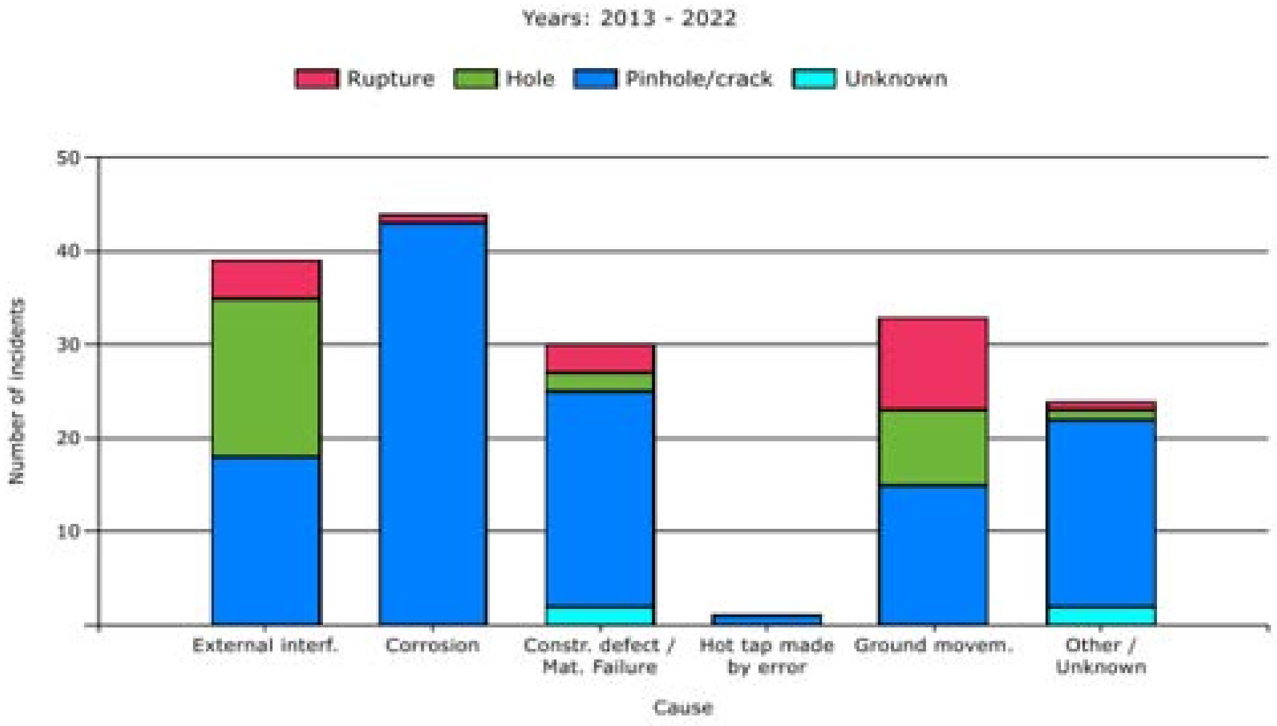


Figure 22: Number of incidents per cause in the period of 2013 to 2022

Societal Risk (SR)

- Societal Risk (SR) is the cumulative probability per year that at least 10, 100, or 1000 people will be killed as a direct result of their presence within the impact area of an establishment and the occurrence of an accident—estimation of casualties per event
  - E.g., per phenomenon, per each possible weather class, per specific wind direction, etc.
- SR can be presented as an F-N curve or SR maps

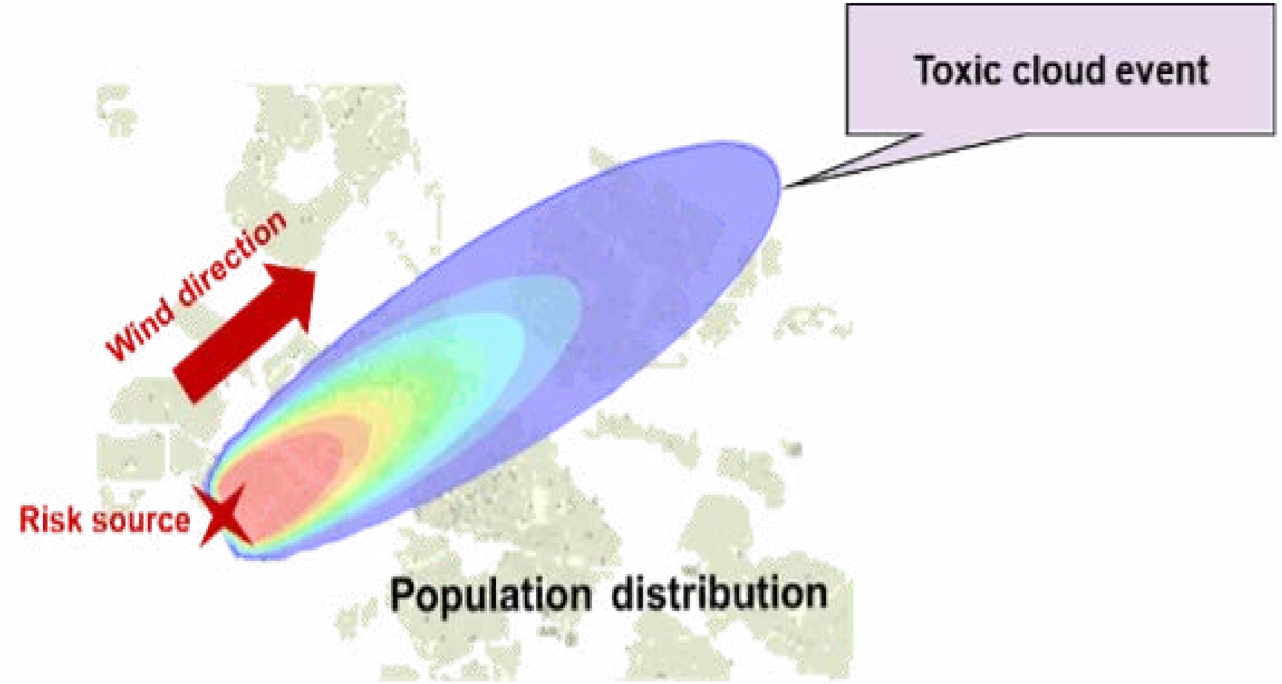


Figure shows toxic dispersion cloud at specific weather conditions affecting certain population

Input—Pasquill Stability Class

Weather conditions

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- Pasquill Stability Classes: e.g., D5 for typical conditions and F2 for worst-case scenarios to determine dispersion potential
- Wind speed: a wind speed of around 2-10 m/s is commonly used for dispersion modeling, with higher windspeeds leading to less dispersion
- In general, the more stable the class the less dispersion, and thus the higher the concentration within the plume
  - Which is why class F is typically used for a ground level, neutrally buoyant, cloud
- Agreement on either taking a weighted average or worst case for CO_2 or such hazardous gases
  - Check for largest radius among different weather categories

Table 2. Pasquill-Gifford stability classes

Class	Definition
A	Extremely unstable
B	Moderately unstable
C	Slightly unstable
D	Neutral
E	Slightly stable
F	Moderately stable

Risk-Based Impact Assessment & Land Use Planning

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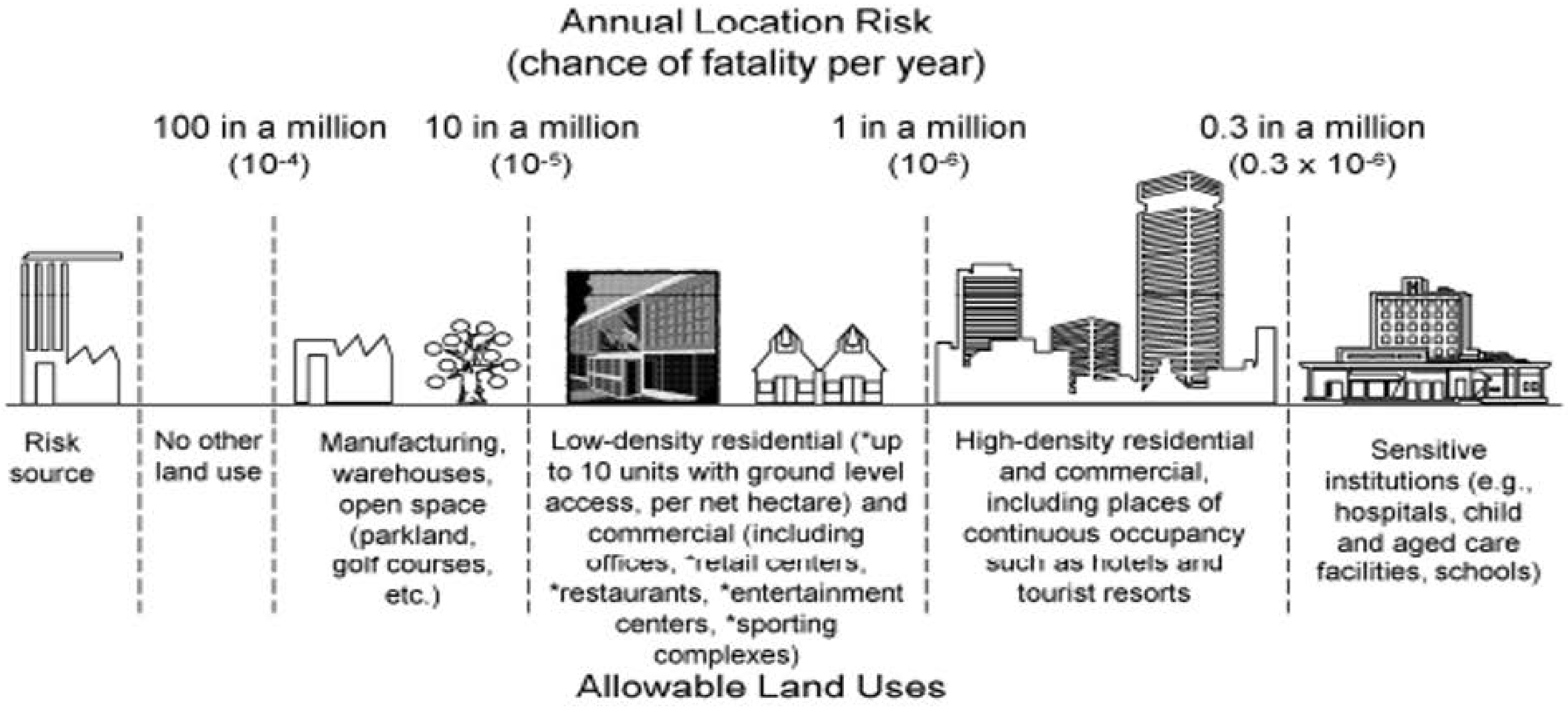
- Major Industrial Accidents Council of Canada (MIACC) provides recommendations for land use based on risk in zones identified based on dispersion modelling results
  - Determines suitability for industrial, commercial, or residential use
- Risk acceptability criteria include:
  - Number of fatalities per million population
  - Specified levels of Individual Risk
  - No acceptable levels of Societal Risk are proposed
  - Societal Risk evaluation can still be useful to establish intervention priorities
- The levels are recommended for use in respect to hazardous substances risk from all sources
  - The acceptability levels are equally applicable
- Guidelines rather than standards
- Similar systems are in place in other countries (e.g., UK)

MIACC

The acceptable levels of public location risk for land use around hazardous facilities (current)

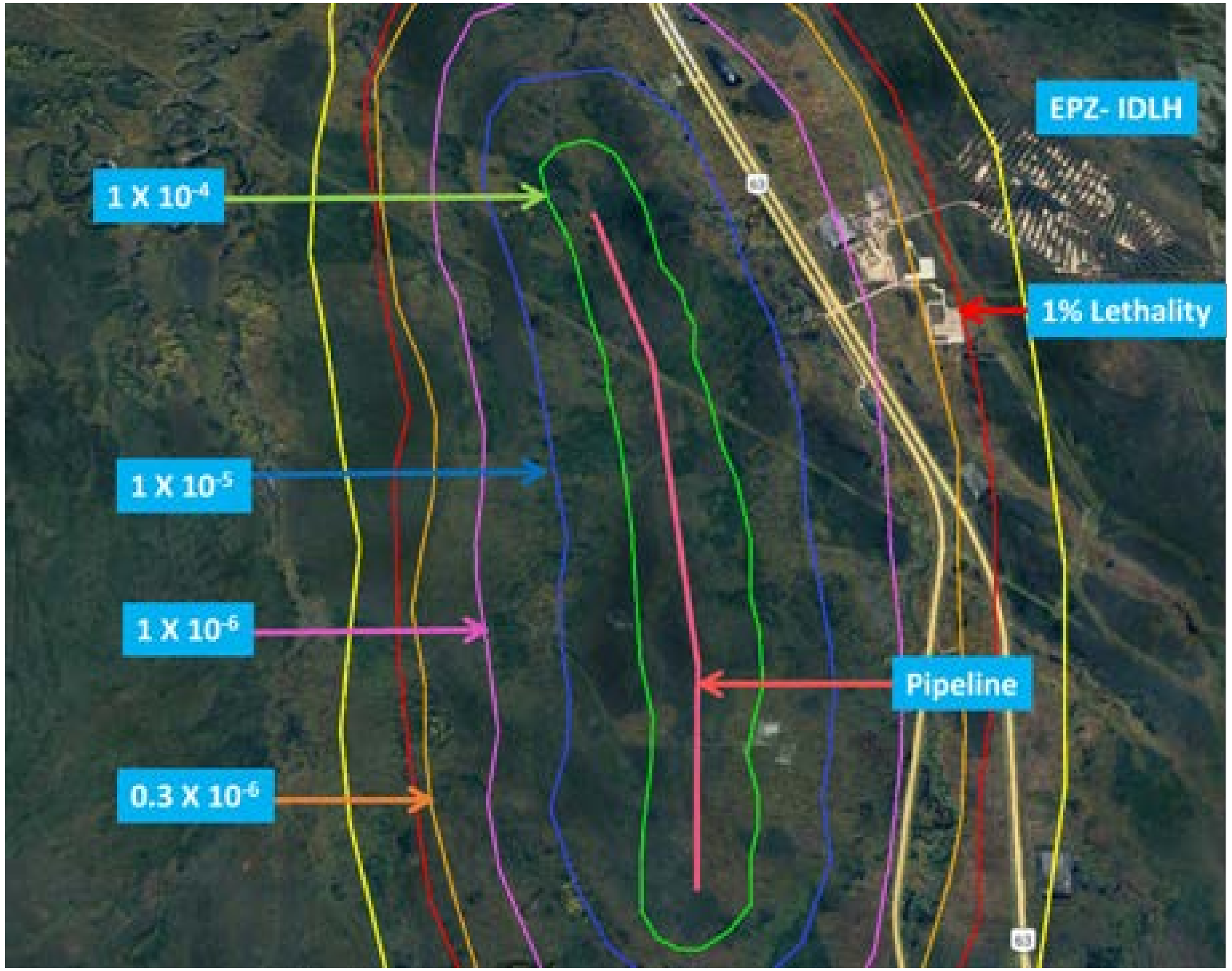


Proposed in 2007 by the CSChE PSM Division,
modified from the 1994 MIACC (Major Industrial Accidents Council of Canada) Guidelines
*further discussion required

Lethality Contours

- 1% lethality contour
- If a unit is inside the 1% lethality contour, what additional considerations need to be taken?
- What is the occupancy of the unit
    - What is the impact of 1%?
- Does it satisfy the organizations risk tolerance?
    - The organizational tolerance could be “no fatality”
    - A fatality ≥ 1 would automatically make it very high risk
- Outside the 1% lethality contour, is it compliant to the organizational risk tolerance?

EPZ, MIACC & Lethality Contours



Technical Approach for a Comprehensive QRA

What other calculations and considerations to determine impacts and risks?

- Emergency Planning Zones (EPZ) distances—Immediately Dangerous to Life and Health (DLH) applied
- 40,000 ppm—Basis for revised IDLH: on acute inhalation toxicity data in humans—The National Institute for Occupational Safety and Health (NIOSH)
- Consequence modelling tools (e.g., Phast™) and quantitative risk modelling tool (e.g., Safeti™)
  - Cleaver Crater Model
  - Defined Area Model (new model using Safeti™ ver. 9)
    - For more detailed analysis of CO_2 pipeline ruptures
    - Validated against COSHER experiments, improving accuracy
- LSIR—MIACC contours
- Concentration analysis
  - Determine radius for high concentration levels and time for gas to reach back to normal levels (30,000 ppm (54,000 mg/m3) STEL-short term exposure limit)
  - Determine concentrations especially for densely occupied installations, houses, or cluster of houses
  - Determining a low-risk lethality radius (1%)
- Apply these contours on a GIS map and check for installations, and how they are placed
  - MIACC compliant? outside 1% lethality? outside EPZ?
- Any future developments identified within high concentration zones
  - Often risk mitigation is taken for only current risks
  - Proactive planning vs. reactive response
- Societal Risk (F-N curve analysis)

Emergency Preparedness

EPZ and the IDLH contour

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- Emergency preparedness should be the first step in evaluating the impacted area and determine the emergency response zone
- Model the pipeline route and determine the dispersion radius
  - Including the MIACC contours and IDLH contour
  - Considering pin hole, hole, and burst
- What are the health effects of different concentrations and exposure durations? (e.g.100,000 ppm for 1 minute)
- What are the concentrations and time durations for IDLH (e.g. 40000 ppm for 30 minutes in case of CO_2)
- Input parameters include pipeline diameter, pressure, gas properties, flow rate, terrain, soil type, weather (Wind Rose Data) and route, and then determine what is the radius for IDLH?
- What is the largest radius?
  - Should you consider uniform EPZ throughout the pipeline (one which is the largest), or different radius in different segments?
- Within the IDLH contour, the risks are high and there is need for emergency preparedness plan and evacuation plans
  - Outside the IDLH contour, risks are minimal

Determining Health Effects of H_2S Exposure

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- Health effects of H_2S exposure
  - **Low-Level Exposure (1-10 ppm)**: can cause irritation of the eyes, nose, and throat, as well as headache, dizziness, and nausea
  - **Moderate-Level Exposure (10-50 ppm)**: may result in more severe respiratory irritation, coughing, and difficulty breathing
  - **High-Level Exposure (>50 ppm)**: can lead to shock, convulsions, inability to breathe, and in severe cases, death
    - Exposure to concentrations of 100 ppm or more is considered immediately dangerous to life and health
- NIOSH sets the IDLH concentration for H_2S at **100 ppm**
  - This is the concentration at which exposure to H_2S could result in irreversible health effects or death, and workers should not be exposed without proper respiratory protection

Effects of CO_2 Concentration

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Concentration	Effects
≥500 ppm (0.05%)	Increased heart rate, increased blood pressure and peripheral blood circulation
≥700 ppm (0.07%)	Sick building syndrome symptoms appear such as headaches, tiredness, fatigue, and irritation of the eye, nose, and throat
≥1000 ppm (0.1%)	Respiratory symptoms in children and noticeable cognitive performance decline, including reduced decision-making capabilities, and increased fatigue
Extended exposure **≥1400 ppm** (0.14%)	Increased oxidative stress leading to cellular damage
Long-term CO_2 exposure at **≥2000 ppm** (0.2)	Metabolic dysregulation, inflammation, and increased strain on the heart muscles, possible chronic high blood pressure heart attacks, stroke, and heat failure
≥10,000 ppm (1%)—unlikely to be found in typical indoor environments	Increased respiratory rate, possible hyperventilation, metabolic stress, and increased brain blood flow
≥30,000 ppm (3%):	Decreased exercise tolerance with resultant difficulty breathing
≥50,000 ppm (5%):	Dizziness, headaches, confusion, and shortness of breath
≥80,000 ppm (8%):	Dimmed vision, sweating, tremor unconsciousness, and possible death

Determining Health Effects of CO_2 Exposure

Table 1: Concentration vs time consequences for CO_2 inhalation

Inhalation exposure time	SLOT: 1-5% Fatalities		SLOD: 50% Fatalities	
	CO_2 Concentration in air*		CO_2 Concentration in air*	
	%	ppm	%	ppm
60 min	6.3%	63 000 ppm	8.4%	84 000 ppm
30 min	6.9%	69 000 ppm	9.2%	92 000 ppm
20 min	7.2%	72 000 ppm	9.6%	96 000 ppm
10 min	7.9%	79 000 ppm	10.5%	105 000 ppm
5 min	8.6%	86 000 ppm	11.5%	115 000 ppm
1 min	10.5%	105 000 ppm	14%	140 000 ppm

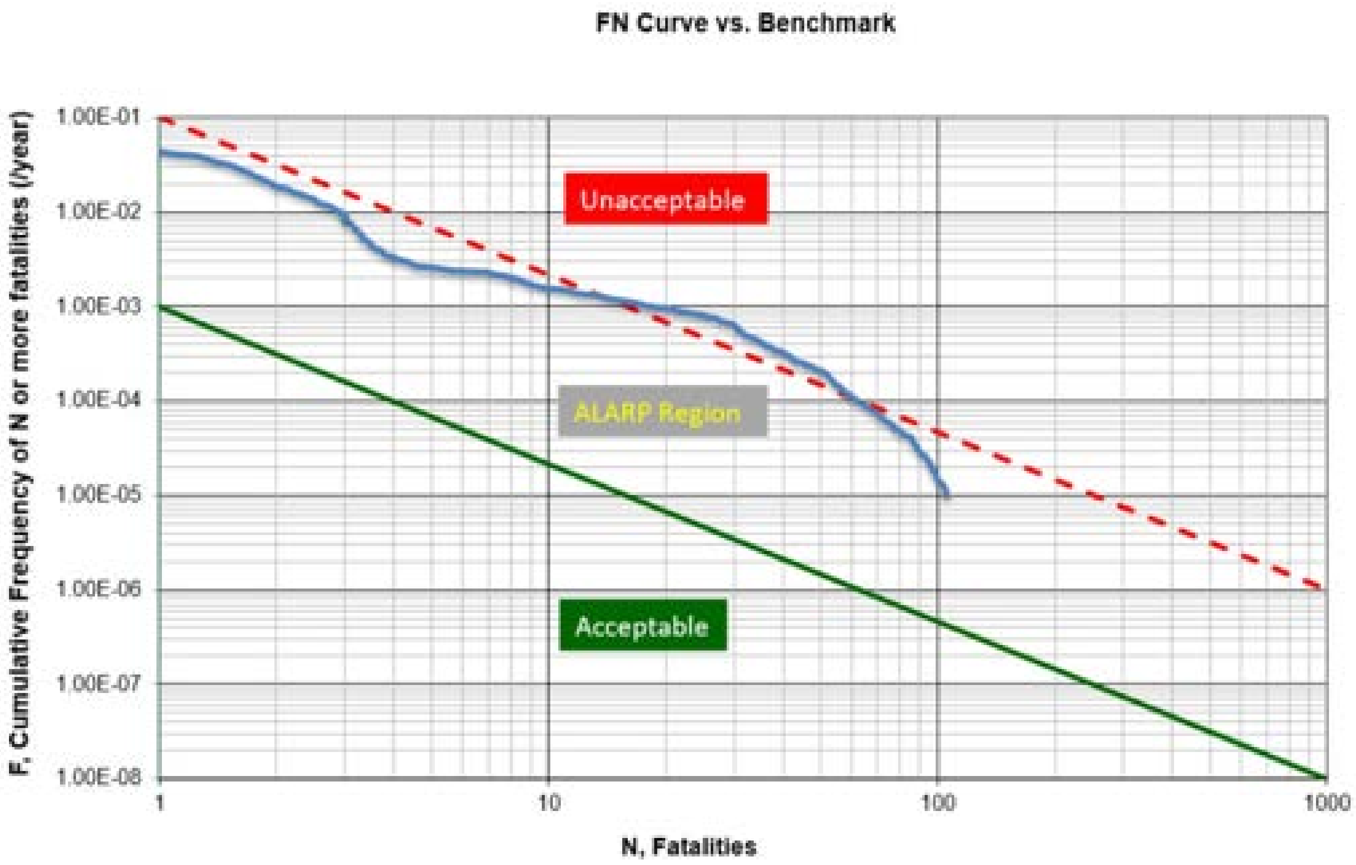
Note: * Concentration by volume

Concentration versus time consequences for CO_2 inhalation

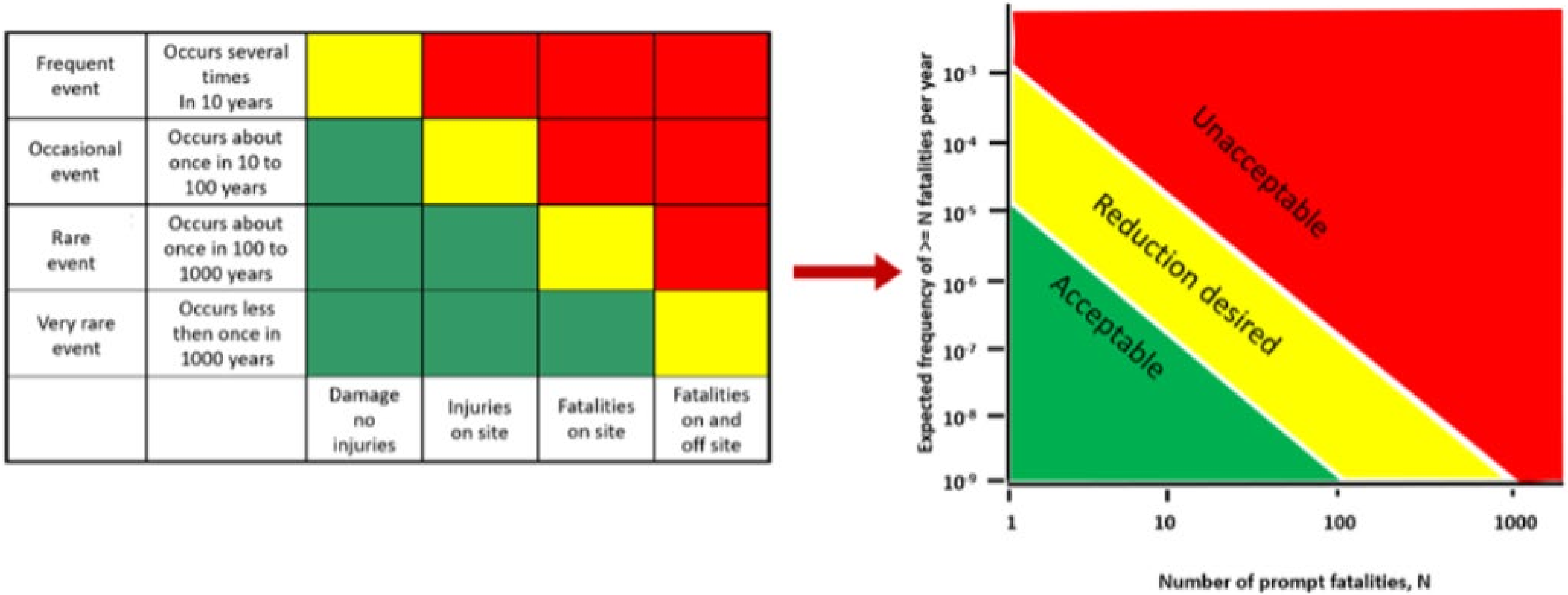
Societal Risks

F-N curve analysis

- An **F-N curve** is a graphical representation used in risk assessment that illustrates the relationship between the frequency of an event and the cumulative severity of its outcomes
- It plots the frequency (F) of incidents on the Y-axis against the number of fatalities (N) on the X-axis
- It is often used to communicate risk levels associated with various activities or projects
- In summary, the F-N curve is **a crucial tool in understanding and managing SR**



Organizations Risk Matrix & F-N Curve



Frequent event	Occurs several times In 10 years				
Occasional event	Occurs about once in 10 to 100 years				
Rare event	Occurs about once in 100 to 1000 years				
Very rare event	Occurs less then once in 1000 years				
		Damage no injuries	Injuries on site	Fatalities on site	Fatalities on and off site

Figure 2. Translation of risk matrix to f-N curve to determine the acceptability of risk

Regulatory Setbacks

Challenges and considerations

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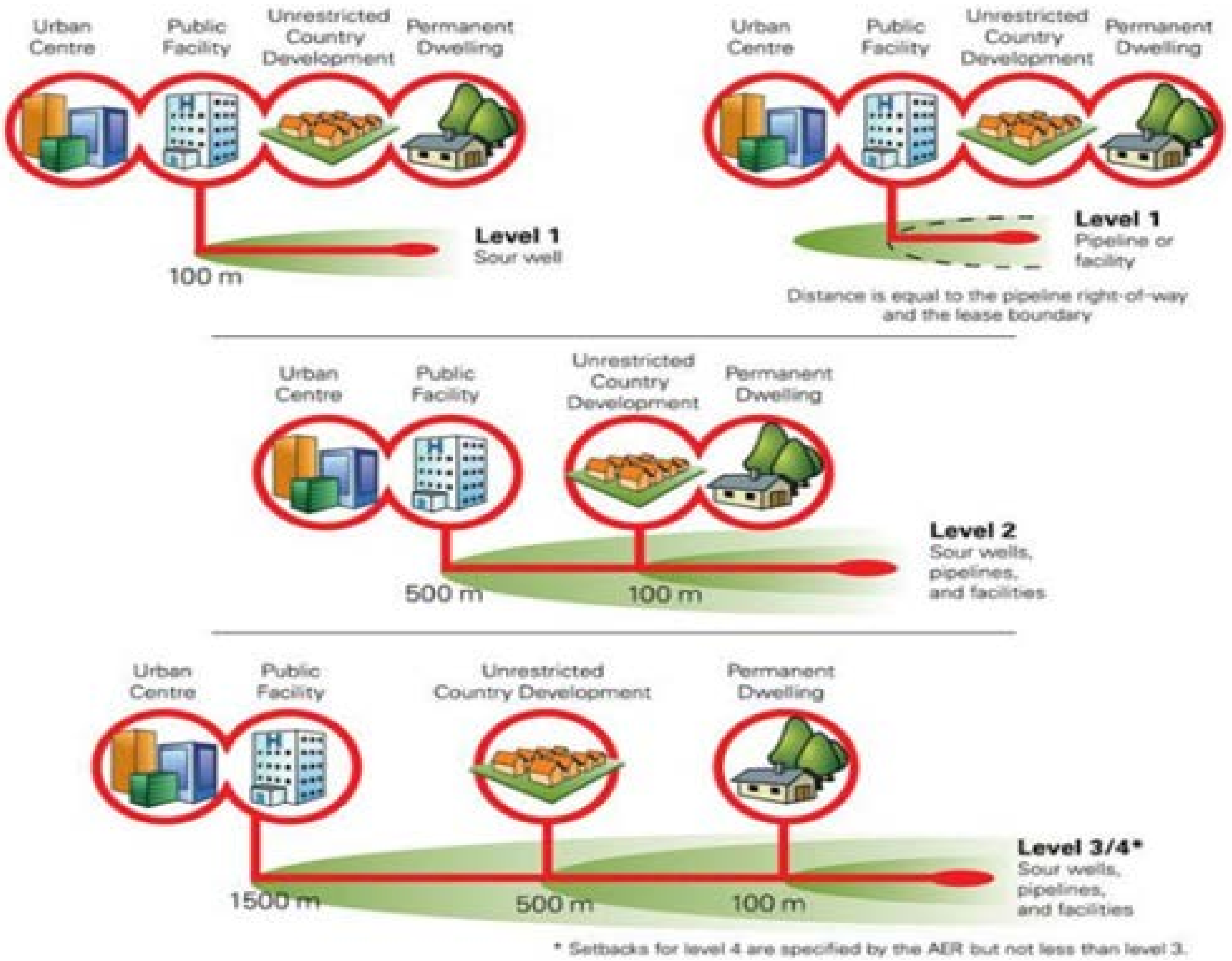
- The AER categorizes sour gas facilities into **four hazard levels** based on well release rates, pipeline release volumes, and hydrogen sulfide (H_2S) content
- There are predetermined setback distances for each level of sour gas facility



Challenges

- Economic considerations—land cost
- Balancing economic development with safety
- Public resistance
- Resistance by elected
- Need for national standards and consistency

Causes of Leaks & Their Mitigations

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- The last step of a QRA process is to evaluate and analyze risk to determine whether risk reduction measures need to be implemented on-site
- Examples of possible risk reduction measures that can be concluded from a QRA's results are:
  - Potential causes: third-party interference, corrosion, material defects, geotechnical issues, construction problems, other contributing factors
  - Reducing occurrence: barricading, barriers and warning signs for third parties, strict crossing permits, security systems
  - Corrosion and material protection: cathodic protection and AC mitigation, pipe material selection/specification, coating selection and inspections, holiday detection surveys, integrity assessments
  - Quality and construction assurance: inspections for material defects, construction inspection specifications, welding process specifications, non-destructive testing
  - Geotechnical and environmental controls: geotechnical evaluations, ground movement assessments, slope stabilization, horizontal directional drilling, flood assessment and control, buoyancy control
  - Containment and detection measures: barriers for dispersion, crack arrestors, increased wall thickness / high-strength materials, rapid leak detection and alarm systems, cameras (including infrared), gas detectors
  - Integrity and operational monitoring: enhanced integrity monitoring, frequent surveys and patrols, additional valves and auto-closing valves, integrity management program with ongoing risk management and regular pipeline assessments

The Steps to Achieve a Low-risk Pipeline Based On Dispersion

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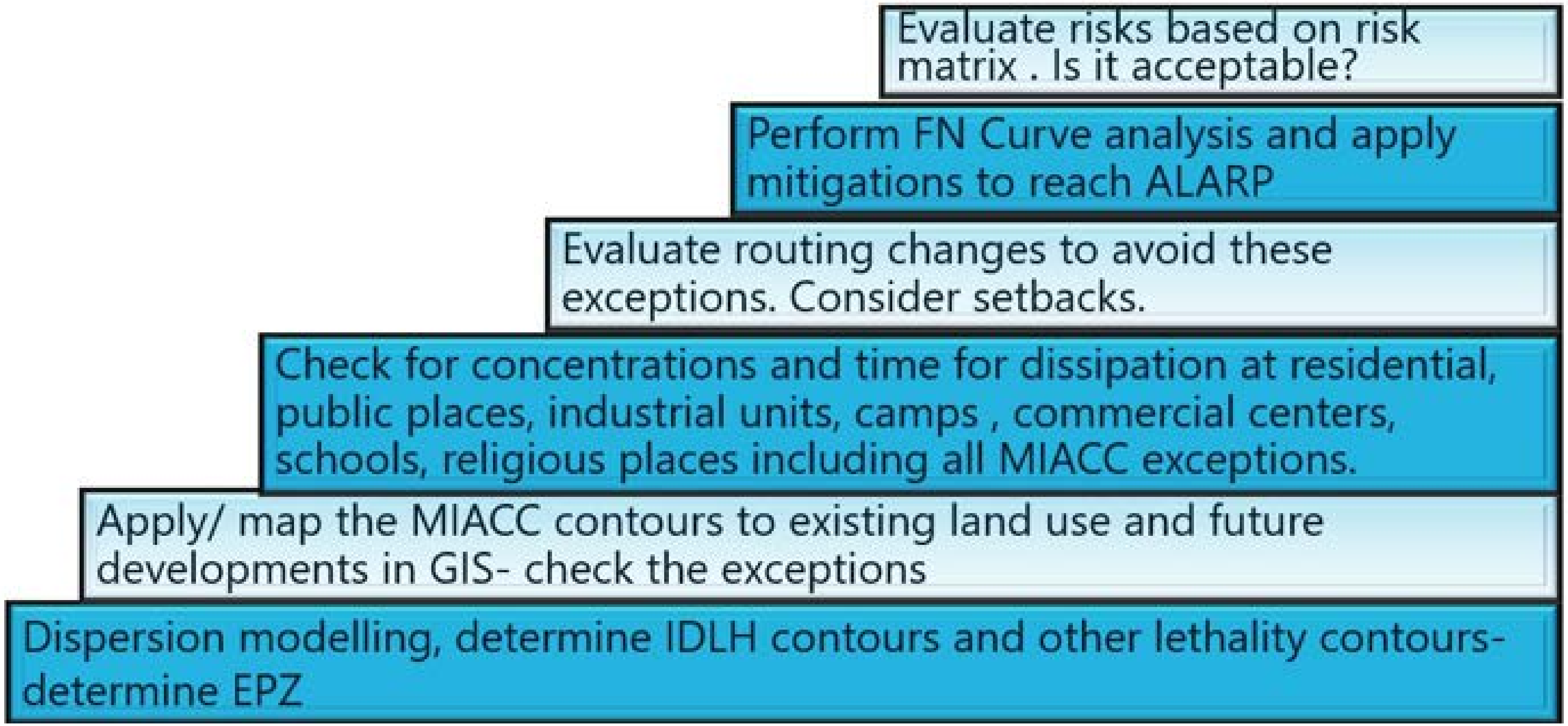

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End-to-end solutions in the energy space

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