

OVERVIEW OF INDUSTRIAL RISK ASSESSMENT



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Requirements in the Directive

- **Top Tier Sites - Article 9(b)** - demonstrating that major-accident hazards have been identified and that the necessary measures have been taken to prevent such accidents and to limit their consequences for man and the environment;
- **Lower Tier Sites - ANNEX III(ii)** - identification and evaluation of major hazards — adoption and implementation of procedures for systematically identifying major hazards arising from normal and abnormal operation and the assessment of their likelihood and severity;



Definition of Hazard and Risk

- *Hazard*: the property of a substance or situation with the potential for creating damage
- *Risk*: the likelihood of a specific effect within a specified period
 - complex function of *probability*, *consequences* and *vulnerability*



Risk Assessment

Risk assessment and risk analysis of technical systems can be defined as a set of systematic methods to:

- Identify hazards
- Quantify risks
- Determine components, safety measures and/or human interventions important for plant safety



Risk assessment

Risk analysis is teamwork

Ideally risk analysis should be done by bringing together experts with different backgrounds:

- chemicals
- human error
- process equipment

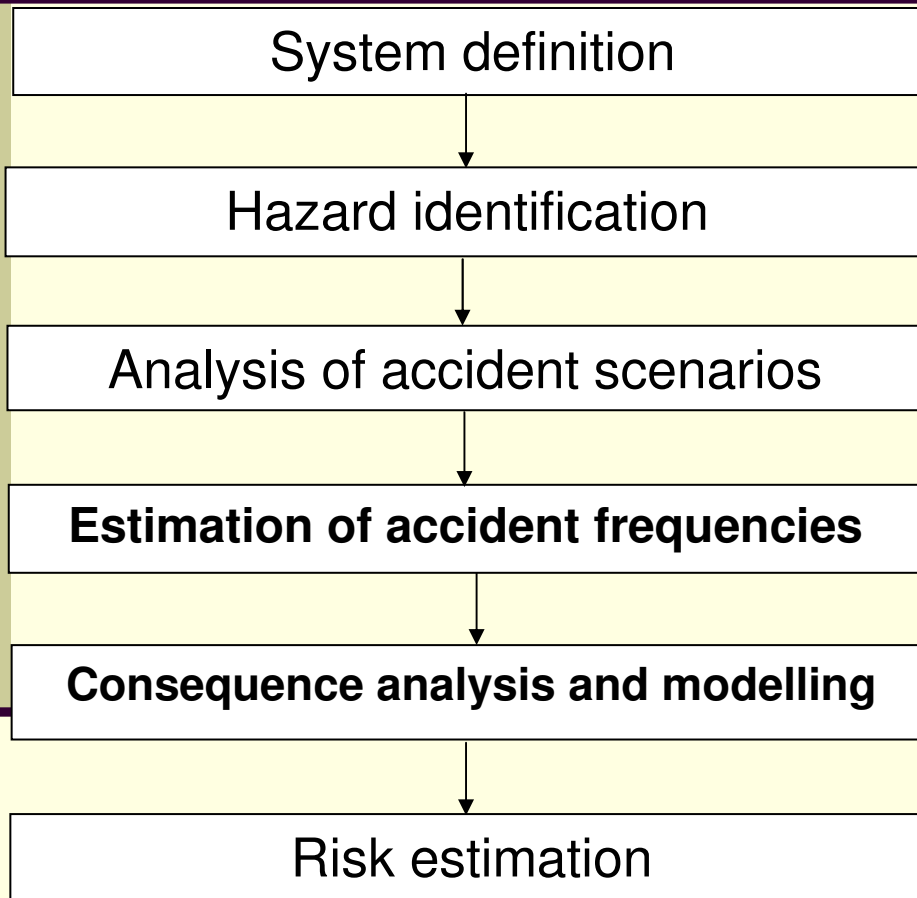
**Risk assessment is a
continuous process!**



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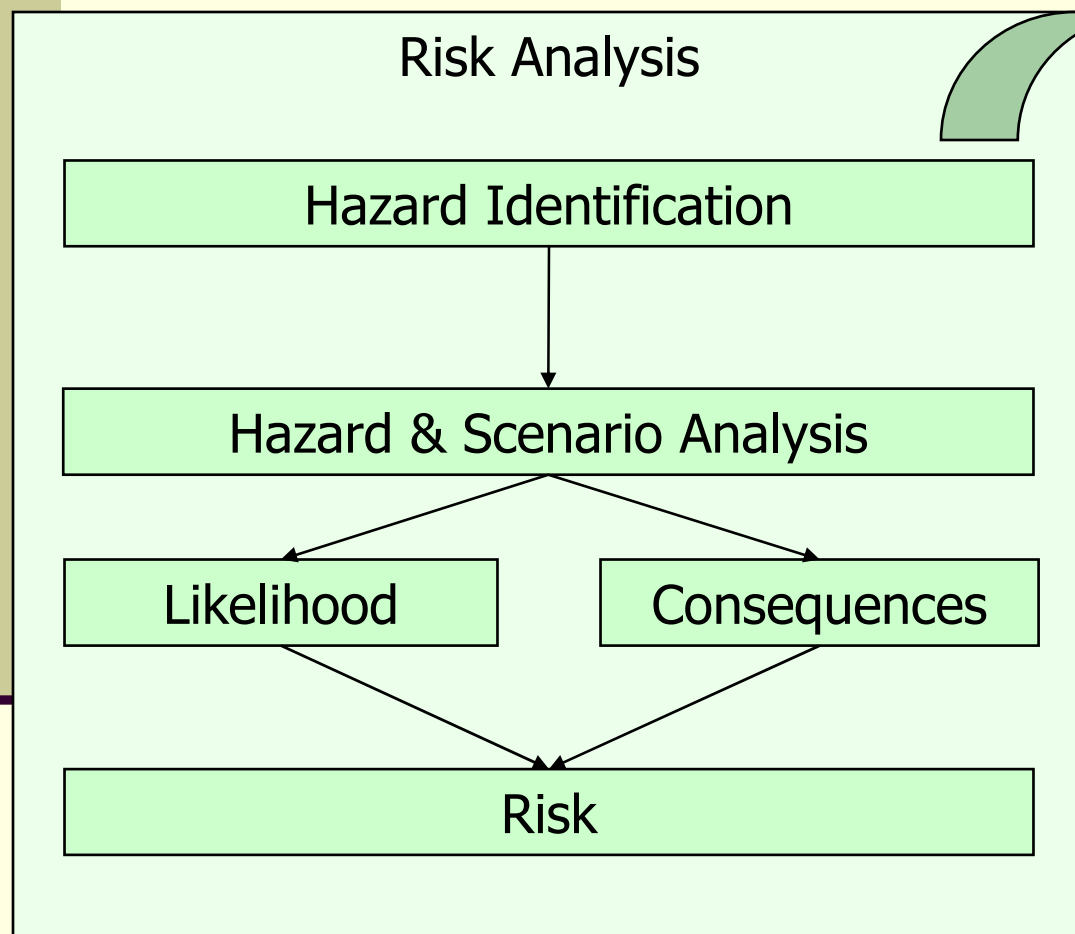
Risk Assessment



- Scheme for qualitative and quantitative assessments
- At all steps, risk reducing measures need to be considered



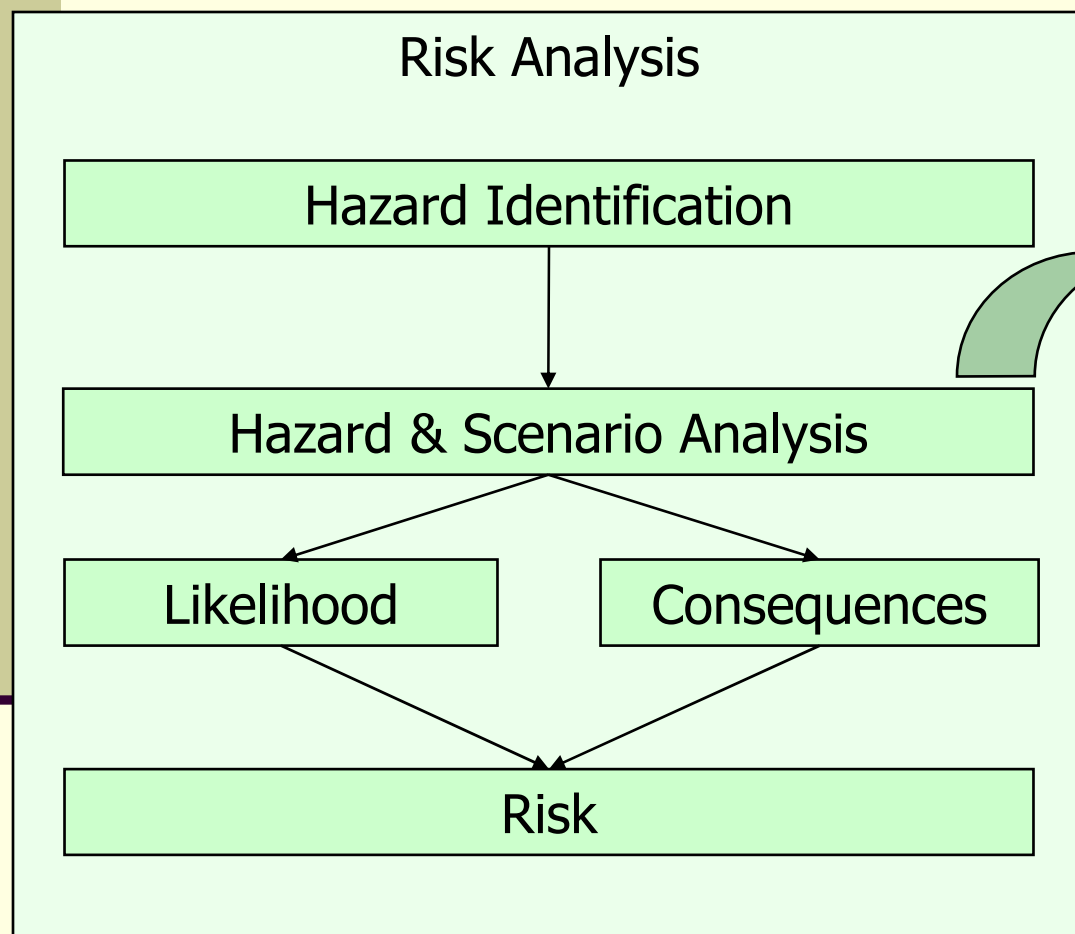
Risk Analysis – Main Steps



- "What if"
- Checklists
- HAZOP
- Task analysis
- Index (Dow, Mond)



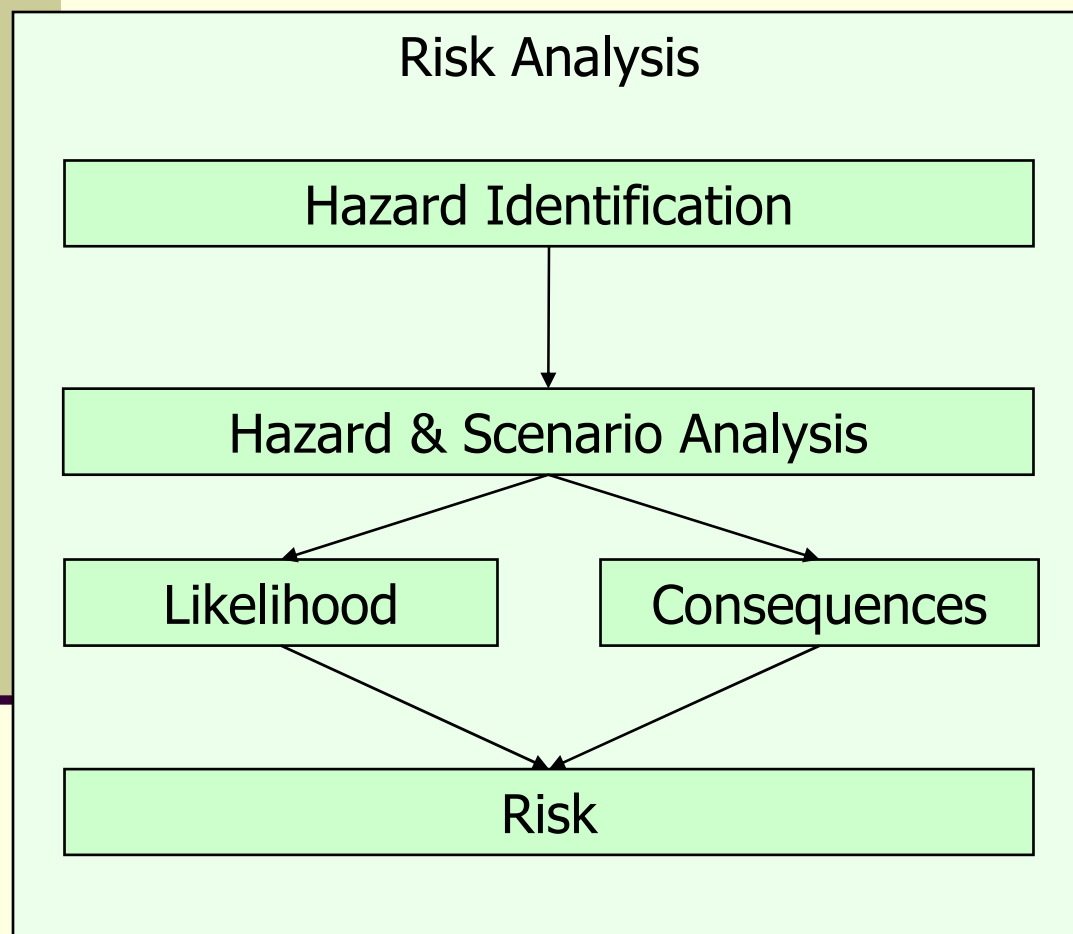
Risk Analysis – Main Steps



- Fault tree analysis
- Event tree analysis
- Bowties
- Barrier diagrams
- Reliability data
- Human reliability
- Consequence models



Risk Analysis – Main Steps



**Identify
Safety
Barriers**



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Preliminary hazard identification

Identification of safety relevant sections of the establishment, considering

- raw materials and products
- plant equipment and facility layout
- operation environment
- operational activities
- interfaces among system components

**Important to secure Completeness,
Consistency and Correctness**



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Methods for hazard identification

- "What if"
- Checklists
- HAZOP
- Task analysis
- Index (Dow, Mond)
- Failure mode and effects analysis (FMEA)



The HAZOP Method

- **HAZOP analysis** is a systematic technique for identifying hazards and operability problems throughout an entire facility. It is particularly useful to identify unwanted hazards designed into facilities due to lack of information, or introduced into existing facilities due to changes in process conditions or operating procedures.
- **The objectives of a HAZOP** study are to detect any predictable deviation (undesirable event) in a process or a system. This purpose is achieved by a systematic study of the operations in each process phase.



The HAZOP Method

- The system is divided into functional blocks
- Every part of the process is examined for possible deviations from the design intention
- Can the deviations cause any hazard or inconvenience?
- Every phase of the process
- Each system and person
- Questions formulated around guide words
- Each deviation is considered to decide how it could be caused and what the consequences would be
- For the hazards preventive/remedying actions are defined



HAZOP Study Consequence

1. Definition of the objectives and scope of the study, e.g. hazards having only off-site impact or only on-site impact, areas of the plant to be considered, etc.
2. Assembly of a HAZOP study team.
3. Collection of the required documentation, drawings and process description.
4. Analysis of each major item of equipment, and all supporting equipment, piping and instrumentation
5. Documentation of the consequences of any deviation from normal and highlights of those which are considered hazardous and credible.



HAZOP Study team

- HAZOP studies are normally carried out by multi-disciplinary teams. There are two types of team members, namely those who will make a technical contribution and those play a supporting and structuring role.



Example of HAZOP Matrix

Guide word Process-variable	No	Low	High	Part of	Also	Other than	Reverse
Flow	No flow	Low flow	High flow	Missing ingredients	Impurities	Wrong material	Reverse flow
Level	Empty	Low level	High level	Low interface	High interface	-	-
Pressure	Open to atmosphere	Low pressure	High pressure	-	-	-	Vacuum
Temperature	Freezing	Low temp.	High temp.	-	-	-	Auto refrigeration
Agitation	No agitation	Poor mixing	Excessive mixing	Irregular-mixing	Foaming	-	Phase separation
Reaction	No reaction	Slow reaction	"Runaway reaction"	Partial reaction	Side reaction	Wrong reaction	Decomposition
Other	Utility failure	External leak	External rupture	-	-	Start-up Shutdown Maintenance	-

HAZOP Criticality analysis

Criticality - combination of **severity** of an effect and the **probability** or expected frequency of occurrence.

The **objective** of a criticality analysis is **to quantify the relative importance of each failure effect**, so that **priorities to reduce the probability or to mitigate the severity** can be taken.

Example formula for Criticality:

$$Cr = P \times B \times S$$

Cr: criticality number

P: probability of occurrence in an year

B: conditional probability that the severest consequence will occur

S: severity of the severest consequence



HAZOP Criticality analysis

The criticality number

- used to rank the identified deviations in a HAZOP or FMEA study
- cannot be used as a risk measure
- product of three rough estimates

Before a criticality analysis can be performed guidelines have to be developed on how to determine **P**, **B** and **S**.

There are no generally accepted criteria for criticality applicable to a system.



Example values for P, B and S

Categories					
Probability P		Cond. Probabil B		Severity S	
Very rare	1	Very low	1	Low	1
Rare	2	Low	2	Significant	2
Likely	3	Significant	3	High	3
Frequent	4	high	4	Very high	4



Interpretation of the values

Probability (P)

- very rare - less than once in 100 years
- rare - between once in 10 y. and once in 100 y.
- likely - between once a year and once in 10 years
- frequent - more frequent than once a year

Conditional probability (B)

- very low - less than once every 1000 occurrences of the cause
- low - less than once every 100 occurrences of the cause
- significant - less than once every 10 occurrences of the cause
- high - more than once every 10 occurrences of the cause

Severity (S)

- low - no or minor economical loss/small, transient environmental damage
- significant - considerable economic losses/considerable transient environmental damage/slight non-permanent injury
- high - major economic loss/considerable release of hazardous material/serious temporary injury
- very high - major release of hazardous material/permanent injury or fatality



Decision making

Criticality	Judgement	Meaning
$Cr < X$	Acceptable	No action required
$X < Cr < Y$	Consider modification	Should be mitigated within a reasonable time period unless costs demonstrably outweigh benefits
$Cr > Y$	Not acceptable	Should be mitigated as soon as possible

The values X and Y have to be determined by a decision-maker. It might be necessary to formulate some additional criteria, for instance: every deviation for which the severity is classified as “very high severity” shall be evaluated to investigate the possibilities of reducing the undesired consequences.



Risk Assessment Using Index-based Methods

- Indexes can be used for risk ranking
- Process units can be assigned a score or index based on
 - Type of substance (flammable, explosive and/or toxic properties)
 - Type of process (pressure, temperature, chemical reactions)
 - Quantity
- Ranking of the hazards
- Focus attention on hazard analysis for the most hazardous units



Examples of Substance indexes

- Substance Hazard Index (SHI): Proposed by the Organization of Resources Counsellors (ORC) to OSHA.
 - Based on a ratio of the equilibrium vapour pressure(EVP) at 20 °C divided by the toxicity concentration.
- Material Hazard Index (MHI): Used by the state of California to determine threshold quantities of acutely hazardous materials for which risk management and prevention programs must be developed.



Substance and process indexes

- Dow Fire and Explosion Index (F&EI):
Evaluates fire and explosion hazards associated with discrete process units.
- Mond Fire and Explosion Index: Developed by ICI's Mond Division, an extension of the Dow F&EI.
 - These indices focus on fire and explosion hazards, e.g. Butane has a Dow Material Index of 21, and Ammonia 4.



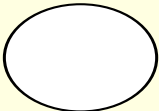

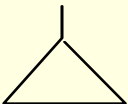
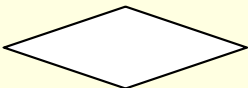


Fault Tree Analysis

- Graphical representation of the logical structure displaying the relationship between an undesired potential event (top event) and all its probable causes
 - top-down approach to failure analysis
 - starting with a potential undesirable event - top event
 - determining all the ways in which it can occur
 - mitigation measures can be developed to minimize the probability of the undesired event
- Fault Tree can help to:
 - Quantifying probability of top event occurrence
 - Evaluating proposed system architecture attributes
 - Assessing design modifications and identify areas requiring attention
 - Complying with qualitative and quantitative safety/reliability objectives
 - Qualitatively illustrate failure condition classification of a top-level event
 - Establishing maintenance tasks and intervals from safety/reliability assessments



Fault tree construction

	<p>AND gate</p> <p>The AND-gate is used to show that the output event occurs only if all the input events occur</p>
	<p>OR gate</p> <p>The OR-gate is used to show that the output event occurs only if one or more of the input events occur</p>
	<p>Basic event</p> <p>A basic event requires no further development because the appropriate limit of resolution has been reached</p>
	<p>Intermediate event</p> <p>A fault tree event occurs because of one or more antecedent causes acting through logic gates have occurred</p>
	<p>Transfer</p> <p>A triangle indicates that the tree is developed further at the occurrence of the corresponding transfer symbol</p>
	<p>Undeveloped event</p> <p>A diamond is used to define an event which is not further developed either because it is of insufficient consequence or because information is unavailable</p>



Fault tree development procedure

- Идентифициране на всички логически знаци и на всички ОСНОВНИ събития.
- Достигане до ОСНОВНИТЕ събития
- Отстраняване на дублиращи се събития в рамките на едно съчетание
- Премахване на всички супер съчетания (съчетания, които съдържат други съчетания като подсъчетания).

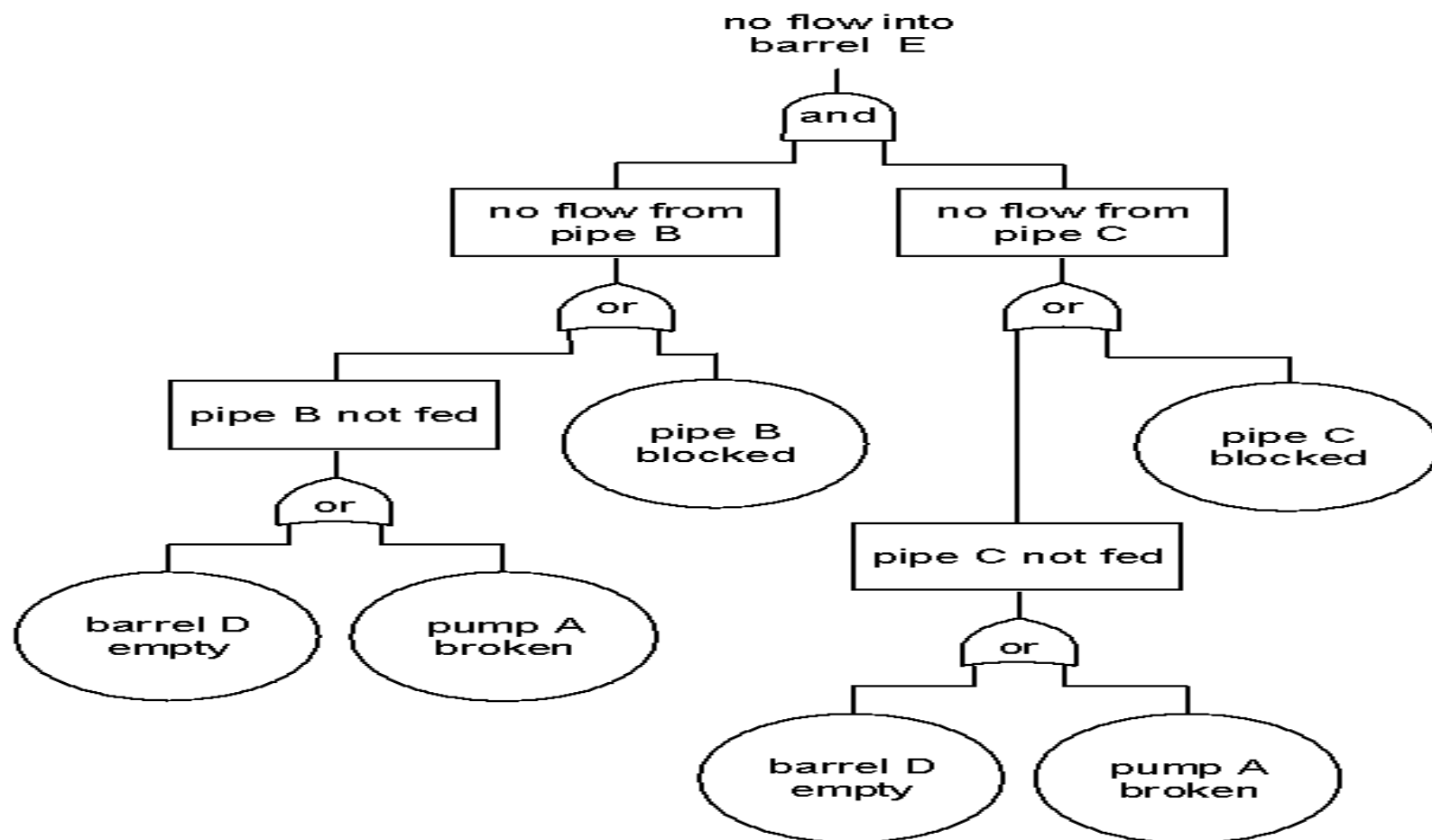


Guidelines for developing a fault tree

- Replace an abstract event by a less abstract event.
- Classify an event into more elementary events.
- Identify distinct causes for an event.
- Couple trigger event with 'no protective action'.
- Find co-operative causes for an event.
- Pinpoint a component failure event.



Example Fault Tree



Event Tree Analysis

- graphical representation of a logic model
 - identifies and quantifies the possible outcomes following an initiating event
 - provides an inductive approach to reliability assessment as they are constructed using forward logic.



Event tree development procedure

Step 1: Identification of the initiating event

Step 2: Identification of safety function

Step 3: Construction of the event tree

Step 4: Classification of outcomes

Step 5: Estimation of the conditional probability of each branch

Step 6: Quantification of outcomes

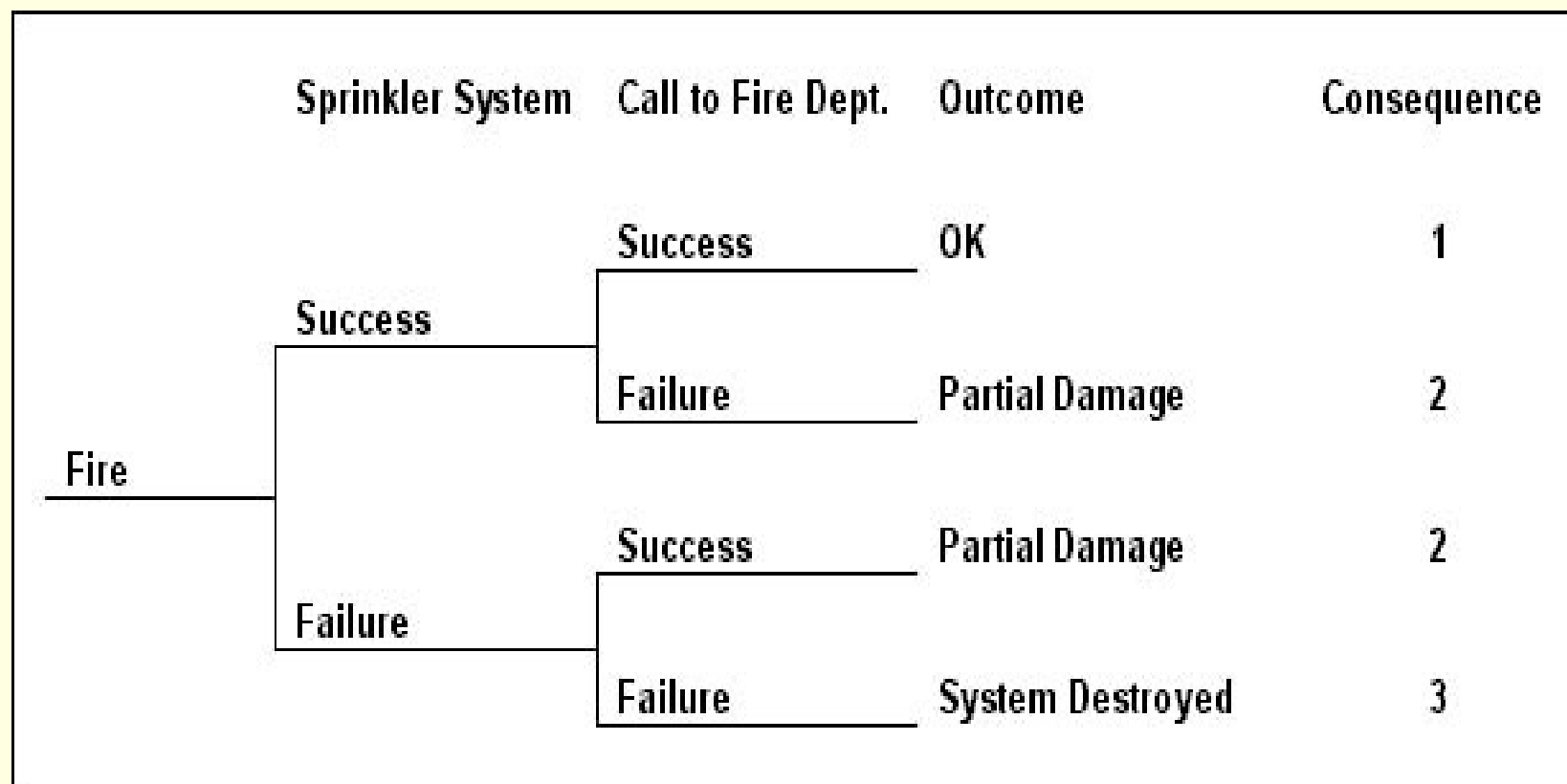
Step 7: Evaluation



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Example Event Tree

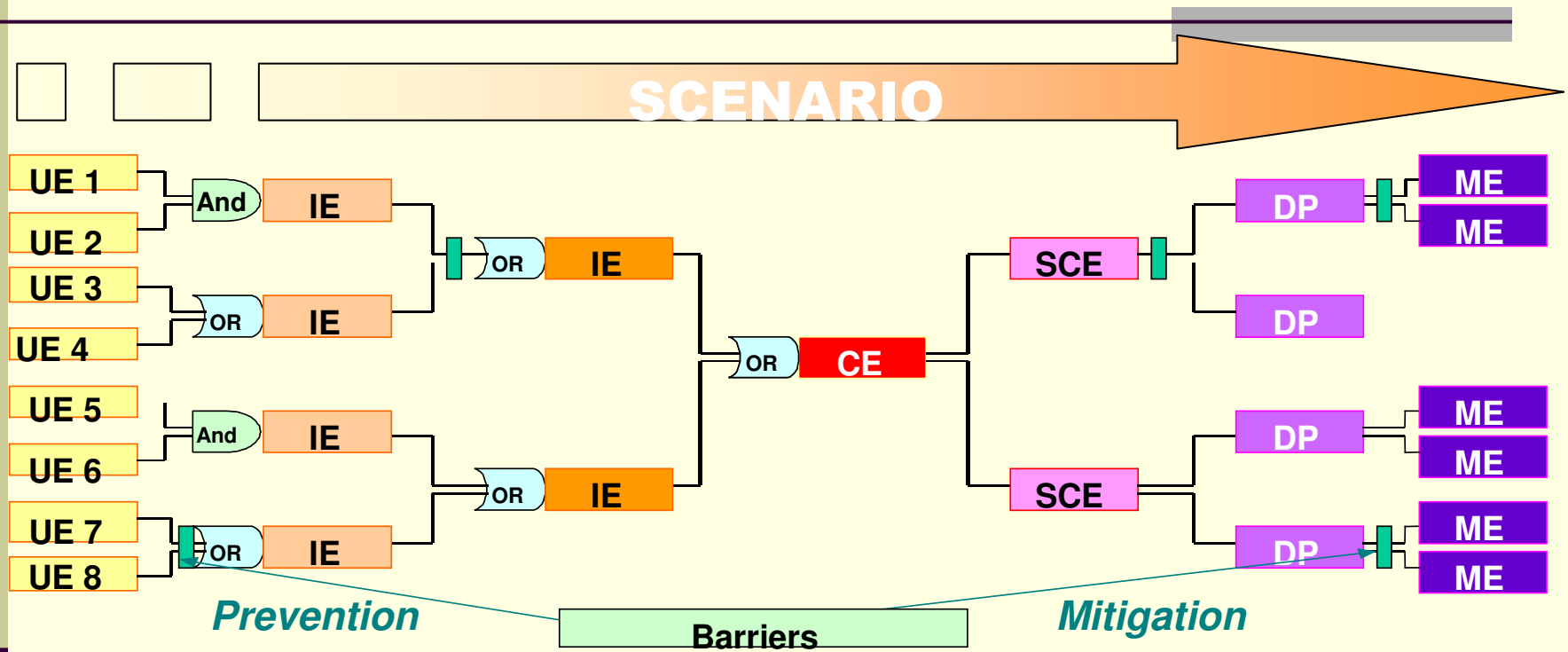


Bowtie Analysis

- Synergistic adaptation of *Fault Tree Analysis*, *Causal Factors Charting* and *Event Tree Analysis*
 - highly effective for initial Process Hazard Analysis
 - ensures identification of high probability-high consequence events
 - combined application of a high-level fault/event trees
 - representation of the causes of a hazardous scenario event, likely outcomes, and the measures in place to prevent, mitigate, or control hazards
 - Existing safeguards (barriers) identified and evaluated
 - Typical cause scenarios identified and depicted on the pre-event side (left side) of the bow-tie diagram
 - Credible consequences and scenario outcomes are depicted on the post-event side (right side) of the diagram
 - associated barrier safeguards included
 - the risks are readily understandable to all levels of operation and management.



Example Bowtie Tree



Fault Tree

Event tree

Unwanted Events (UE) / Initiating Events (IE) / Critical Events (CE) : *Loss of Containment (LOC) or Loss of Physical Integrity (LPI)* / Secondary Critical Events (SCE) / Dangerous Phenomena (DP) / Major Events (ME)



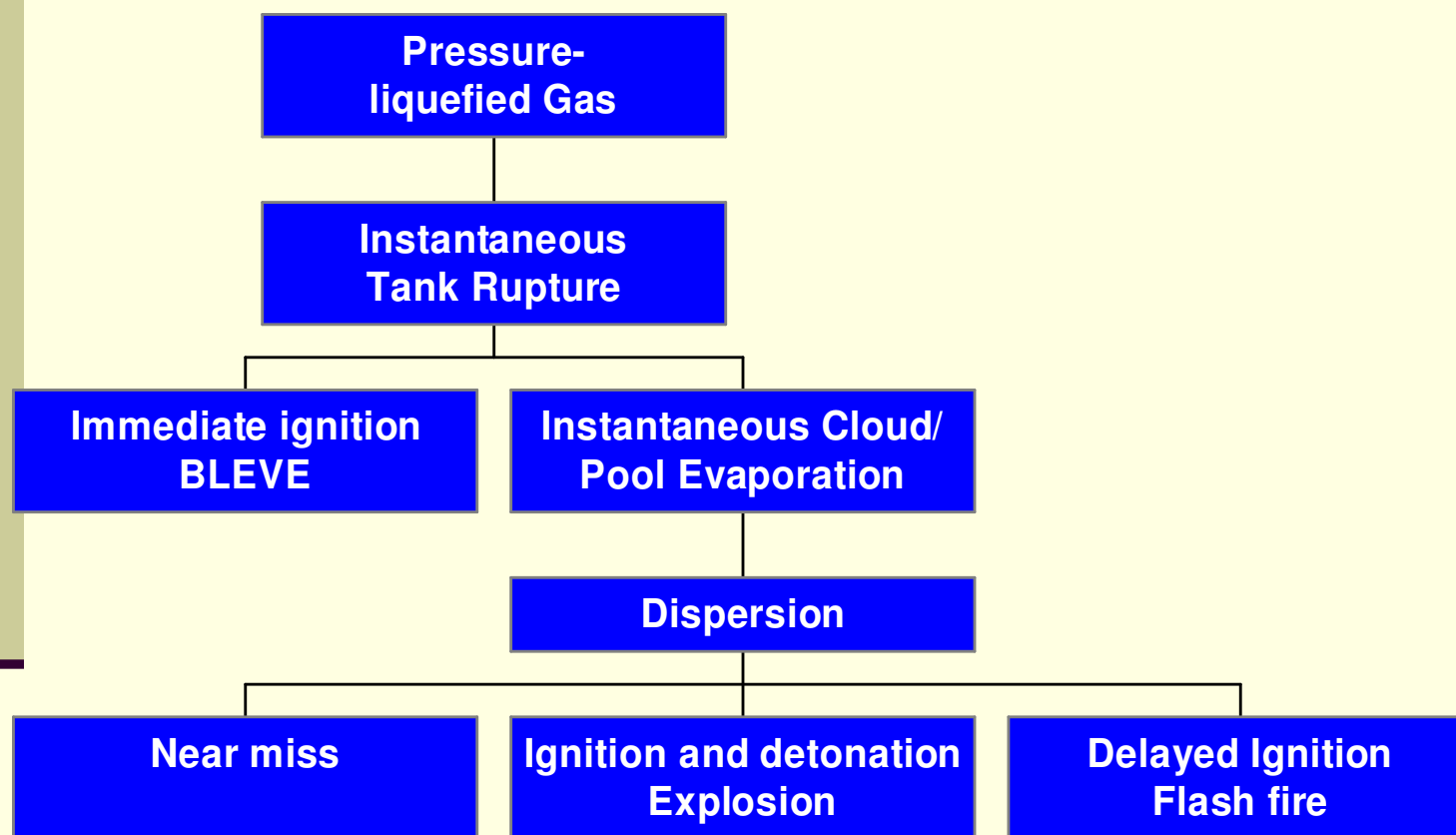
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Consequence assessment

- The consequence assessment is used to estimate:
 - The extent or distance to which casualties or damage may occur as a consequence of an accident;
 - The conditional probability of loss of life or damage as a consequence of an accident;



Consequence event tree for a flammable pressure-liquefied gas – instantaneous rupture



Example BLEVE



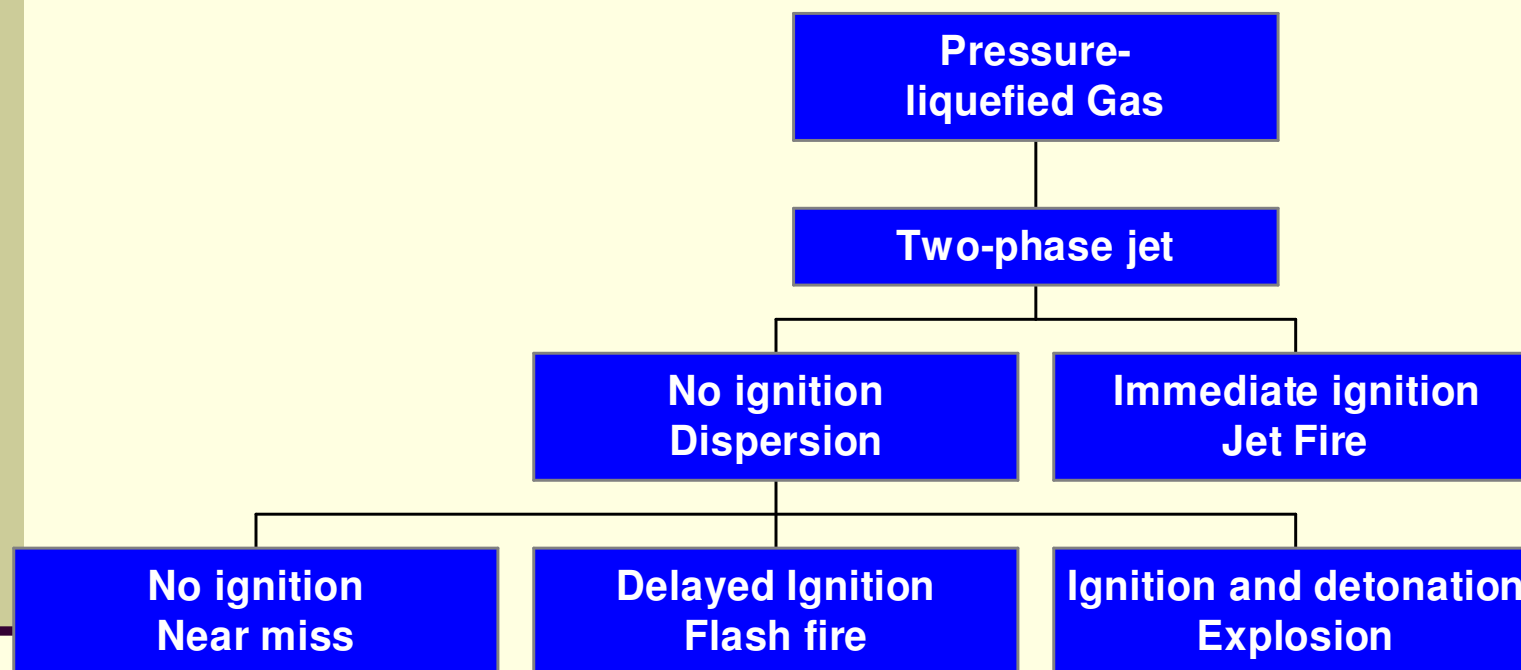
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Consequence event tree for a flammable pressure-liquefied gas – hole below liquid level



Example 2-phase jet



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Different forms of dispersion in the atmosphere

- Jet

- High speed (high momentum), rapid mixing, single direction

- Dense (= denser than air) clouds:

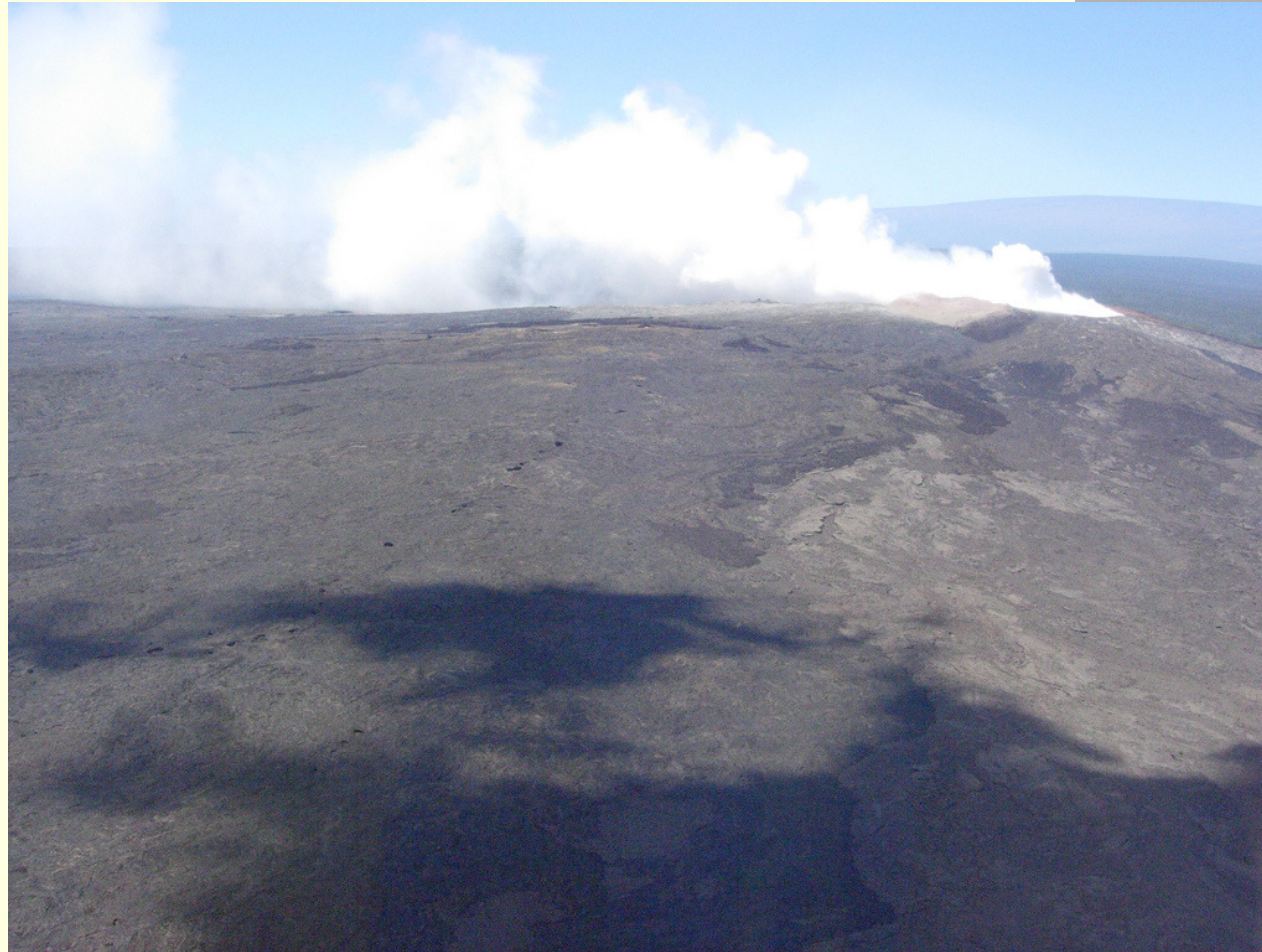
- Dense gas "slumps" in all directions (even against the wind)
 - Dense clouds are shallow
 - Density layering (stratification) reduces mixing

- Buoyant (= lighter than air) plume

- plume rise



Example of dense gas cloud



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QRA - Impact in all directions

- Impacts of BLEVE's, explosions, etc., are in general only dependent on distance to accident location

- $P_{death,BLEVE}(x,y) =$

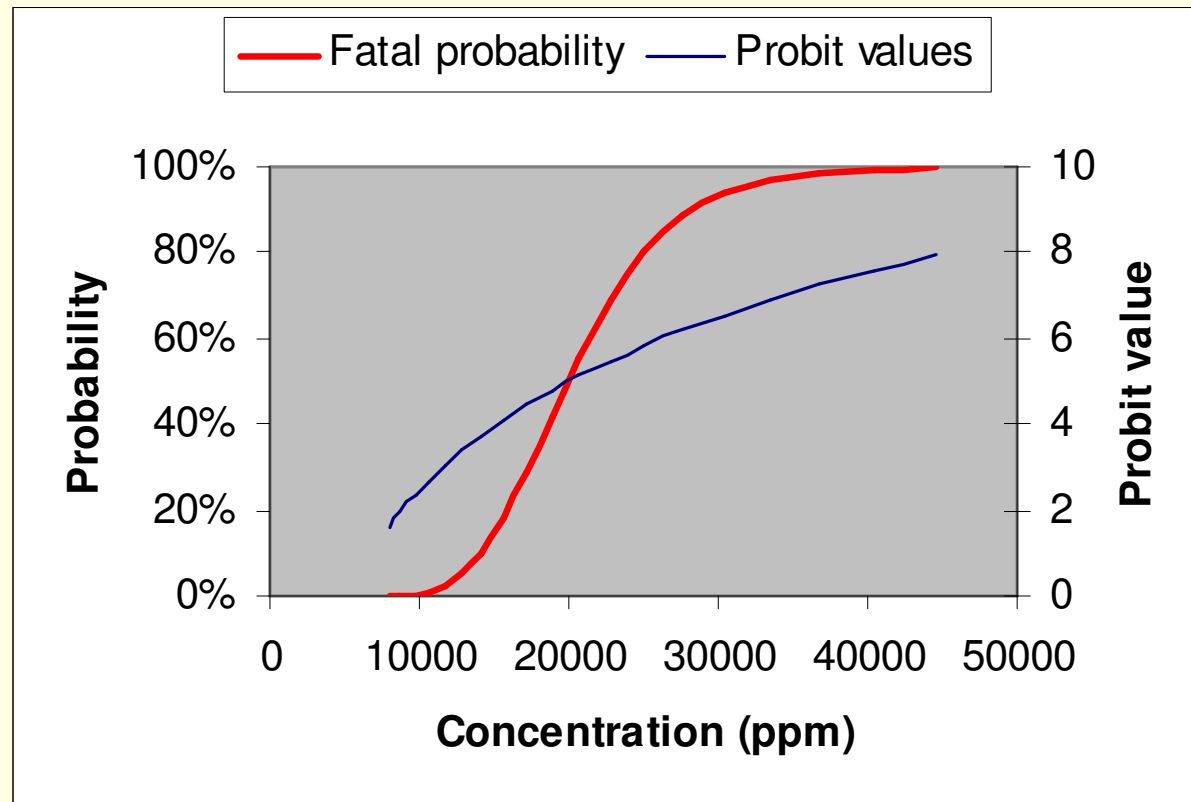
$P(BLEVE) \cdot$ (probability (fraction) of death at (x,y) for this BLEVE)



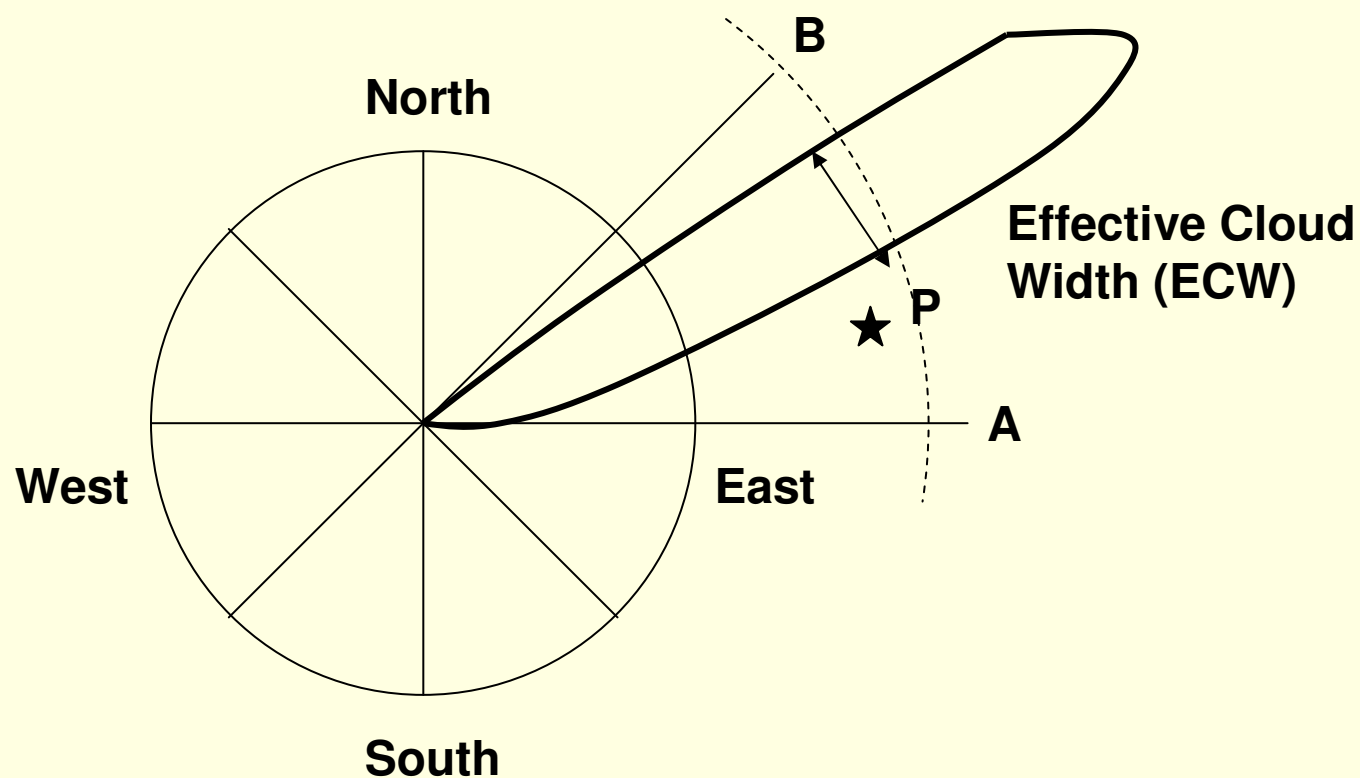
Ammonia toxicity

- Probit function $Pr = -35.9 + 1.85 \ln(C^2 \times t)$

Exposure during 10 minutes



QRA - Wind direction and cloud width



Details on how to do a QRA can be found in the Purple Book



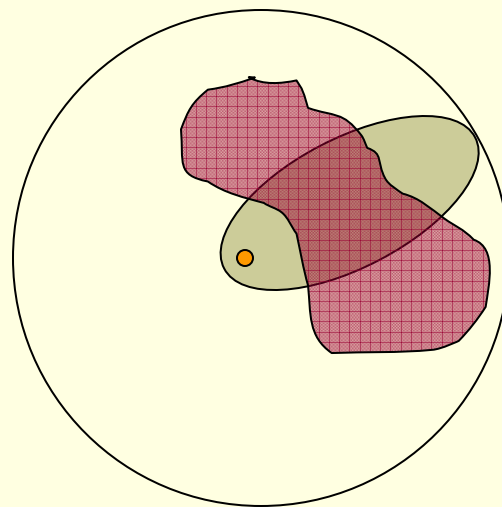
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”Quick and dirty” Methods

- IAEA-TECDOC-727 (1996)
”Manual for the Classification and Prioritization of Risks Due to Major Accidents in Process and Related Industries”
- *Number of fatalities =
Consequence Area (green) x
Population density x
fraction of Consequence area
covering populated area (blue) x
effect of mitigation effects.*
- Consequence Area look-up tables for 46 substances/scenarios and size of inventory



Consequence assessment in practice

- Consequence assessment is often an expert-activity (performed by consultants)
- Most "complete" consequence assessment software packages are proprietary and expensive
- Some freeware is available for specific consequences (ARCHIE, ALOHA etc.)
- Some models are described in detail in handbooks (e.g. "Yellow Book, TNO, Netherlands)



Failure Rates in QRA

- Typology of Equipment (Guidelines for Quantitative Risk Assessment. The Purple Book)
 - Stationary tanks and vessels, pressurised
 - Stationary tanks and vessels, atmospheric
 - Gas cylinders
 - Pipes
 - Pumps
 - Heat exchanges
 - Pressure relief devices
 - Warehouses
 - Storage of explosives
 - Road tankers
 - Tank wagons
 - Ships



Failure Rates in QRA

Typology of Equipment (ARAMIS, MIMAH)

Storage equipment	<ul style="list-style-type: none">– Mass solid storage– Storage of solid in small packages– Storage of fluid in small packages– Pressure storage– Padded storage– Atmospheric storage– Cryogenic storage
Process equipment	<ul style="list-style-type: none">– Intermediate storage equipm. integrated into the process– Equipment devoted to physical or chemical separation of substances– Equipment involving chemical reactions– Equipment designed for energy production and supply– Packaging equipment– Other facilities
Transport equipment	<ol style="list-style-type: none">1. Pressure transport equipment2. Atmospheric transport equipment
Pipes networks	



Complete Set of Causes for LOCs

Generic causes of LOCs

cover all failure causes not considered explicitly, like corrosion, construction errors, welding failures and blocking of tank vents

External-impact causes of LOCs

are considered explicitly for transport units. For stationary installations and pipelines they are assumed to be either already included in the generic LOCs or should be included by adding an extra frequency

LOCs caused by loading and unloading

cover the transshipment of material from transport units to stationary installations and vice versa

Specific causes of LOCs

cover the causes specific to the process conditions, process design, materials and plant layout. Examples are runaway reactions and domino effects



Frequencies of LOCs for Stationary Vessels

Installation	Instantaneous	Continuous, 10 min	Continuous, Ø10 mm
Pressure vessel	$5 \times 10^7 \text{ y}^{-1}$	$5 \times 10^7 \text{ y}^{-1}$	$1 \times 10^5 \text{ y}^{-1}$
Process vessel	$5 \times 10^6 \text{ y}^{-1}$	$5 \times 10^6 \text{ y}^{-1}$	$1 \times 10^4 \text{ y}^{-1}$
Reactor vessel	$5 \times 10^6 \text{ y}^{-1}$	$5 \times 10^6 \text{ y}^{-1}$	$1 \times 10^4 \text{ y}^{-1}$



Frequencies of LOCs for Atmospheric Tanks

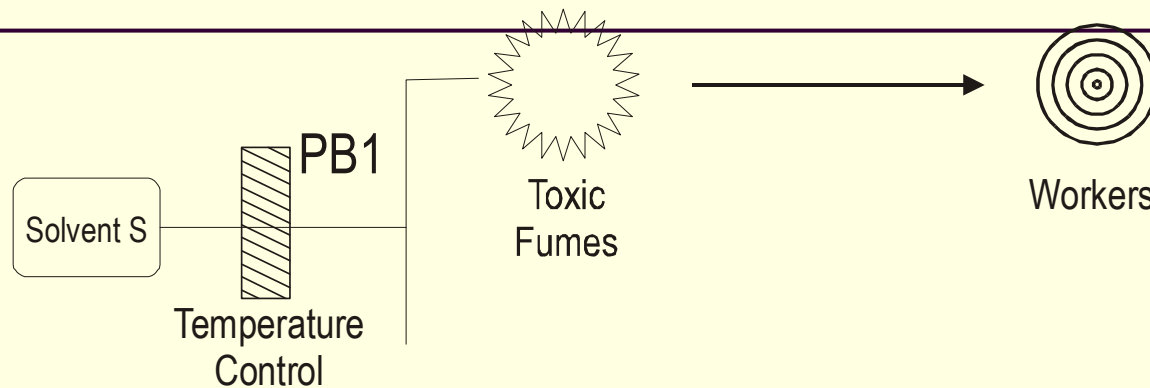
Installation (Tank)	1a. Instant. release to atmosphere	1b. Instant. release to secondary container	2a. Contin. 10 min to atmosphere	2b. Contin. 10 min to secondary container	3a. Contin. Ø10 mm to atmosphere	3b. Contin. Ø10 mm to secondary container
Single containment	$5 \times 10^{-6} \text{ y}^{-1}$		$5 \times 10^{-6} \text{ y}^{-1}$		$1 \times 10^{-4} \text{ y}^{-1}$	
With a protective outer shell	$5 \times 10^{-7} \text{ y}^{-1}$	$5 \times 10^{-7} \text{ y}^{-1}$	$5 \times 10^{-7} \text{ y}^{-1}$	$5 \times 10^{-7} \text{ y}^{-1}$		$1 \times 10^{-4} \text{ y}^{-1}$
Double containment	$1.25 \times 10^{-8} \text{ y}^{-1}$	$5 \times 10^{-8} \text{ y}^{-1}$	$1.25 \times 10^{-8} \text{ y}^{-1}$	$5 \times 10^{-8} \text{ y}^{-1}$		$1 \times 10^{-4} \text{ y}^{-1}$
Full containment	$1 \times 10^{-8} \text{ y}^{-1}$					
Membrane	see note					
In-ground		$1 \times 10^{-8} \text{ y}^{-1}$				
Mounded	$1 \times 10^{-8} \text{ y}^{-1}$					

The failure frequency of a membrane tank, determined by the strength of the secondary container, should be estimated case by case using the data on the other types of atmospheric tanks

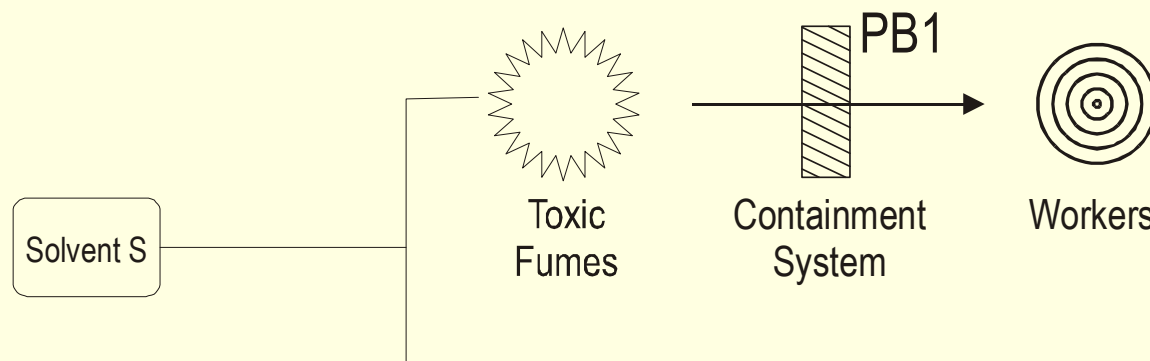


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Preventive and Mitigative barriers



Temperature control prevents the formation of toxic fumes

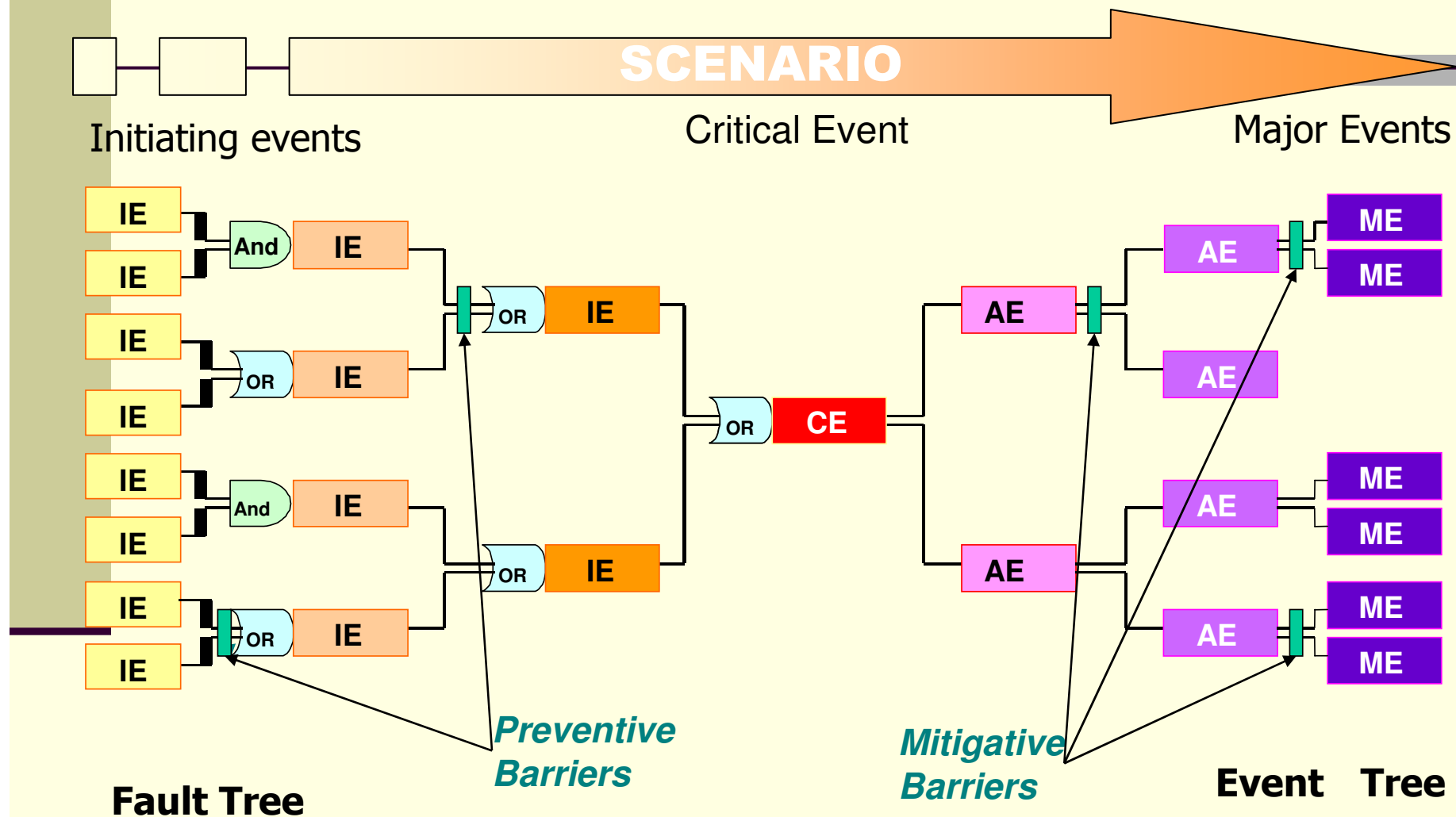


Containment reduces the expose of workers to the toxic fumes



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Bow-tie



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What are barriers?

- Barriers can be passive
 - *material barriers*: container, dike, fence,
 - *behavioural barriers*: Keep away from, do not interfere with
- Barriers can be active
 - Active barriers follow a sequence:
"Detect – Diagnose – Act"
 - Active barriers can consist of any combination of
 - Hardware
 - Software
 - Lifeware (human action, behaviour)



Examples of passive barriers

	Probability of Failure on Demand (PFD)
Dike	$10^{-2} - 10^{-3}$
Fireproofing	$10^{-2} - 10^{-3}$
Blast-wall or bunker	$10^{-2} - 10^{-3}$
Flame or Detonation arrestor	$10^{-1} - 10^{-3}$



Examples of active barriers

¹ IEC - International Electrotechnical Commission, develops electric, electronic and electrotechnical international standards	Probability of Failure on Demand (PFD)
Pressure relief valve	$10^{-1} - 10^{-5}$
Water spray, deluges, foam systems	$1 - 10^{-1}$
Basic Process Control System	$10^{-1} - 10^{-2}$
Safety Instrumented Function (SIF) - reliability depends on Safety Integrity Level (SIL) according to IEC ¹ 61511	SIL 1: $10^{-1} - 10^{-2}$ SIL 2: $10^{-2} - 10^{-3}$ SIL 3: $10^{-3} - 10^{-4}$

Human response as a barrier

- Responses can be skill-, rule-, and/or knowledge based
 - Skill based: routine, highly practiced tasks and responses
 - I.e. steering a car
 - Rule based: responses covered by procedures and training
 - I.e. obeying traffic rules
 - Knowledge based: responses to novel situations
 - I.e. finding the way to a new destination
- Skill- and rule based responses can be relatively fast and reliable, knowledge based responses are slow and not so reliable



Examples of human response barriers

	Probability of Failure on Demand (PFD)
Human action with 10 min. response time, simple, well documented action with clear and reliable indication that the action is required	$1 - 10^{-1}$
Human response to Control system warning or Alarm with 40 min. response time, simple, well documented action with clear and reliable indication that the action is required	10^{-1}
Human action with 40 min. response time, simple, well documented action with clear and reliable indication that the action is required	$10^{-1} - 10^{-2}$



The following are NOT barriers, but functions of Safety Management :

- Training and education.
 - provides the competence to respond properly
- Procedures
 - paperwork is not a barrier, only the response itself
- Maintenance and inspection
 - necessary to ensure functioning of primary barriers over time
- Communications and instructions

they influence barrier reliability a lot!



Risk management in Europe

- “*Generic distances*” based on environmental impact in general (noise, smell, dust, etc.).
- *Consequence based (“deterministic” or “Qualitative”)*
Safety distances are based on the extent of consequences (effects) of distinct accident scenarios (“worst case” or “reference” scenarios).
- *Risk based (“probabilistic” or “Quantitative”)*
Quantitative risk analysis (QRA) includes an analysis of all relevant accident scenarios with respect to consequences and likelihood (expected frequency), and results in calculated values of individual risk and societal risk, which can be compared with acceptance criteria.



Quantitative vs. qualitative risk analysis

- Identify all hazards
 - Select a large set of scenarios
 - Determine the expected frequency (likelihood) of all these scenarios
 - Determine the consequences of all these scenarios
 - Combine all these results (using wind direction statistics, etc) and calculate Individual Risk around the plant
 - Draw Individual Risk on map and compare with acceptance criteria
- Identify all hazards
 - Select a small set of scenarios with the largest consequences
 - Obtain some “feel” for the likelihood of these scenarios
 - Determine the consequences of these scenarios
 - Draw safety distances on a map



Qualitative=Consequence-based: advantages and disadvantages

- Analysis is (relatively) easy and fast
- Decision process is simple (either “safe” or “unsafe”)
- Results are easy to communicate (based on easy-to-understand accident scenarios)
- Selection of scenarios and assessment of “improbable = (?) impossible” accidents is often tacit or implicit.
- Can give a wrong impression of precision and safety
- Use of “worst case” scenarios leads to conservative results (expensive for society) (Results are determined by the worst-case – but unlikely accidents)
- Tendency to “forget” less severe scenarios in risk control and safety management



QRA=risk based: advantages and disadvantages

- Complete analysis, opportunity for setting priorities, focus on most “risky” items.
- Transparent (for experts?), both probabilities and consequences are included explicitly
- Results can be compared with criteria for risk acceptance
- Results for different types of facilities can easily be compared
- Not dominated by a single accident scenario – not sensitive for selection of scenarios
- Expensive and cumbersome analysis, which requires expert knowledge
- The “probabilistic” element in the result is hard to communicate
- Result suggests large accuracy, but it includes large uncertainty
- The presence of accept criteria (hard political decision) is necessary beforehand

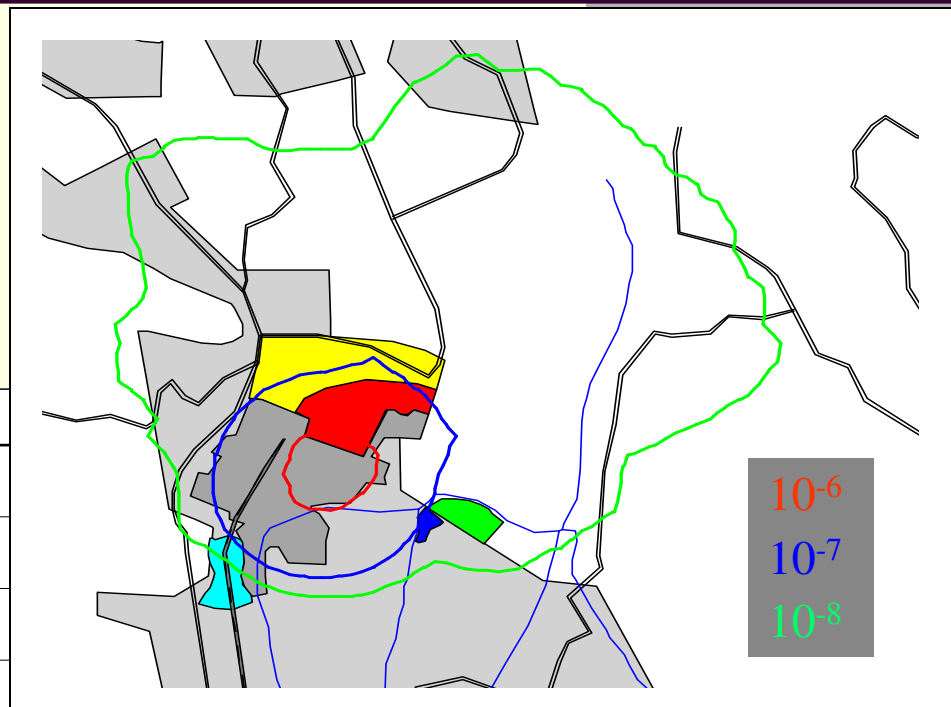
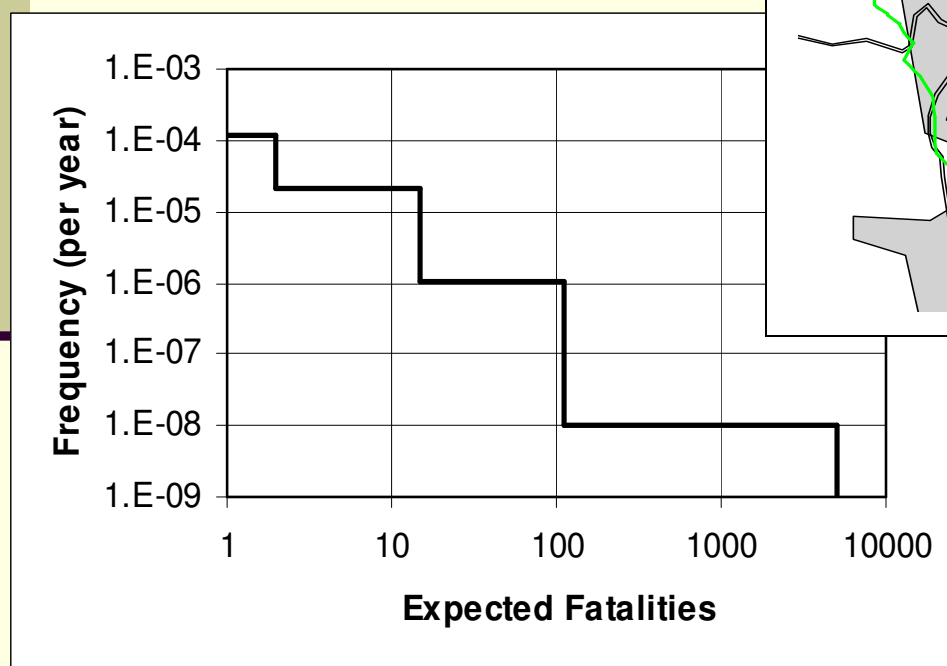


QRA - Probability assessment of scenarios

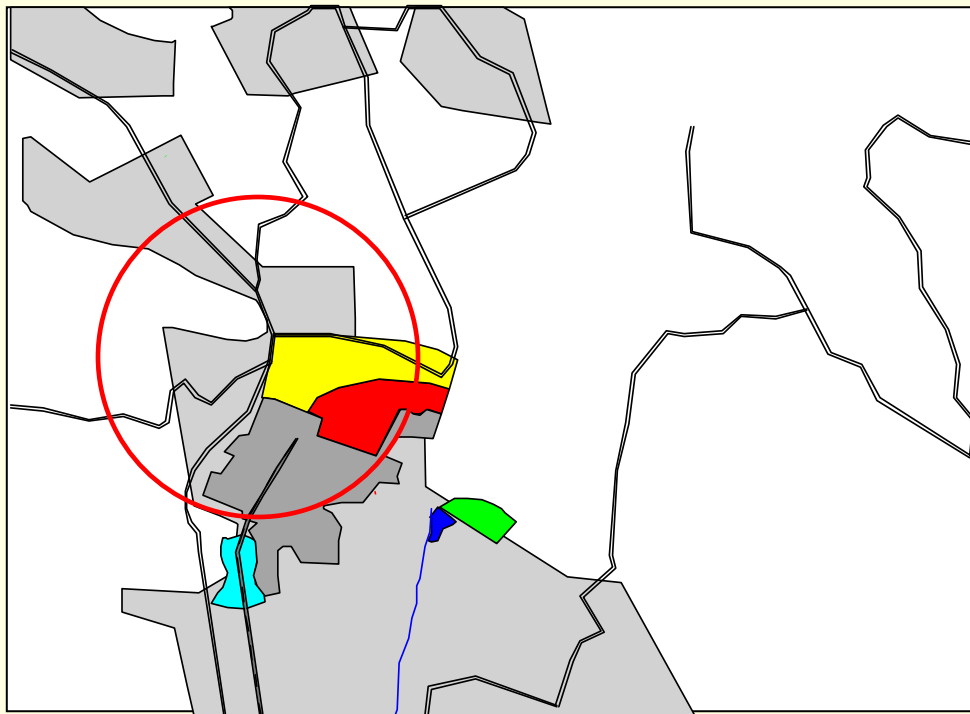
- Loss of Containment events (each of them happening with a certain likelihood) are developed into event trees (scenarios)
- Event trees identify the conditional probability of important conditions (ignition, wind direction)
- For **each** scenario, consequences are quantified (e.g. fatality rate foot print of a toxic cloud, i.e. probability of fatality at a position (x,y) for that scenario)
- For every point on the map (x,y), sum the contribution of **all** the scenarios to the risk at that point.



Results of QRA: Individual Risk and Societal Risk



Qualitative analysis – results: safety distance



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Qualitative analysis – results: risk matrix

	Severity			
Likelihood per year	Limited damage	Reversible damage	Severe (fatalities)	Catastrophe (off-site fatalities)
e-3				
e-4				
e-5				
e-6				
e-7				
e-8				



Acceptable

"ALARA", scenarios to be analysed on consequences

Unacceptable

Scenarios for consequence analysis are typically in the yellow zone

But don't forget to manage the scenarios in the green zone!

Is there a difference?

- Kirchsteiger (1999) concludes:

"... that there is neither a strictly deterministic nor a strictly probabilistic approach to risk analysis. Each probabilistic approach to risk analysis involves deterministic arguments, each deterministic approach includes quantitative arguments which decide how the likelihood of events is going to be addressed."



Risk acceptance

- For society's acceptance the following factors play a role:
 - Risk aversion
 - “Cost/benefit” and ALARA principle
 - The source of the risk: fatality risk in apartments is a factor 150 less acceptable than in traffic (Swedish study)
- Existing risk criteria are founded on comparison with general fatality risk (ca. 10^{-4} per year for young people) and the costs, society is willing to pay for saving a human life



Acceptance criteria

- For consequence-based method:
 - Highest likelihood of scenarios that cause significant consequences, typically between 10^{-7} and 10^{-9} per year
 - Scheme for the number of safety barriers depending on likelihood and severity (force scenario in the green or yellow part of the risk matrix)
- For risk-based method:
 - Individual Risk between 10^{-5} and 10^{-6} per year
 - Criterion for societal risk, e.g. Netherlands:
 $F < 10^{-3}/N^2$



Risk acceptance – final consideration

- Report on the inquiry of the Flixborough accident states:

“... for what is or is not acceptable depends in the end upon current social tolerance and what is regarded as tolerable at one time may well be regarded as intolerable at another.”

