Quantitative Risk Analyses in the Process Industries: Methodology, Case Studies, and Cost-Benefit Analysis

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Abstract…

This presentation demonstrates the quantitative risk analysis technique as applied to process industries, with references to several case studies. Demonstration of successful execution, how these studies assisted in reducing overall risk, and the cost-benefit aspect will be addressed.

Types of hazardous consequences which can contribute to overall risk will be outlined as well, including fire, toxic and explosive effects. The effect of likelihood is addressed in terms of mechanical failure rates, meteorological data, population densities and ignition probabilities.

Quantitative risk analysis is a widely accepted technique within the chemical and process industries. It has been adopted to form legislative requirements in many countries within Europe and Asia.

Quantitative risk analysis typically assesses the risk to society as a whole, or to individuals affected by process operations.

Contents…

History of QRA…

Early Development:

- Original technique pioneered in nuclear industry in 1960s
- Chemical & Process industry applications began in the late 1970s and early 1980s by HSE, UK (Canvey Reports) and Rijnmond Public Authority, Netherlands (Rijnmond Report)

Early Drivers:

- Flixborough, UK (1974, Vapor Cloud Explosion, 28 deaths)
- Seveso, Italy (1976, Toxic Gas Cloud, 0 deaths)
- Bhopal, India (1984, Toxic Gas Cloud, 4000 deaths)
- Mexico City, Mexico (1984, Vapor Cloud Explosion, BLEVE, 650 deaths)

Basics of QRA…

Two main ways to classify process risk:

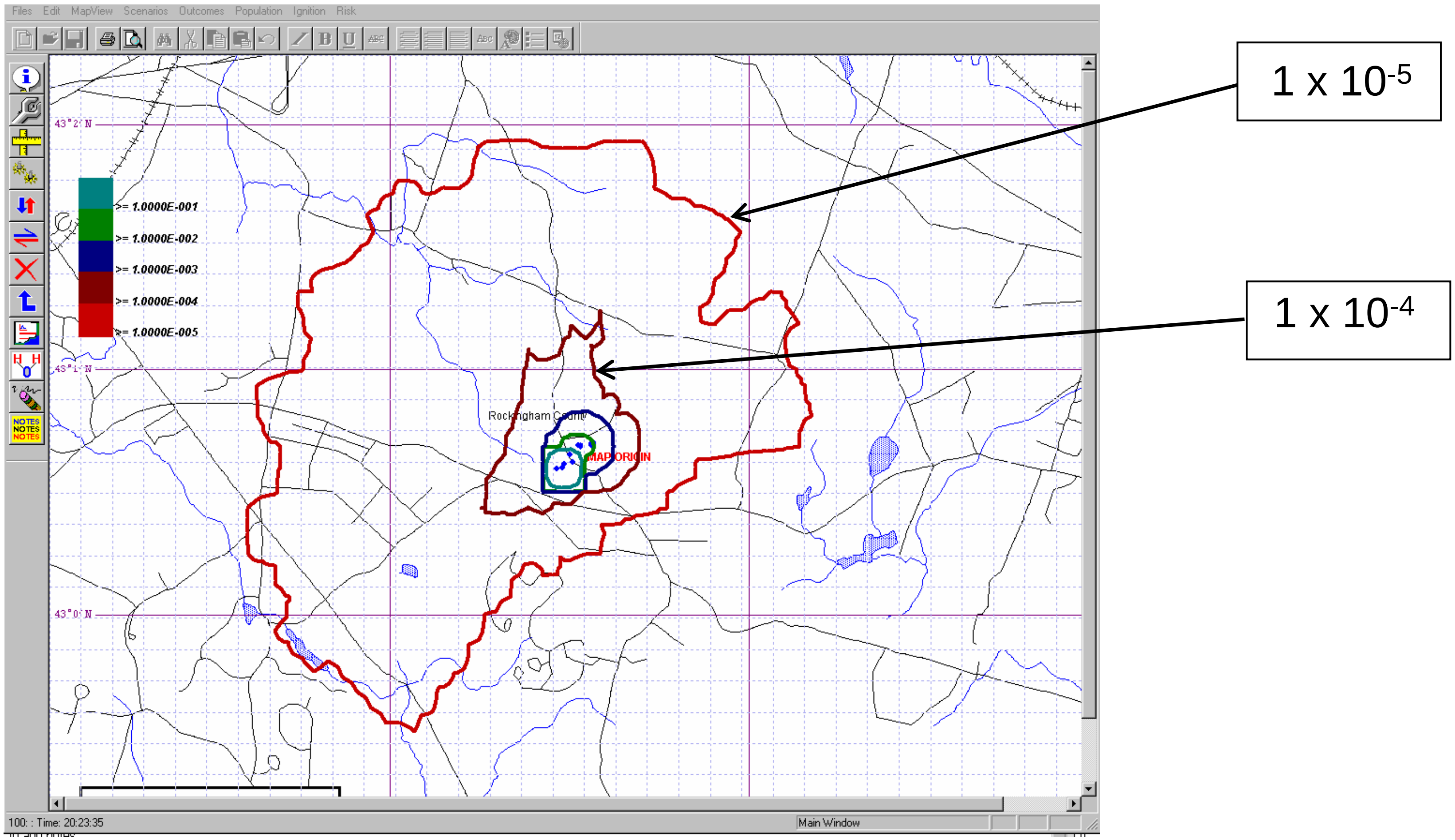
Individual Risk:

"Individual Risk is the risk of some specified event or agent harming a statistical (or hypothetical) person assumed to have representative characteristics." - HSE, 1995

- Typically assumes recipient is outside 24 hours per day
- Assumes no protective action is taken
- Does not take into account actual population present
- Results typically given as likelihood of death (or dangerous dose) per year
- Useful in facility siting, and land use planning

Basics of QRA…

Individual Risk Contour plot generated using SuperChems™:



Basics of QRA…

Two main ways to classify process risk:

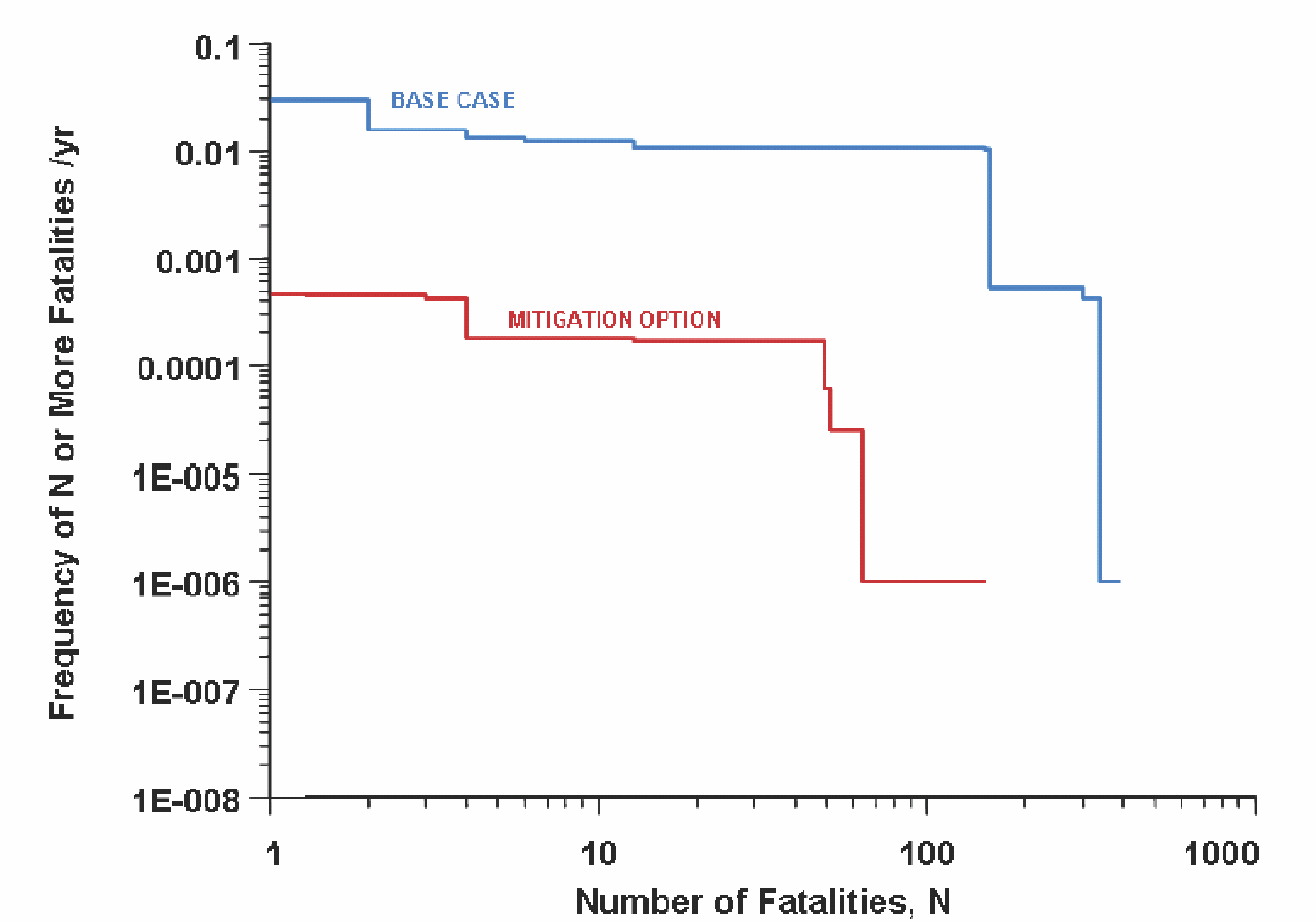
Societal Risk:

"Societal Risk is the risk of widespread or large scale detriment from the realisation of a defined hazard." - HSE, 1995

- Takes into account actual population present
- Shows frequency (F) of accidents involving N or more fatalities (F-N plot)
- Can be presented as a single number: Average Rate of Death (ROD), or Potential Loss of Life (PLL)
- Technique can be modified to show financial risk rather than fatality risk

Basics of QRA…

Societal Risk as shown on a F-N plot generated using SuperChems™:



Acceptance of QRA…

Changing attitudes to Chemical & Process QRA….

1980: Major Oil Company Representative

> *"QRA is equivalent to counting the number of angels that can stand on the head of a pin. It can be concluded that risk analysis is likely to be a waste of time if applied to chemical processes."*

1993: Major Oil Company Risk Engineering Standard

> *"QRA is a tool which helps translate hindsight (accidents) into foresight (planning)…showing ways and means (improved engineering, procedures and supervision) to prevent the calculated accidents from happening."*

Source: "QRA: Alchemy to Acceptability" Conference, London, 1993

QRA in practice…

Countries using QRA-related regulations:

- United Kingdom
- Netherlands
- Australia
- Belgium
- Norway
- Sweden
- Malaysia
- Hong Kong
- Switzerland
- Singapore

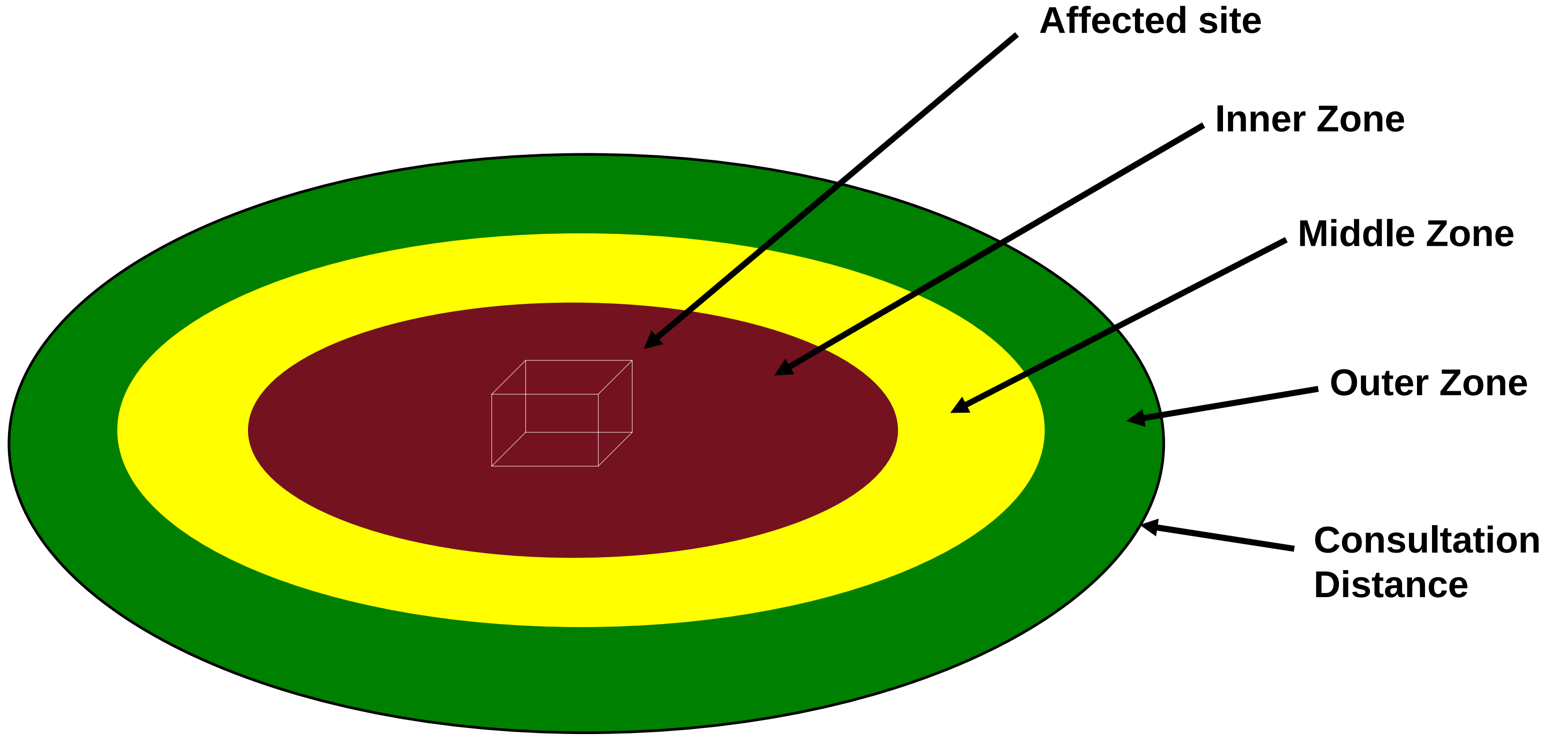
Other countries are considering applying risk-related legislation.

Most major operating companies throughout the world performing QRA to internal standards.

Some countries still wary of risk-related legislation for legal reasons.

UK legislation…

How QRA legislation is applied within the UK:



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UK legislation…

How QRA legislation is applied within the UK:

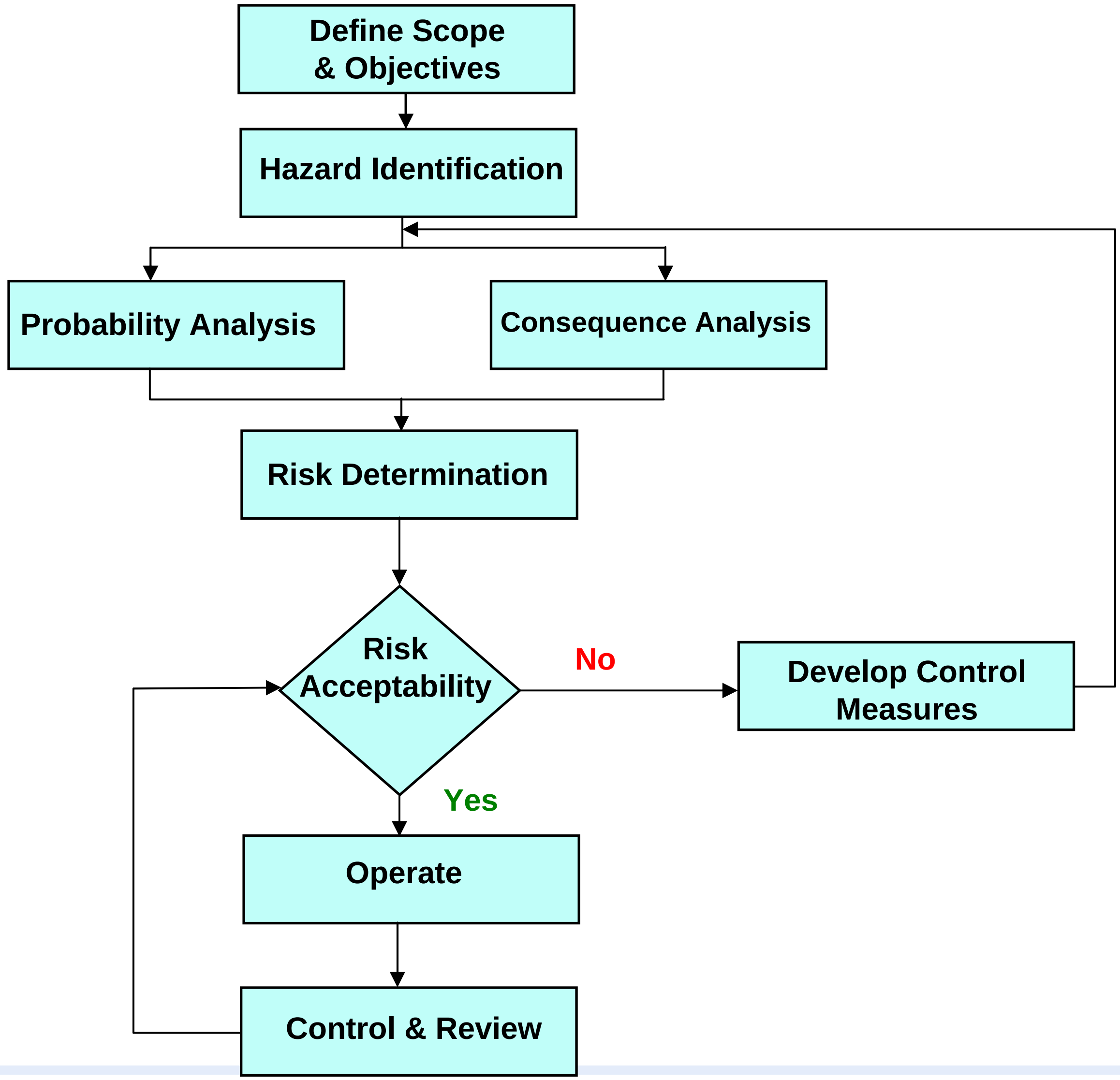
HSE considers three hazard zones: Inner, Middle, Outer

- Inner Zone: 10 chances per million (cpm) per year, of receiving a dangerous dose
- Middle Zone: 1 chance per million per year, of receiving a dangerous dose
- Outer Zone: 0.3 chances per million per year, of receiving a dangerous dose

Where a dangerous dose would lead to:

- Severe distress to all
- A substantial number requiring medical attention
- Some requiring hospital treatment
- Some (about 1%) fatalities

QRA methodology…



Hazard Identification…

Commonly applied techniques of hazard identification:

- Hazard & Operability Study (HAZOP)
  - Most rigorous technique for process industries
  - Uses systematic guidewords to identify deviations from normal operation
- Failure Mode Effect Analysis (FMEA)
  - Well suited to electrical and mechanical failures
- What-If Analysis
  - Broader scope than HAZOP
  - Uses checklist technique
- Preliminary Hazards Analysis
  - Broad overview of potential hazards
  - Identify hazards early on in design stage

Hazards…

What constitutes a hazard:

- Flammable hazards
  - **Jet Fire**
  - **Pool Fire**
  - **Flash Fire**
  - **BLEVE (Boiling Liquid Expanding Vapor Explosion)**
- Explosive hazards
  - **Confined Vapor Cloud Explosion**
  - **Unconfined Vapor Cloud Explosion**
  - **Dust Explosion**
  - **Runaway Reaction**
- Toxic Gas Dispersion hazards

Hazard Identification…

A thorough hazard identification is essential for the overall study to be successful:

"Are we sure that we have identified all the major hazards and all the ways they can occur?....

What has not been identified can neither be assessed nor mitigated…."

- Trevor Kletz

Consequence Modeling…

Now that the hazards are identified, what are the consequences?

Consequence Modeling…

Stages involved:

Discharge

Storage conditions, flow rate, composition, phase, release type (leak, line rupture), release duration, orientation

↓

Dispersion

Weather conditions, topographical conditions, release composition, orientation, concentrations of interest

↓

Consequences

Flammable, Explosive, Toxic

Consequence Modeling…

Flammable consequences:

BLEVE

(Boiling Liquid Expanding Vapor Explosion)

- **Failure of pressure vessel containing pressurised liquid**
- **Pressure drop causes violent boiling, rapid expansion and vaporisation**
- **Typically occurs due to external heat source from other process emergency (e.g. jet fire) impinging on vessel**
- **Flammable liquids lead to fireball**
- **Flame spreads through 360°**
- **Can occur with non-flammable liquids, e.g. steam explosion**

Consequence Modeling…

Flammable consequences:

Jet Fire

- Pressurised release of flammable liquid or vapor
- Intentional (flare)
- Accidental (leak, relief valve)
- Jet is pointed in one direction
- Can be affected by wind

Consequence Modeling…

Flammable consequences:

Pool Fire

- Flammable liquid spilled on land / water
- Storage tank roof fire
- Confined area (tank size, or containment bund), or unconfined
- Heavier hydrocarbons burns with smoky flame, light hydrocarbons burns with much brighter flame

Flammable Criteria…

Flammable consequences:

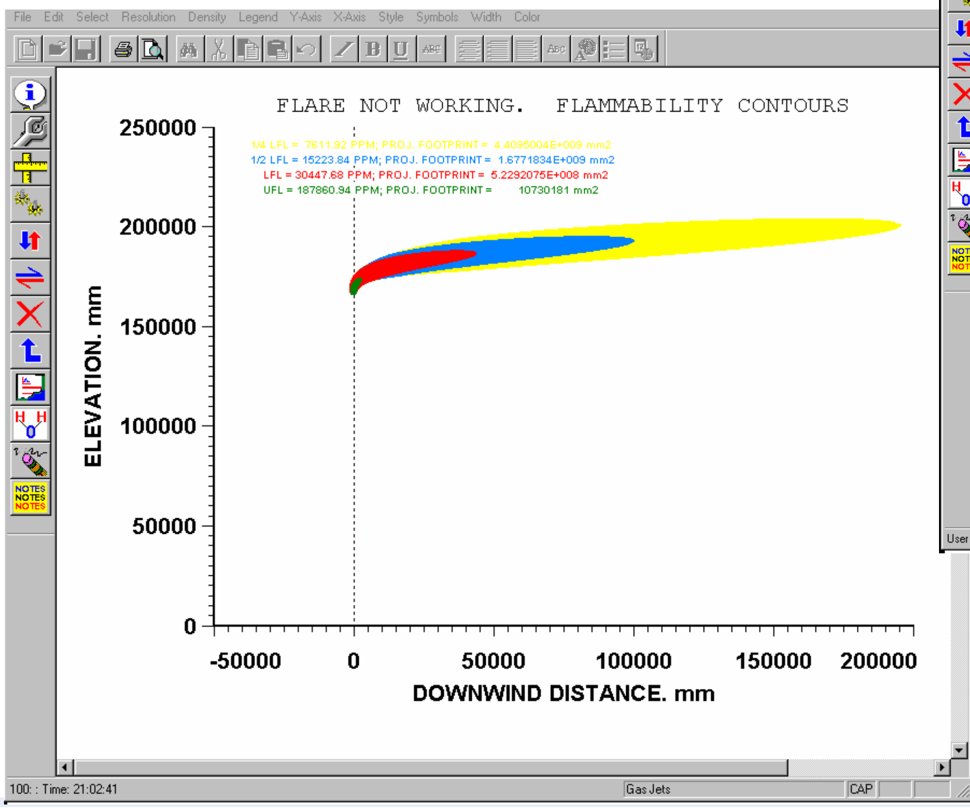
Radiation Intensity (kW/m^2)	Observed Effect (Source: World Bank)
37.5	Sufficient to cause damage to process equipment
12.5	Minimum energy for piloted ignition of wood, melting of plastic tubing
4	Sufficient to cause pain to personnel if unable to reach cover within 20 seconds
1.6	Will cause no discomfort for long exposure

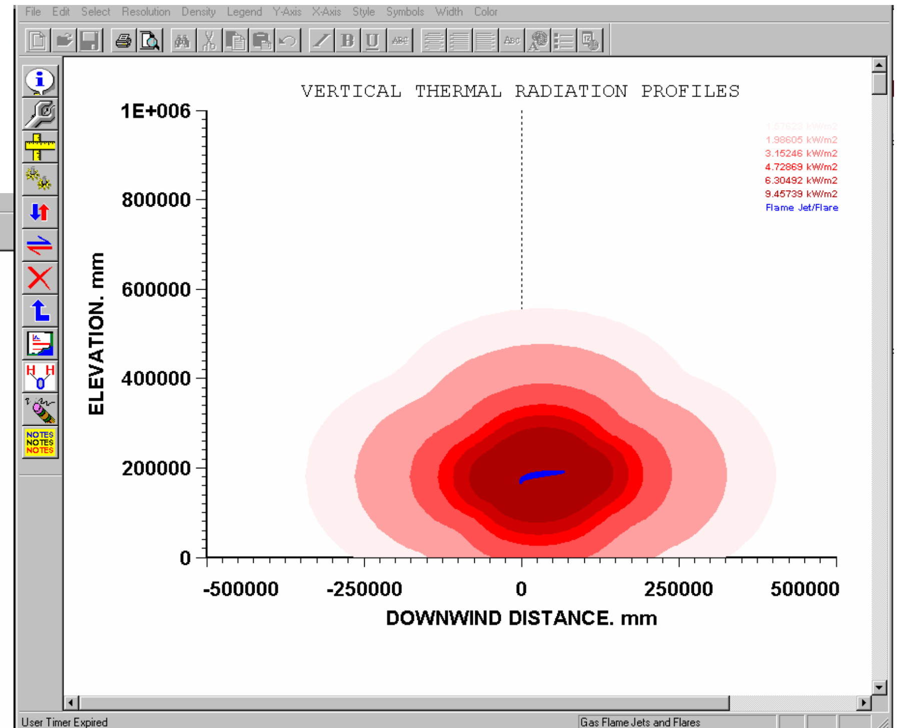
Normal Sunny day = 1 kW/m^2

Exposure time of 20 seconds is usually used for affected personnel

Consequence Modeling…

Flammable consequences:





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Consequence Modeling…

Explosion consequences:

Flixborough, UK 1974

Consequence modeling…

Explosion consequences:

- **Flammable vapor cloud which is within the flammable limits of the fluid**
- **Explosions can be confined or unconfined**
- **Confined explosions are far more hazardous**
- **Degree of confinement increases flame speed**
- **Air burst or ground burst depending on cloud buoyancy**

Explosion Criteria…

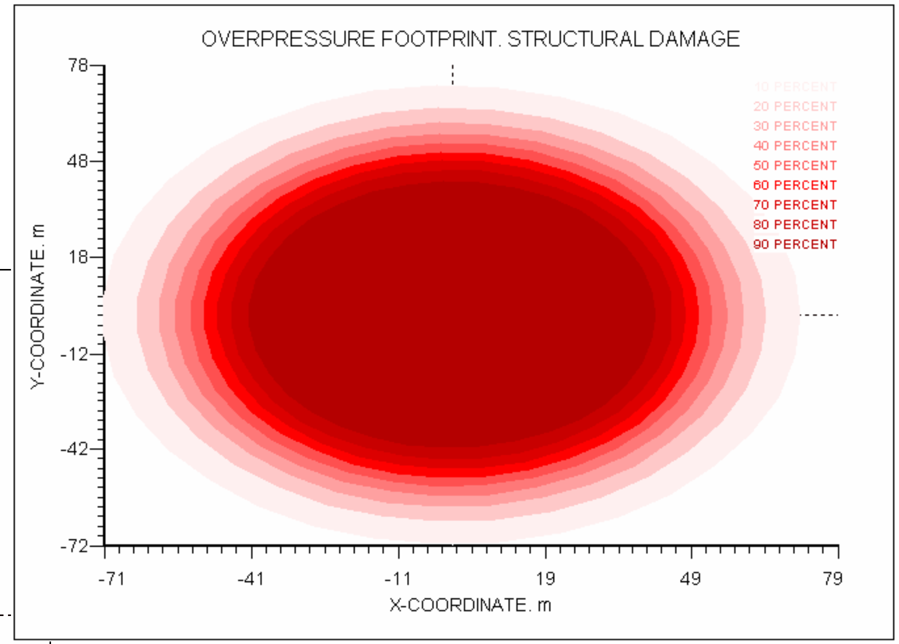
Explosion consequences:

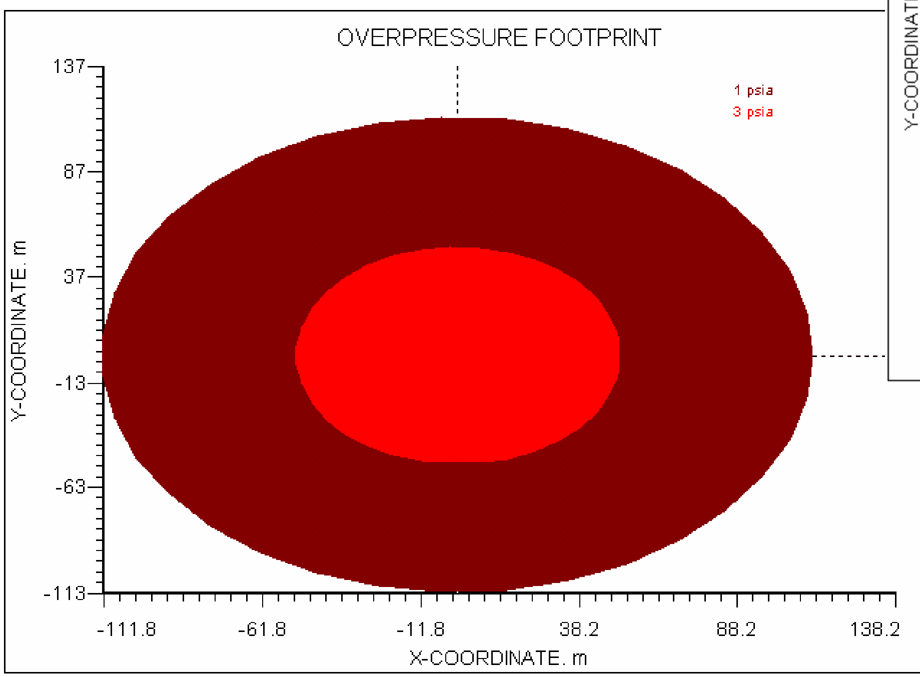
Pressure (psig)	Damage (Source: Clancy)
0.3	"Safe Distance", some damage to roofing, 10% of windows broken
1.0	Partial demolition of houses
3.0	Steel frame buildings distorted and pulled away from foundations
10	Probable total destruction of buildings

Normal Atmospheric Pressure = 14.7 psi

Consequence Modeling…

Explosion consequences:





Consequence Modeling…

Toxic consequences:

Consequence Modeling…

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Toxic consequences:

Consequence Modeling…

Toxic consequences:

Toxicity varies from chemical to chemical

Different methods to categorise toxic effect:

- Emergency Response Planning Guidelines (ERPG) (60 minutes)
  - ERPG 1 – Mild effects, objectionable odor
  - ERPG 2 – Serious health effects
  - ERPG 3 – Life threatening health effects
- Immediately Dangerous to Life and Health (IDLH) (30 minutes)
- Short Term Exposure Limit (STEL) (15 minutes)
- Probit (dependent on dose)

Toxic Criteria…

Toxic consequences:

Sample ERPG values:

Chemical	ERPG1 (ppm)	ERPG2 (ppm)	ERPG3 (ppm)
Ammonia	25	150	750
Chlorine	1	3	20
Hydrogen Sulphide	0.1	30	100
Methyl Isocyanate	0.025	0.25	1.5
Phosgene	N/A	0.2	1

Source: American Industrial Hygiene Association

Consequence Modeling…

Toxic consequences:

Probit Equation

$$Pr = a + b \ln (C^n \times t)$$

Where: *Pr= probit*

C= concentration of toxic vapor in the air being inhaled (ppm)

t= time of exposure (minutes) to concentration C

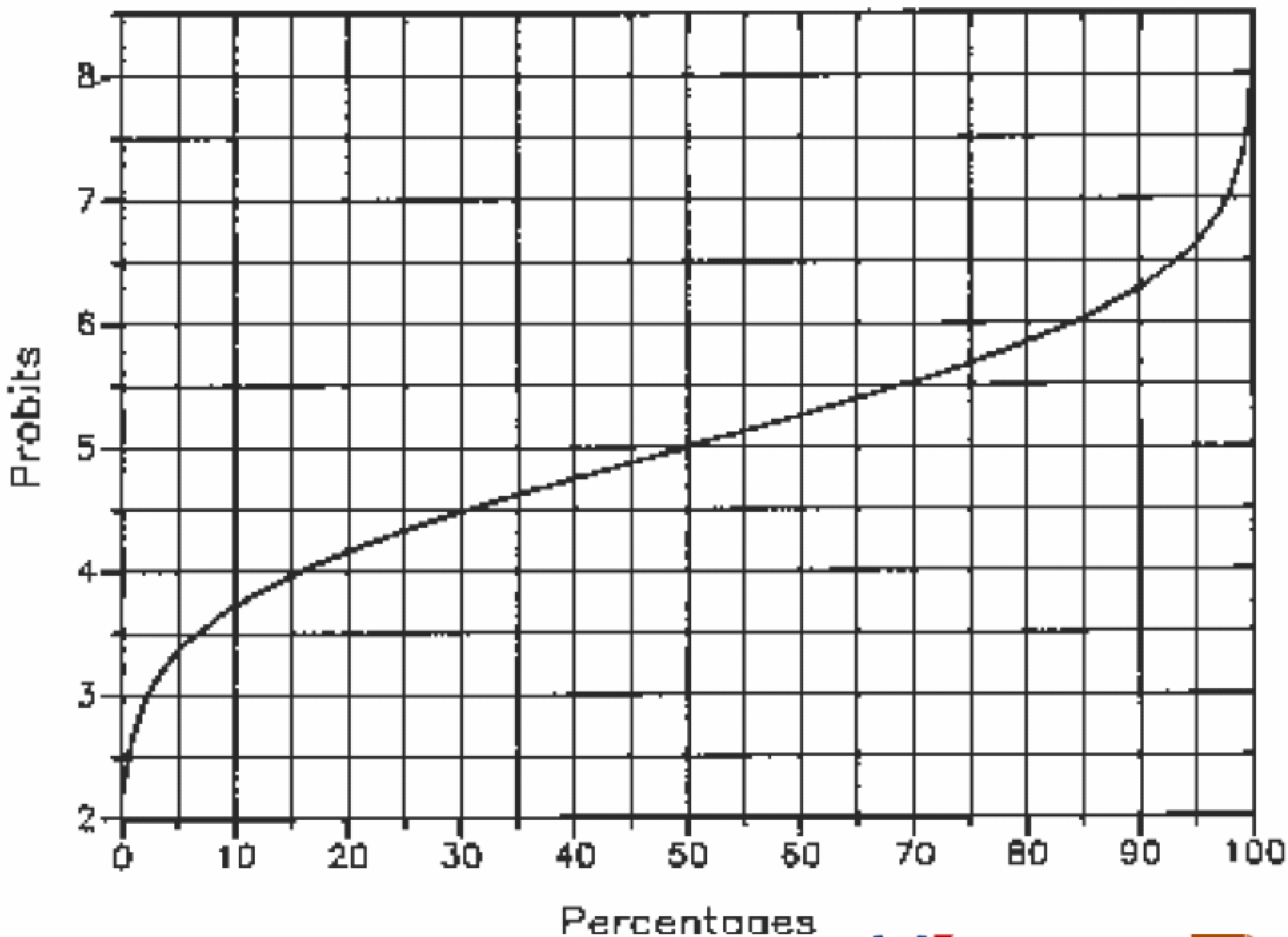
a,b, and n= Probit constants

$C^n \times t$ *= dose*

Probit technique can also be applied to flammable and explosive exposure.

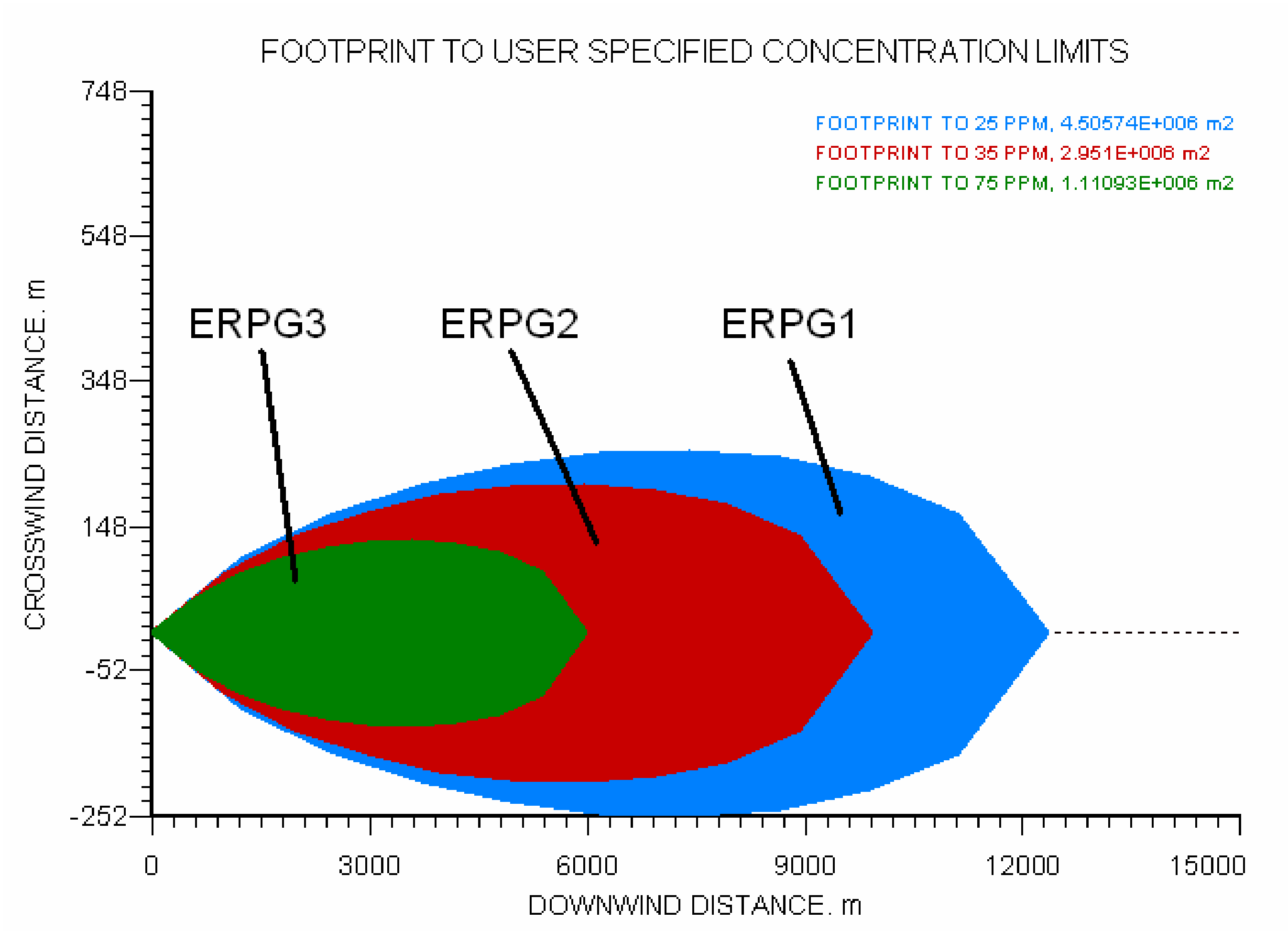
Consequence Modeling…

Toxic consequences:



Consequence Modeling…

Toxic consequences:



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Consequence Modeling…

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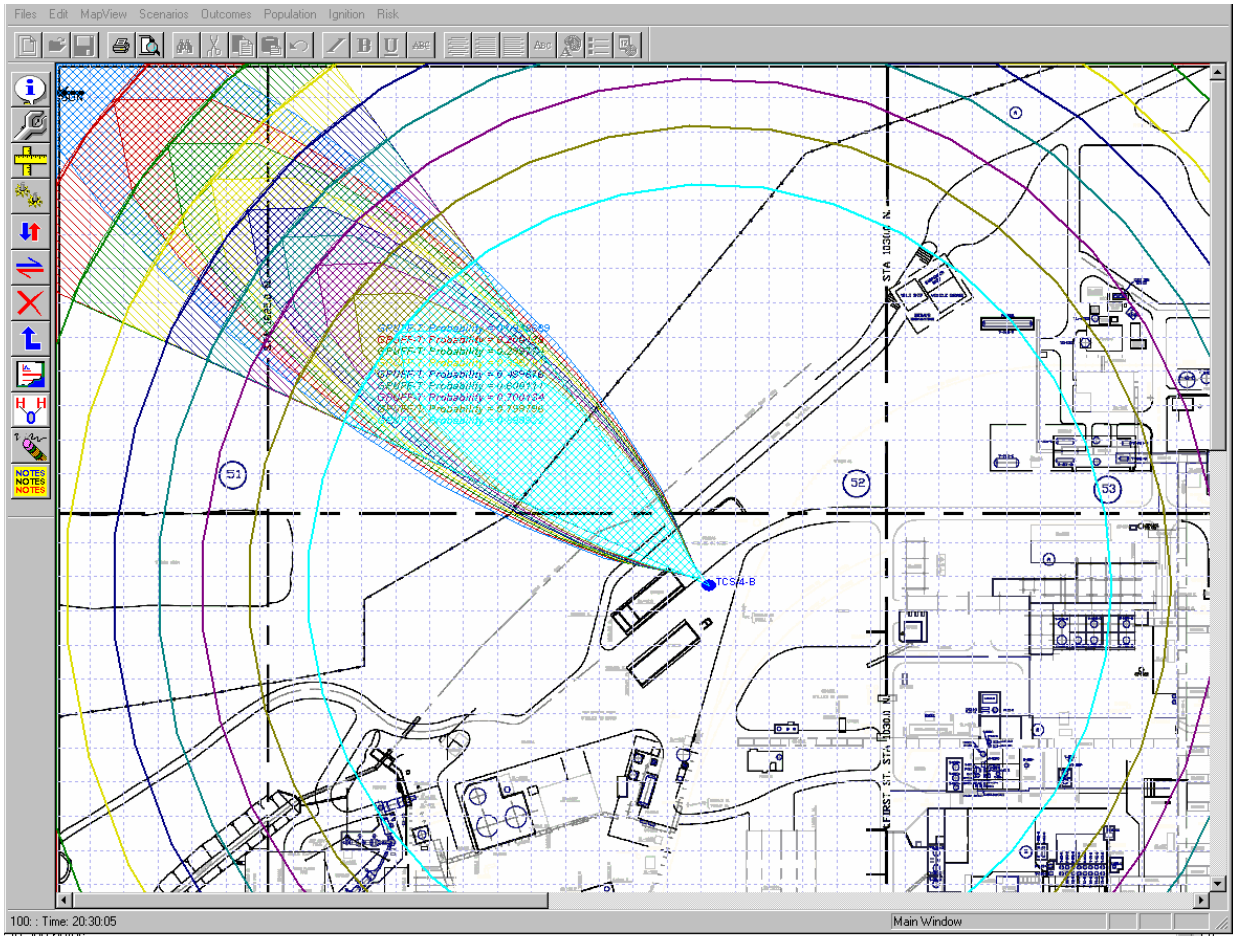

Probability Analysis

- **Introduction**
- **Method**
- **Models**
- **Uncertainties**

QRA as a concept requires that both the probabilities and the consequences has to be quantified

R = p 3 c

Method

1. Organize an analysis group
2. Perform a HAZOP or What-if analysis that gives you the significant scenarios
3. Develop your Decision Tree
4. Analyse the significant scenarios in more detail using e.g. Precision Tree and @Risk
5. The results (probabilities) are then used for calculating the resulting risk and for the CBA

@Risk methodology

1. **Develop a Model** - First, define your problem or situation in a spreadsheet format.
2. **Identifying Uncertainty -** Next, determine which inputs in your model are uncertain, and represent those using ranges of values with @RISK probability distribution functions. Identify which result or output of your model you want to analyse.
3. **Analysing the Model with Simulation -** Run your simulation to determine the range and probabilities of all possible outcomes for the outputs you have identified.
4. **Make a Decision** - Armed with complete information from your analysis, policy and your personal preferences, make your decision.

Method – The Ten Commandments

1. Do your homework with literature, experts and users!
2. Let the problem drive the analysis!
3. Make the analysis as simple as possible, but no simpler!
4. Identify all significant assumptions!
5. Be explicit about decision criteria and policy strategy!
6. Be explicit about uncertainties!
7. Perform systematic sensitivity and uncertainty analysis!
8. Iteratively refine the problem statement and analysis!
9. Document clearly and completely!
10. Expose to peer review!

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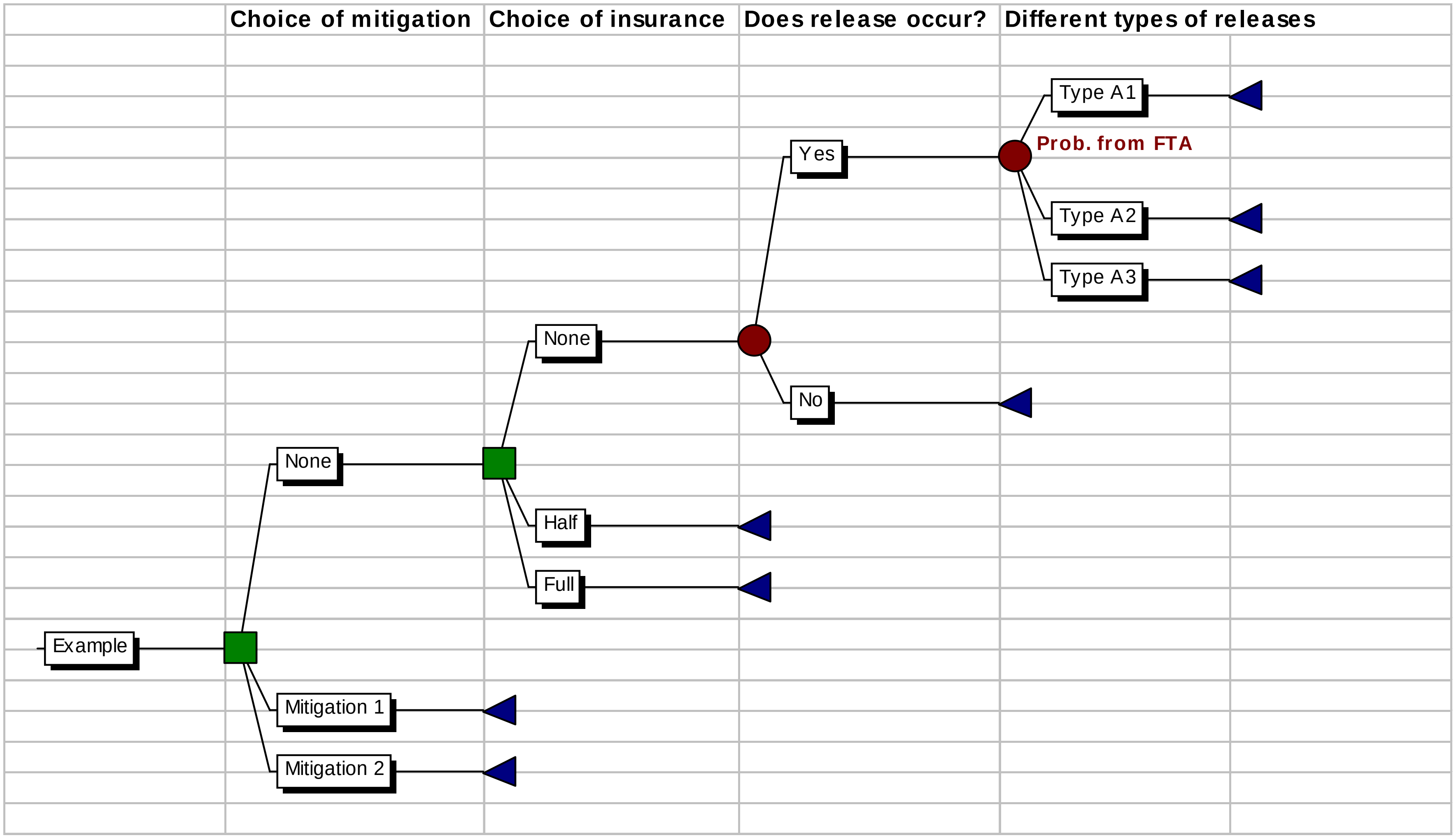
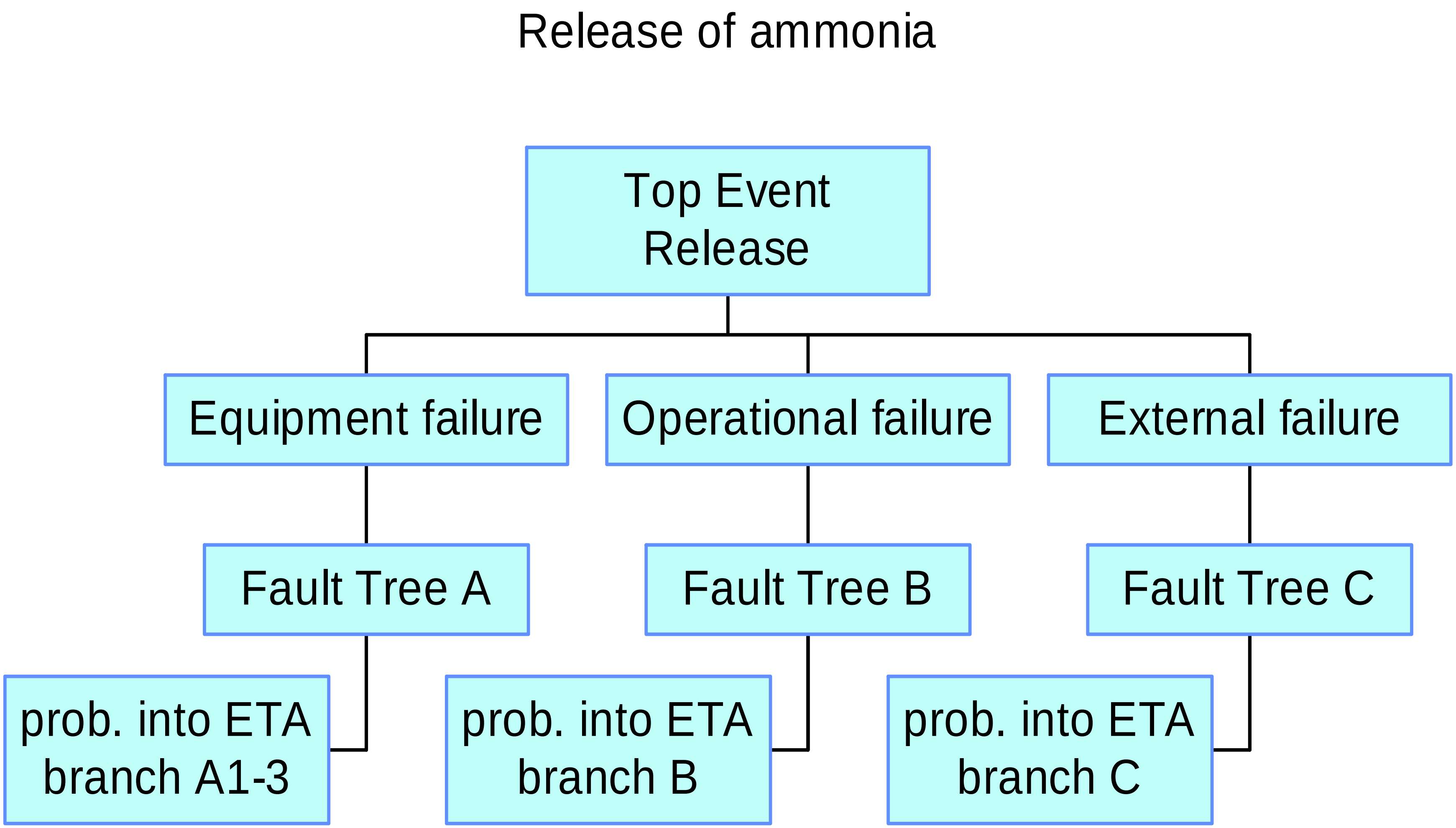
Models

- **Hazard and operability analysis (HAZOP)**
  - Qualitative method used to systematically identify hazards by the use of ”key words”.
- **What-if analysis**
  - Qualitative method used to systematically identify hazards by the use of the question ”what if…?”.

Decision Tree

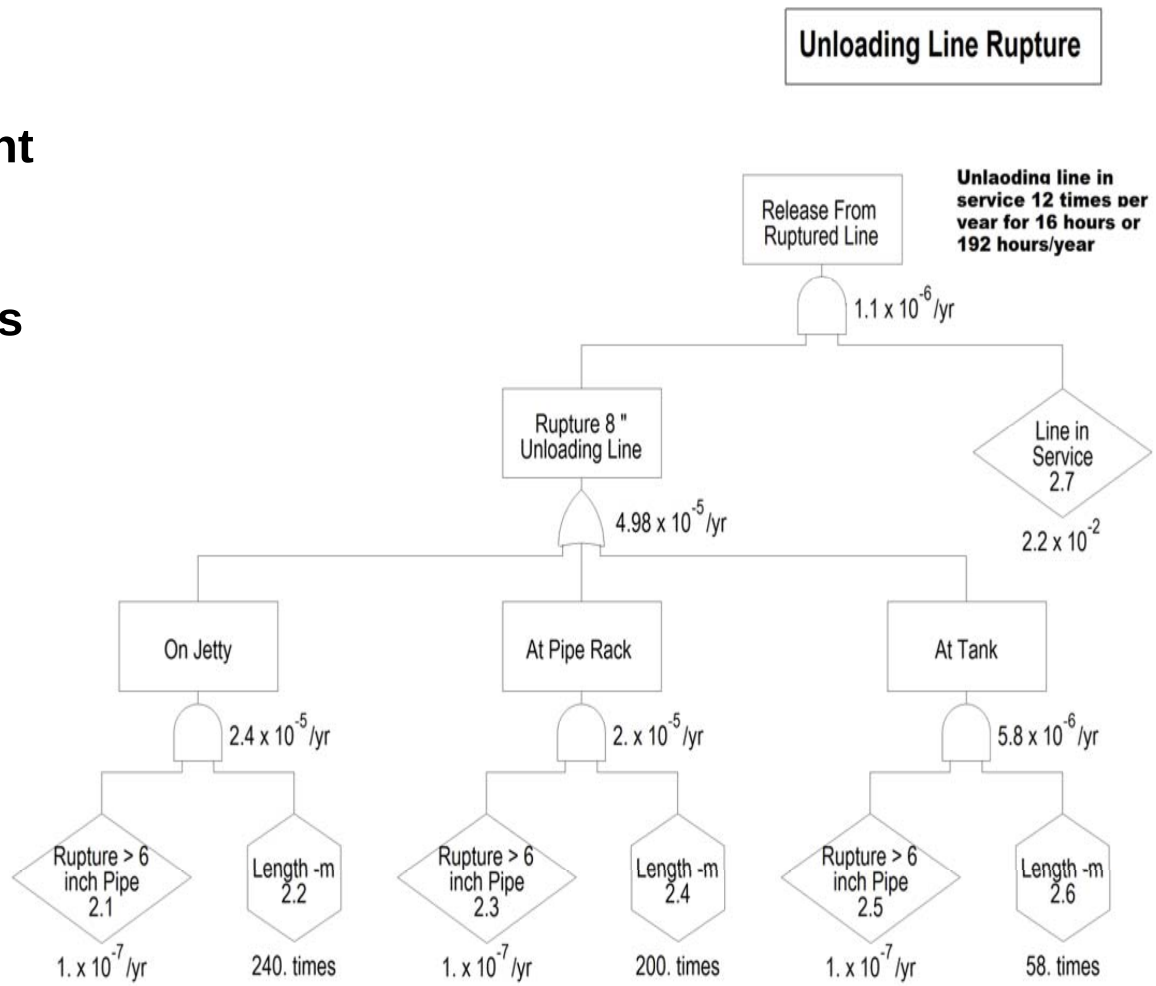


Fault Tree Analysis (FTA)

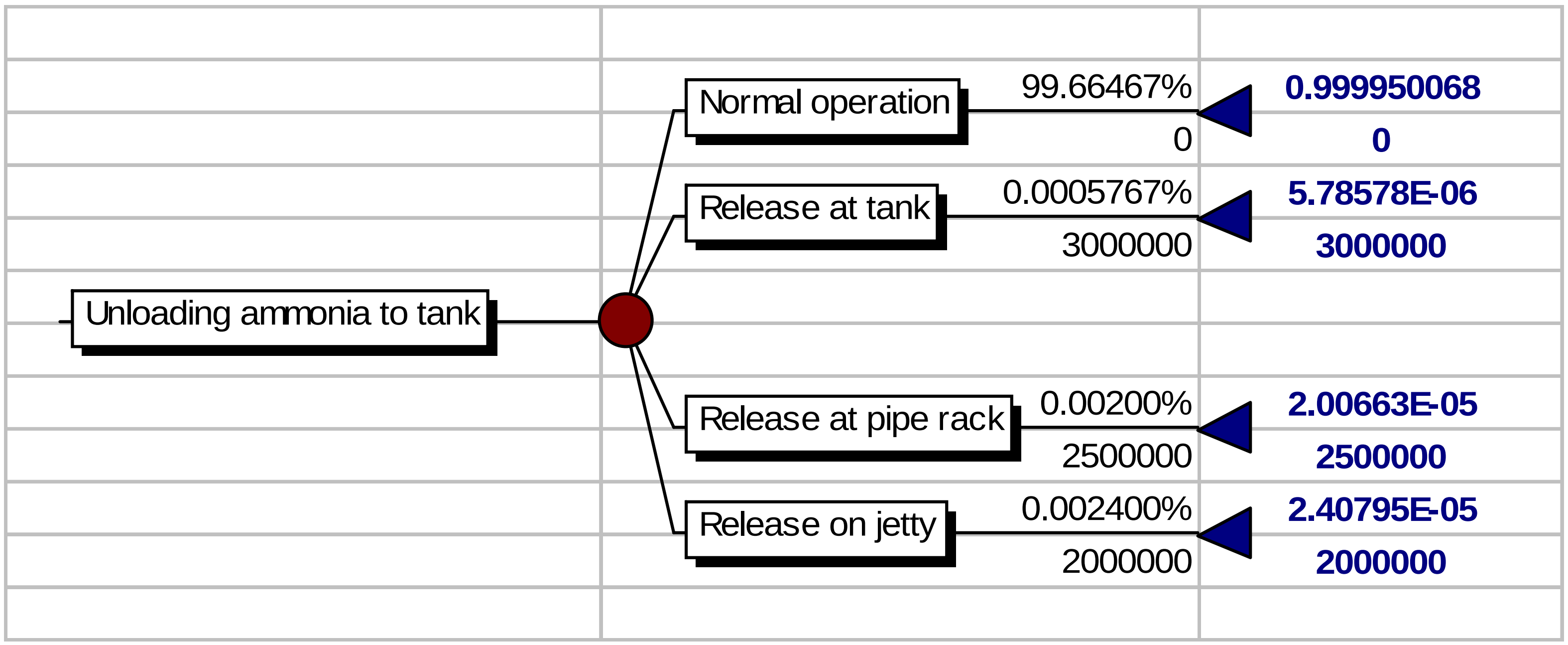


Example of a FTA

- **FTA of equipment failure**
- **The probability is used in the ETA**



Event Tree Analysis (ETA)



Part of the decision tree

Models

- **Fault Tree Analysis (FTA)**
  - Quantitative method assisted by logical diagrams that identifies which human errors and technical failures that leads to a specific Top Event (e.g. Release)
- **Event Tree Analysis (ETA)**
  - Quantitative method assisted by logical diagrams that identifies all chains of events that can occur due to a specific start event. ETA can also be used to quantify the probability for such an event.

Uncertainties

- Your inputs are most certainly going to be uncertain!
- With the use of @Risk you should express your probabilities as functions instead of fixed values.
- Furthermore you should use sensitivity analysis in order to address this issue.

Uncertainties

Where can I find information about the probabilities for specific events?

- Previous analysis
- Experts within the specific area
- Literature
- Statistics

It's up to you to decide how reliable (uncertain) the information you find is!

Risk Mitigation…

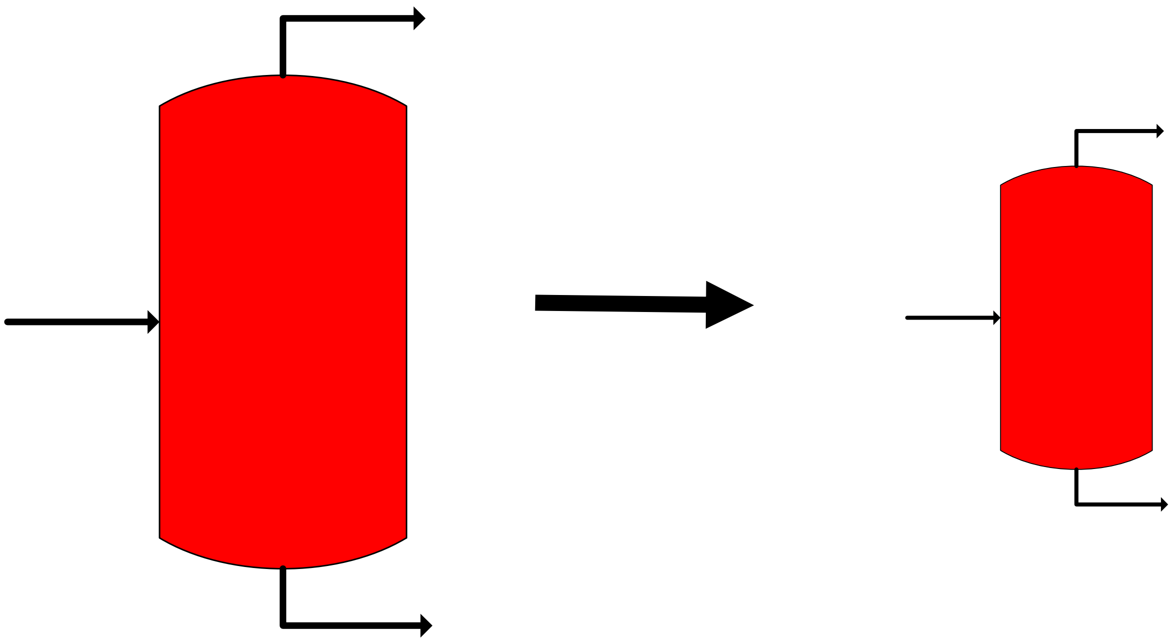
Four Main Approaches (Inherent Safety):

- Reduction
- Substitution
- Moderation
- Simplification

Risk Mitigation…

Four Main Approaches (Inherent Safety):

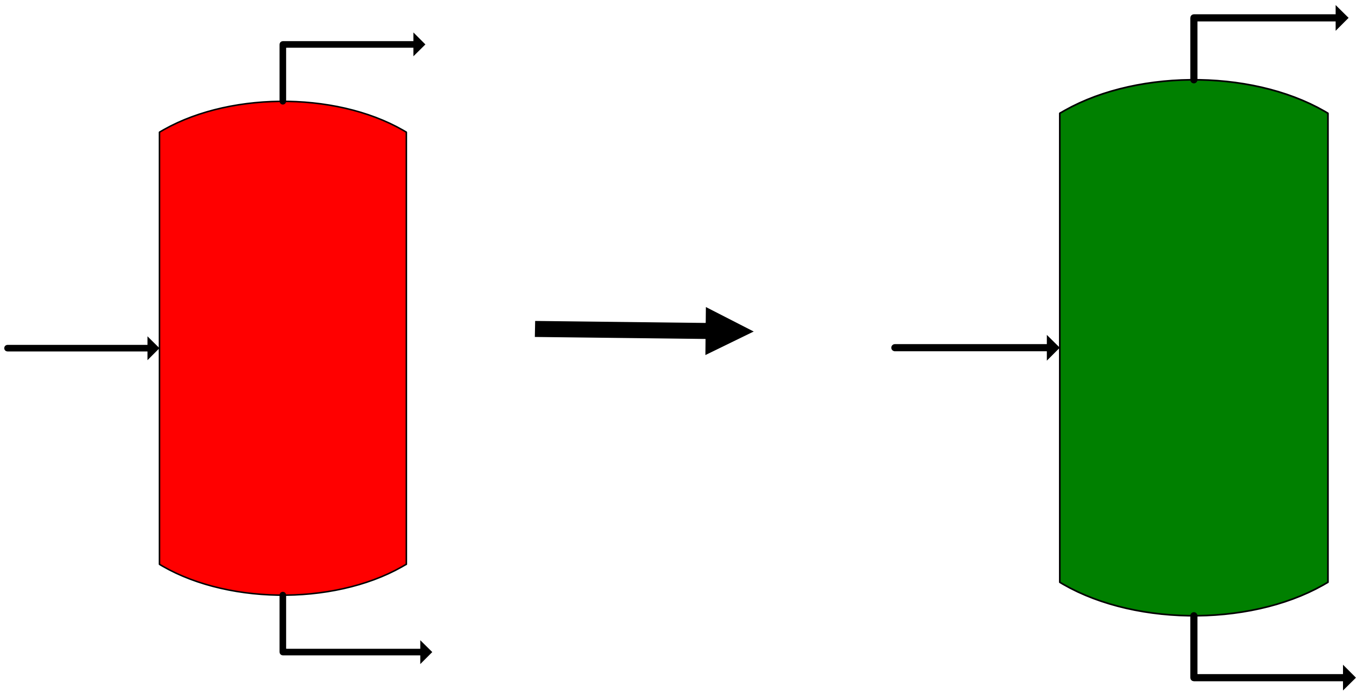
- Reduction - reduce the hazardous inventories



Risk Mitigation…

Four Main Approaches (Inherent Safety):

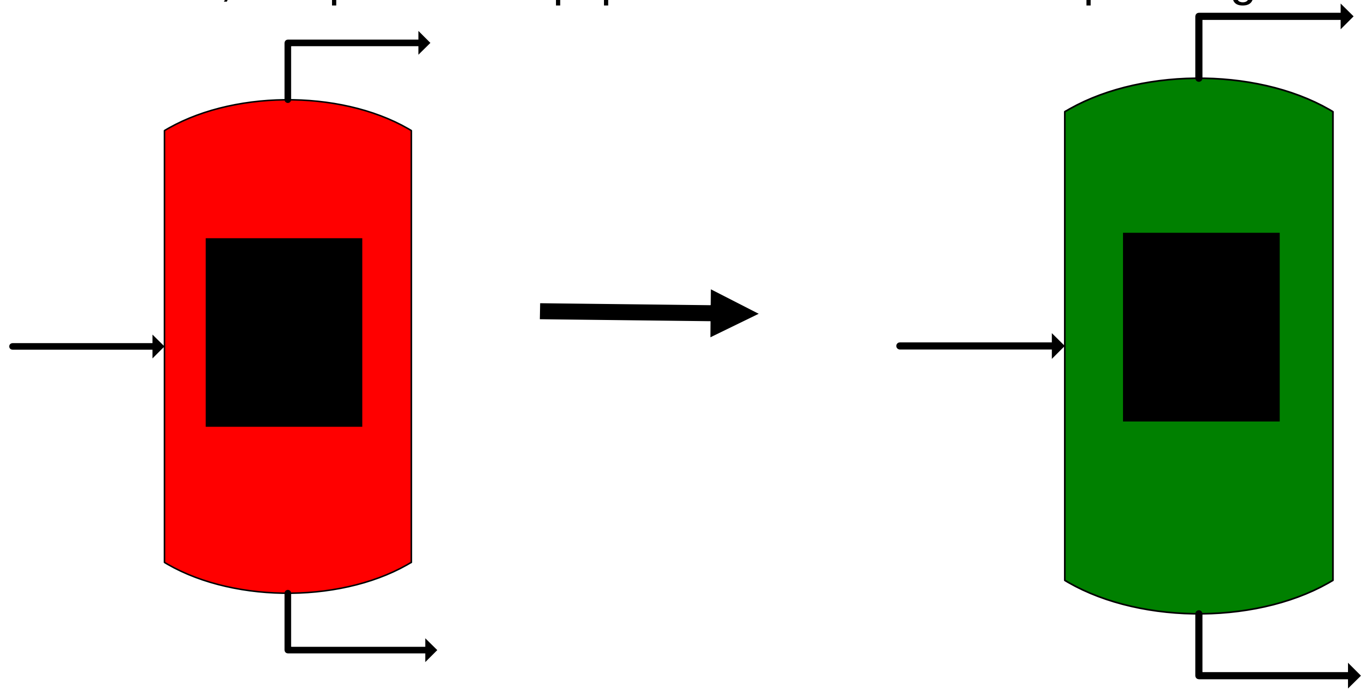
- Substitution - substitution of hazardous materials with less hazardous ones



Risk Mitigation…

Four Main Approaches (Inherent Safety):

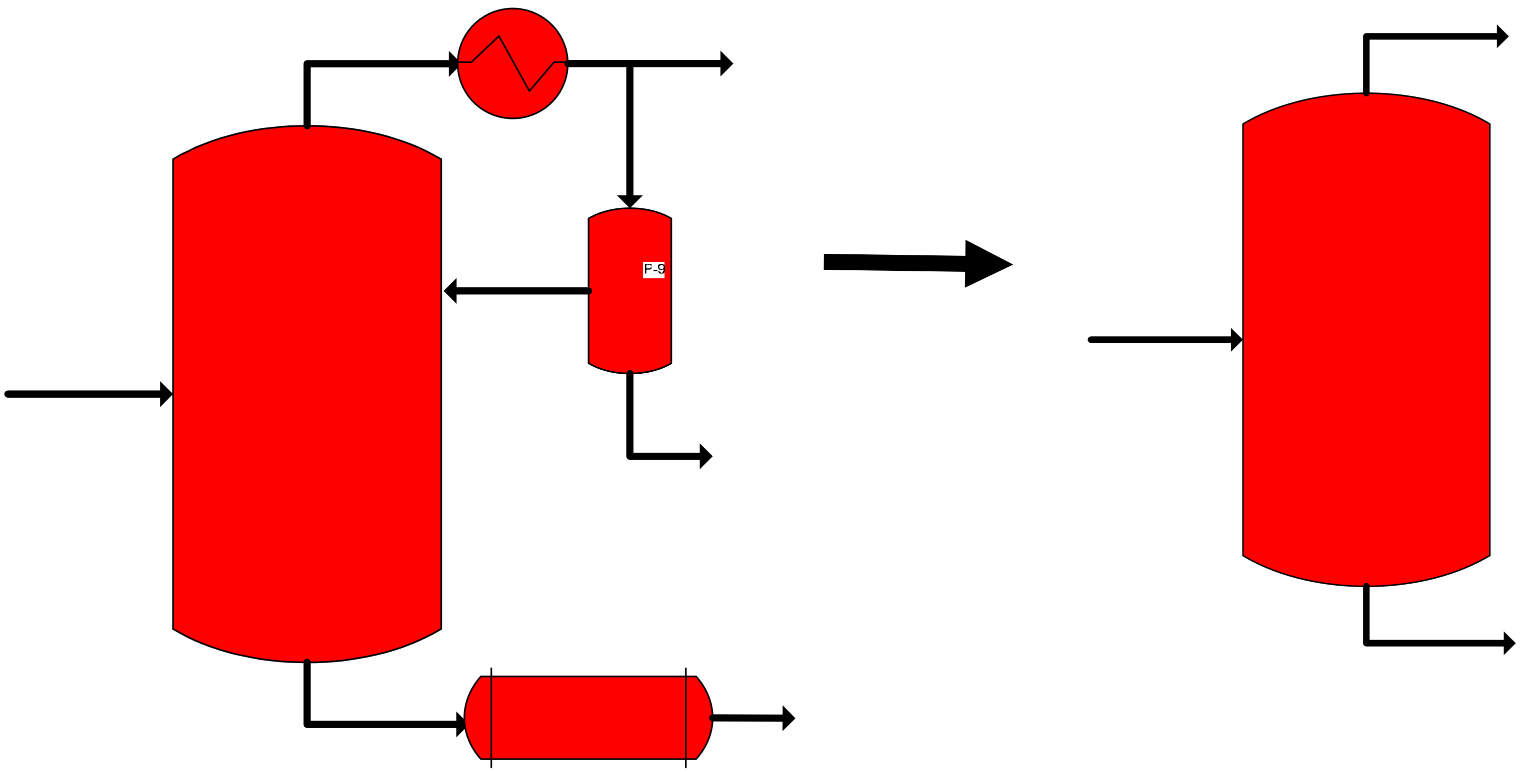
- Moderation - use hazardous material in their least hazardous forms e.g. dissolved in solvent; run process equipment at less severe operating conditions



Risk Mitigation…

Four Main Approaches (Inherent Safety):

- Simplification - make the plant and process simpler to design, build and operate; hence less susceptible to equipment, control or human error



Risk Mitigation…

Consequence Reduction:

- Installation of remote operated valves, for inventory isolation
- Use minimum pipe sizes to minimise potential release rate, in the event of pipe failure
- Reduce the severity of process conditions
- Utilise emergency blowdown / flare systems to divert hazardous inventories to a safe location
- Use water or foam systems to contain or control fires
- Use steam or water curtains to help dilute toxic gas releases

Risk Mitigation…

Consequence Reduction:

- Use fire protection insulation, and blast walls to protect equipment
- Facility siting can locate hazardous inventories away from main operating areas, or areas of population
- Secondary containment – equipment containing highly toxic materials can be located in buildings which can be sealed to the atmosphere

Risk Mitigation…

Likelihood Reduction:

- Use of less corrosive inventories, reducing the likelihood of vessel failure
- Maintain constant operating conditions if possible - pressure or temperature cycling will increase the likelihood of equipment mechanical failure
- Minimise the number of flanged joints
- Use rotary equipment with high integrity seals
- Use equipment/piping with higher design conditions to reduce likelihood of mechanical failure
- Secondary containment – equipment containing highly toxic materials can be located in buildings which can be sealed to the atmosphere
- Use process interlocks/shutdown systems in case of control failure

Risk Mitigation…

Likelihood Reduction:

- Install gas detectors for early identification of toxic or flammable gas releases
- Ensure safe working practices are followed, and all potential hazards have been identified

Risk Mitigation…

Consequence & Likelihood Reduction:

- Each approach varies in effectiveness, complexity, and cost
- Cost-benefit analysis is a useful method to assess preferred options

Cost Benefit Analysis

- **Purpose**
- **Method**
- **Calculation**
- **Uncertainties**
- **Examples**

Purpose

Find the answers to the following questions:

- What is the cost of implementing a safety measure?
- What are the benefits in terms of risk reduction?
- Is it possible to pinpoint the ALARP level?

Method

- Define the policy strategy for the CBA (site and/or legislative)
- Identify all costs
- Identify all benefits

Cost

The total annual cost of the risk reduction measures includes:

- Costs of capital investments written-off over an assumed working lifetime of the measure at an appropriate interest
- Operating expenditure
- Lost profits if the measure involves whithdrawing from an activity altogether

Benefit

The total annual benefits of the risk reduction measures are reduced costs for example:

- Loss of life
- Loss of property
- Loss of production capacity
- Loss of goodwill
- Insurance
- Loss of market shares

Uncertainties

How often do you have complete information?

Prices change, demand fluctuates, costs rise. By using probability distribution functions to represent a range of possible values, @RISK lets you take these and other uncertainties into account.

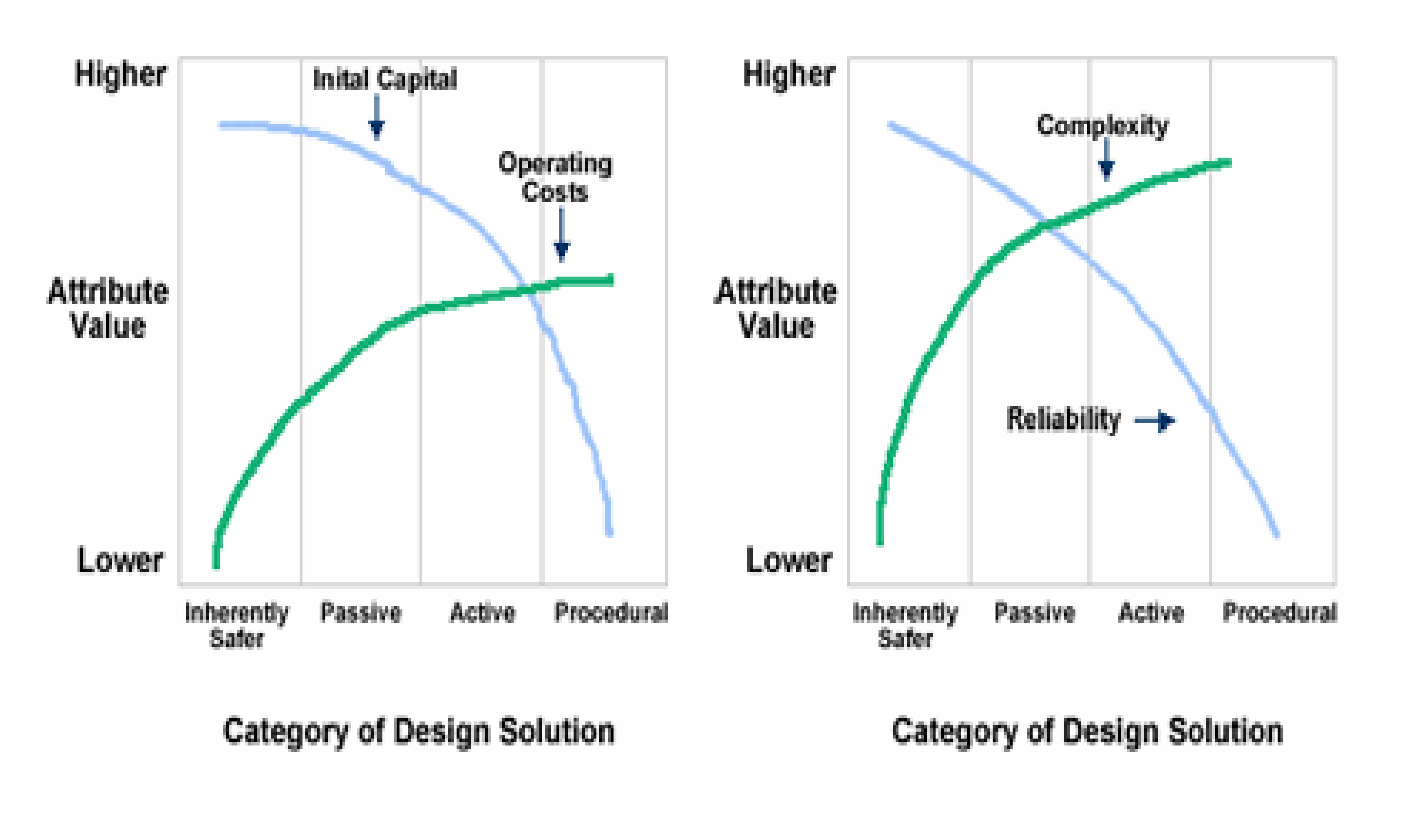
Example 1: Costs for improvement of warehouse

RELOCATION COST	£1m
Working lifetime	25 years
Payback period	10 years
Rate of return	8% pa
Annual cost	£60000 per year (£1m x $(1{,}08^{10/2})$/25)
TRAINING COST	for 10 staff
Duration	1 week per year
Salary	£15000 pa
Employment costs factor	2,0
Annual costs	£6000 per year (£15000 x 1 x 10 x 2,0/52)

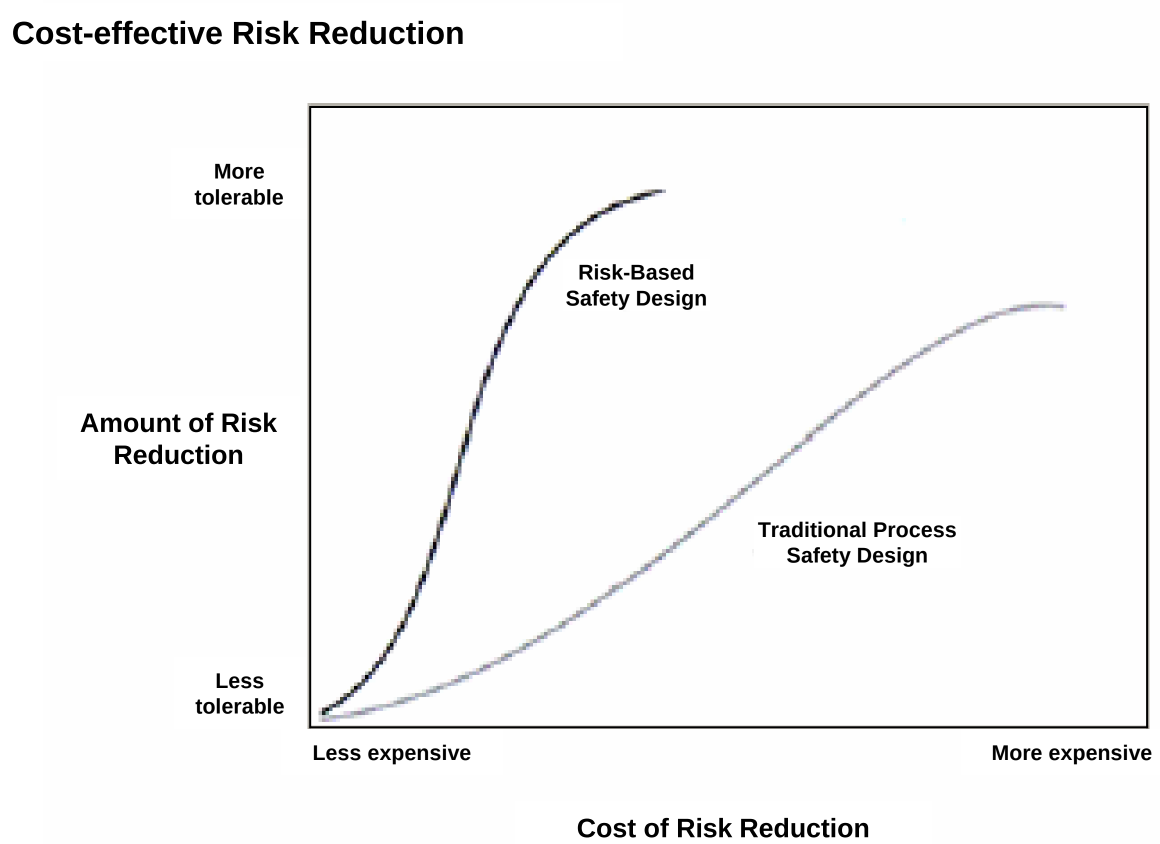
Example 2: Valuations of life for the UK

HUMAN CAPITAL APPROACH
An individual aged 35, with 30 years working life remaining
UK national average income per head £5000 pa (1987 prices)
Average tax rate 26%
Value of life (gross output) £150000 (30 x £5000)
Value of life (net output) £39000 (0,26 x £150000
WILLINGNESS-TO-PAY APPROACH
Department of Transport, £0,66 million (1992 prices) increased yearly by inflation, for evaluating road improvement schemes
An individual will pay £20 per year to reduce the risk of death by 10-5 per year
Implicit value of life £2 million (£20/10-5)
IMPLICIT VALUE IN DECISIONS ON SAFETY MEASURES
The government legislated in favor of measures which proved to cost industry £100 million and saved an estimated total of 50 lives
Implicit value of life £2 million (£100m/50)

Example 3: Inherently safer design



Example 4: Cost-effective risk reduction



Case Study I…

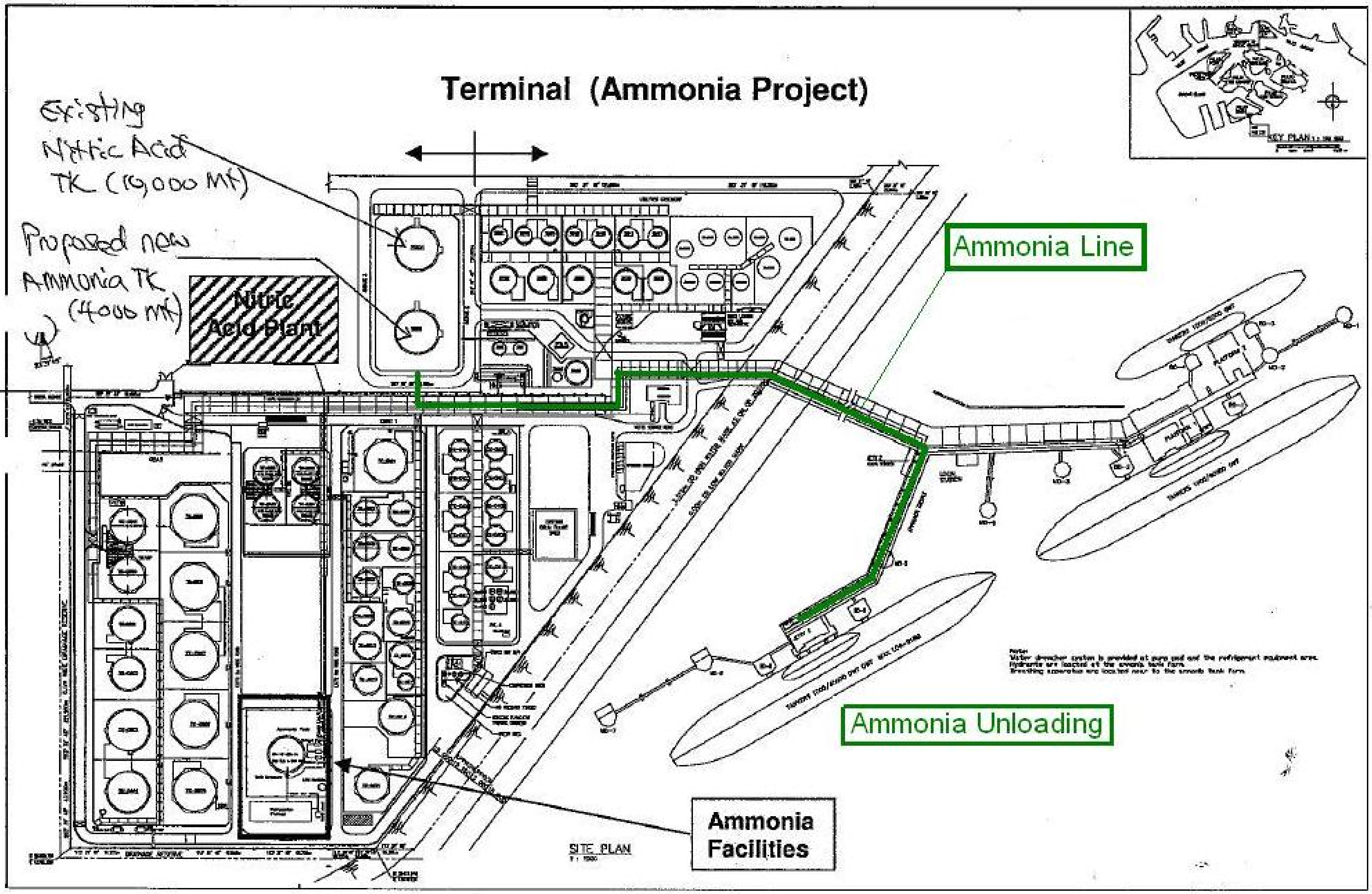
Ammonia Storage Terminal:

- Anhydrous Ammonia
- 3000 tons transferred from supply ship to 4000 tons refrigerated atmospheric storage tank

Purpose of study:

- Identify and quantify hazards and risks related to the unloading and storage of refrigerated ammonia in a new tank at the terminal;
- Determine hazards/risks due to possible accident scenarios which will lead to fire, explosion or toxic release;
- Recommend measures to be incorporated in the design and operation of the plant to keep hazards/risks to as low a level as practical;
- Facilitate the development of emergency response plans to deal with all possible accident scenarios.

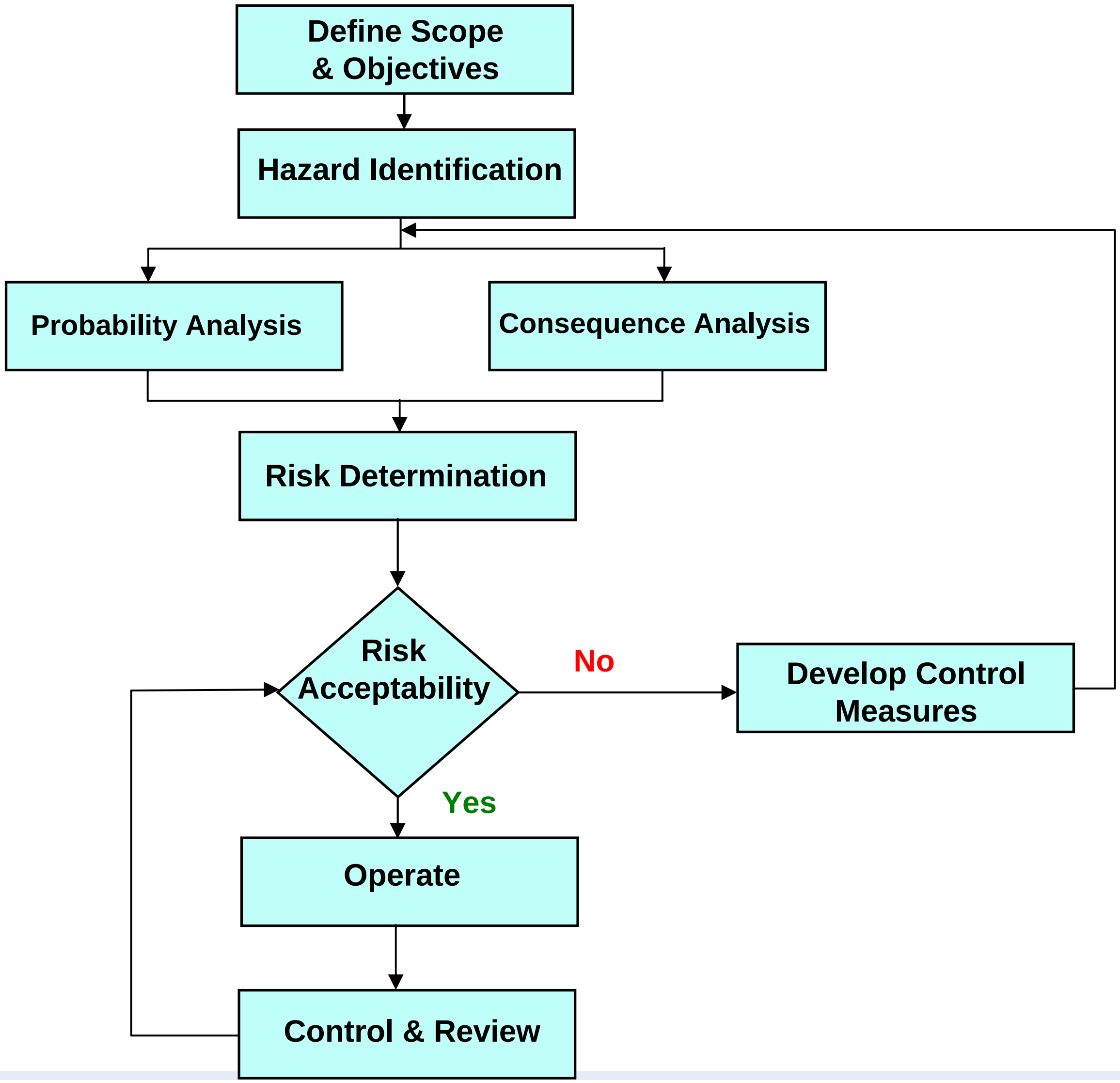
Ammonia Storage Terminal:



Case Study I…

Ammonia Storage Terminal:

QRA methodology…



Hazard Identification…

Operating experience used to determine scenario list:

- 1.Drain Valve: 8-in line with 1-in hole
- 2A. Gasket Leak: 8-in line with 0.8-in hole
- 2B. Gasket Leak: 3-in line with 0.3-in hole
- 3. Feed Pump Casing Failure: 4-in line with 4-in hole
- 4. Gasket Leak – Delivery Line: 2-in line with 0.2-in hole
- 5A. Line Rupture: 8-in line with 8-in hole, spilling on land
- 5B. Line Rupture: 8-in line with 8-in hole, spilling on water
- 6. Released from Failed Flare: 12 inch diameter flame
- 7. Tank Outlet Line Fails: 4-in line with 4-in hole
- 8. NH3 Accum V-103 leaks: 1-in hole
- 9. Fire Exposure V-103, NH3 Accum: Tank Fails
- 10. Loss of Cooling HX-1: Release from failed flare

Criteria…

Determine hazard criteria:

- **Although ammonia is designated as a non-flammable gas for shipping purposes by the United Nations and the US D.O.T., it is flammable in air within a certain range of concentrations.**
- **Flammable range (UFL 28%, LFL 15% per NFPA 325M)**
- **Experiments to ignite a standing pool of liquid ammonia have not been successful**
- **Scenario is outdoors, with minimal level of confinement**
- **Therefore, jet fire, pool fire and explosion hazards resulting from releases of refrigerated liquid ammonia are extremely unlikely**
- **Toxic risk is the only concern**

Criteria…

Determine hazard criteria:

Hazard	Criteria
Toxic	IDLH; = 300 PPM
	3% fatality (for a release duration of less that 30 minutes); Ammonia Probit TLV = 25 PPM, ERPG-2 = 150 PPM
Fire (Radiation)	Not considered (see previous)
BLEVE (Overpressure)	5psi, 1psi and 0.5psi

Criteria based on legislative compliance with local Environmental Pollution Control Act.

Criteria…

Determine weather criteria:

Wind Speed (m/s)	Atmospheric Stability
1	F
2	B
3	C

Determine risk criteria:

Individual Fatality Risk (IR) contours	**Requirement**
$5x10^{-5}$ per year	**That this contour remains on-site**
$5x10^{-6}$ per year	**That this contour extends into industrial developments only**
$1x10^{-6}$ per year	**That this contour extends into commercial and industrial developments only**

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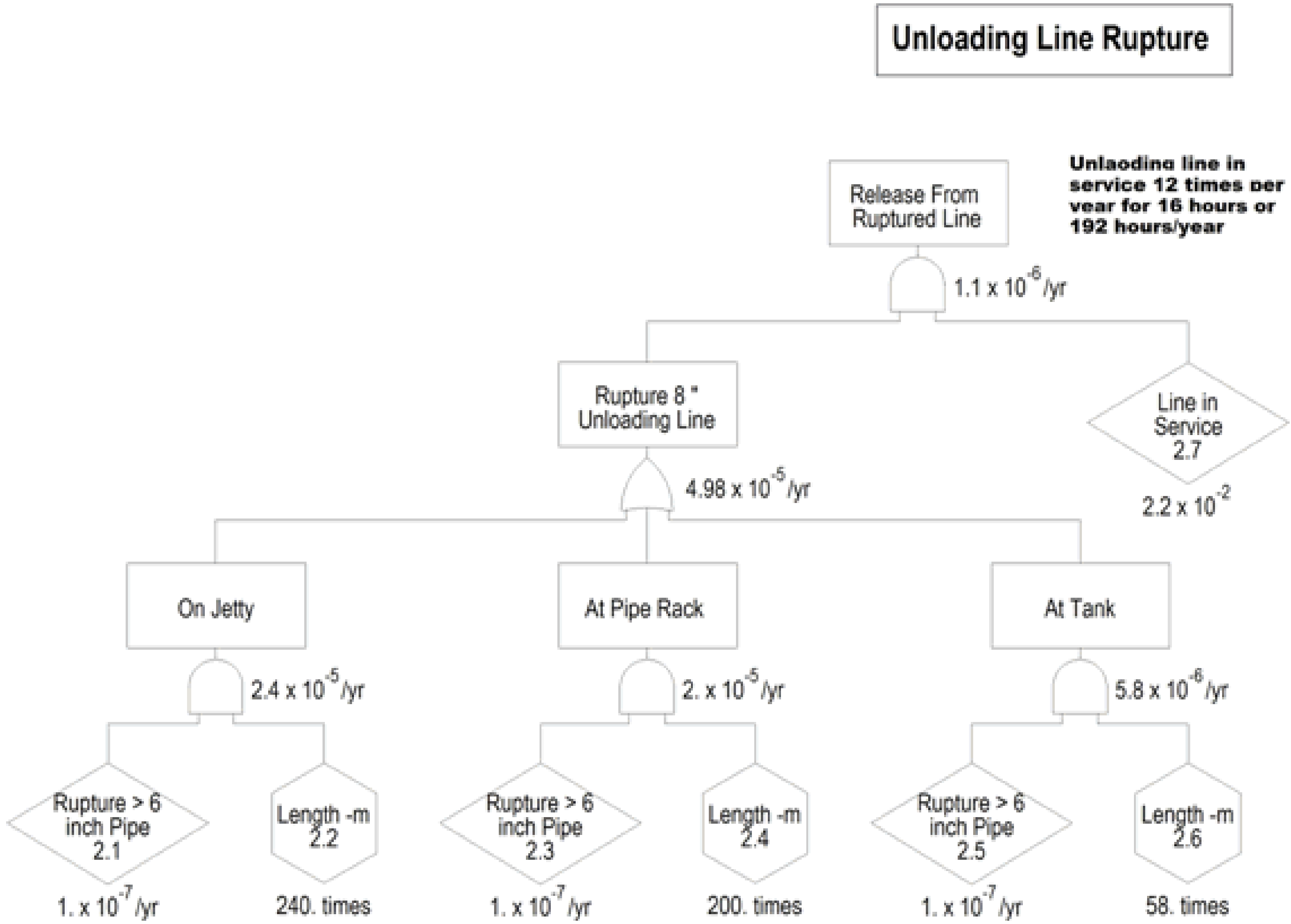
Probability Analysis…

Fault Tree Analysis technique applied to each scenario:



Probability Analysis…

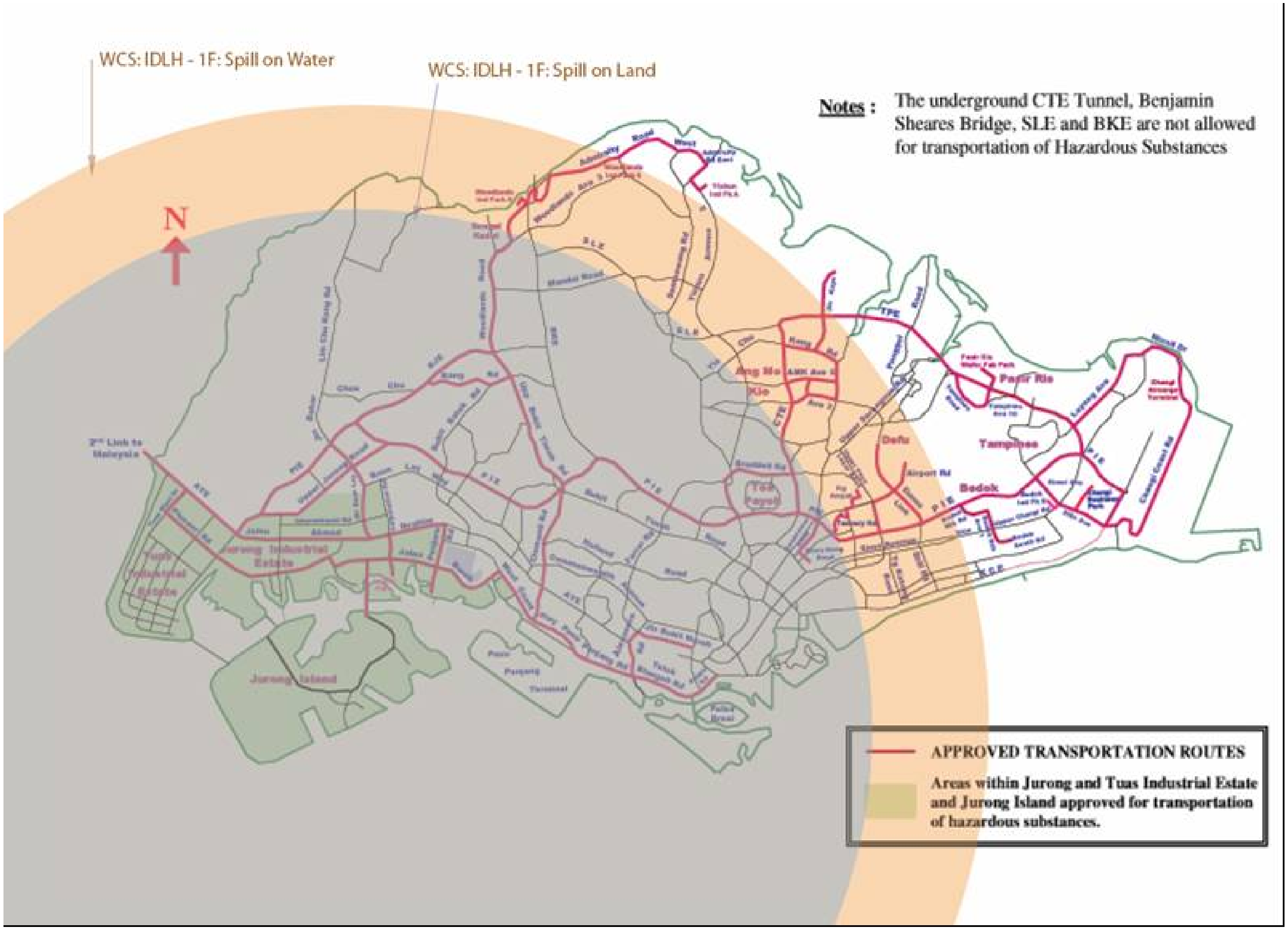
Fault tree core data:

Item	Event	Statistic	Source/Discussion
2.1	Piping rupture >6 inch	$1x10^{-7}$/m-yr	Rijnmond give $1x10^{-7}$/m-yr for rupture of piping >6 inch
2.2	Pipe length at Jetty	240 m	Estimated from PID
2.3	Piping rupture >6 inch	$1x10^{-7}$/m-yr	Same as 2.1
2.4	Pipe length at pipe rack	200 m	Estimated from PID
2.5	Piping rupture >6 inch	$1x10^{-7}$/m-yr	Same as 2.1
2.6	Pipe length at Tank	58 m	Estimated from PID
2.7	Line in Service	$2.2 x10^{-2}$	16 hours per cooldown and transfer x 12 times per yr. gives 192 hrs/yr.

Results Summary…

Accident Scenario[1]	Release Rate & Duration	Mass Released (kg)	Event[1]		Consequence Distance[2] (km)			Event Frequency Yr^{-1}	Key Assumptions Safety / Mitigation Measures[3]
					1F	2B	3C		
5A. Line Rupture: 8-in line with 8-in hole, spilling on land	4,125 kg/min [~1600 gpm] for 15 minutes	61,875	Toxic	TLV	63.94	5.87	7.60	1.1E-6	This event can be mitigated by the correct specification and installation of the line. Additionally the line should be placed so it is protected from any impact that could cause its rupture.
				ERPG-2	26.73	2.08	2.65		
				IDLH	17.87	1.40	1.76		
				3% Fatality	2.34	0.19	0.26		
5B. Line Rupture: 8-in line with 8-in hole, spilling on water	4,125 kg/min [~1600 gpm] for 15 minutes	61,875	Toxic	TLV	66.75	7.82	10.67	1.1E-6	This event can be mitigated by the correct specification and installation of the line. Additionally the line should be placed so it is protected from any impact that could cause its rupture.
				ERPG-2	31.63	3.21	3.90		
				IDLH	23.41	2.18	2.60		
				3% Fatality	4.39	0.33	0.38		

Results Summary…



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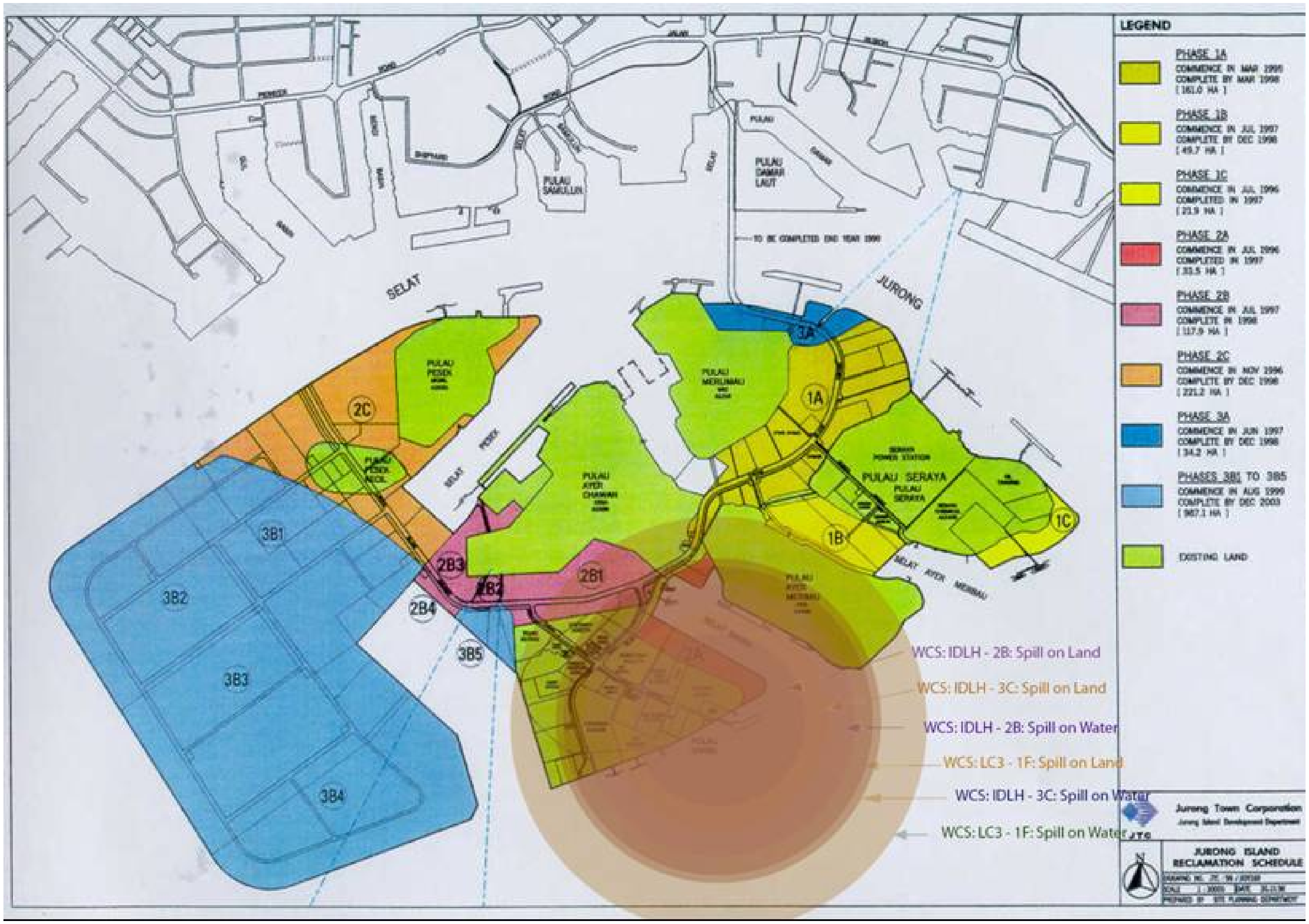
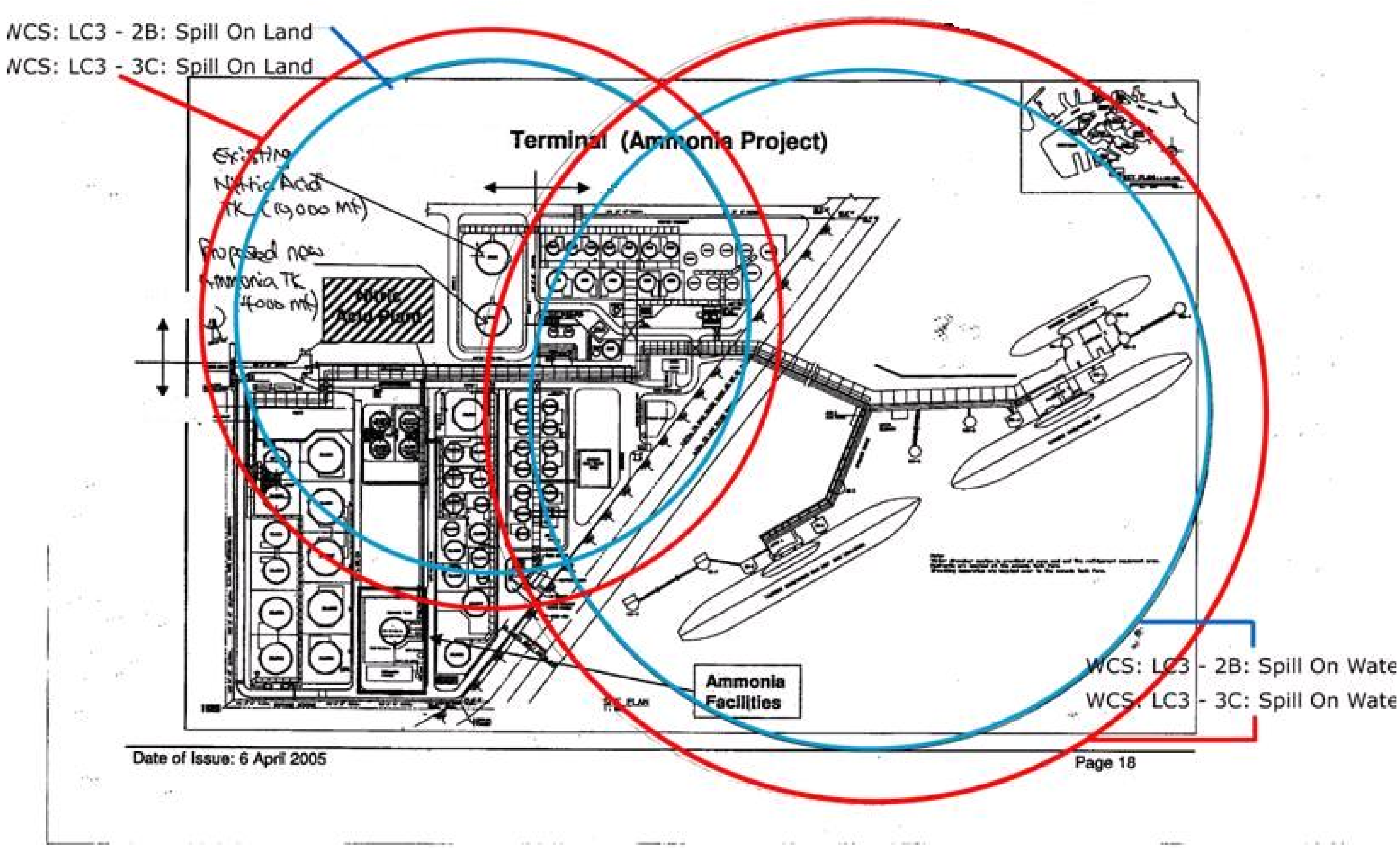
Results Summary…



Results Summary…



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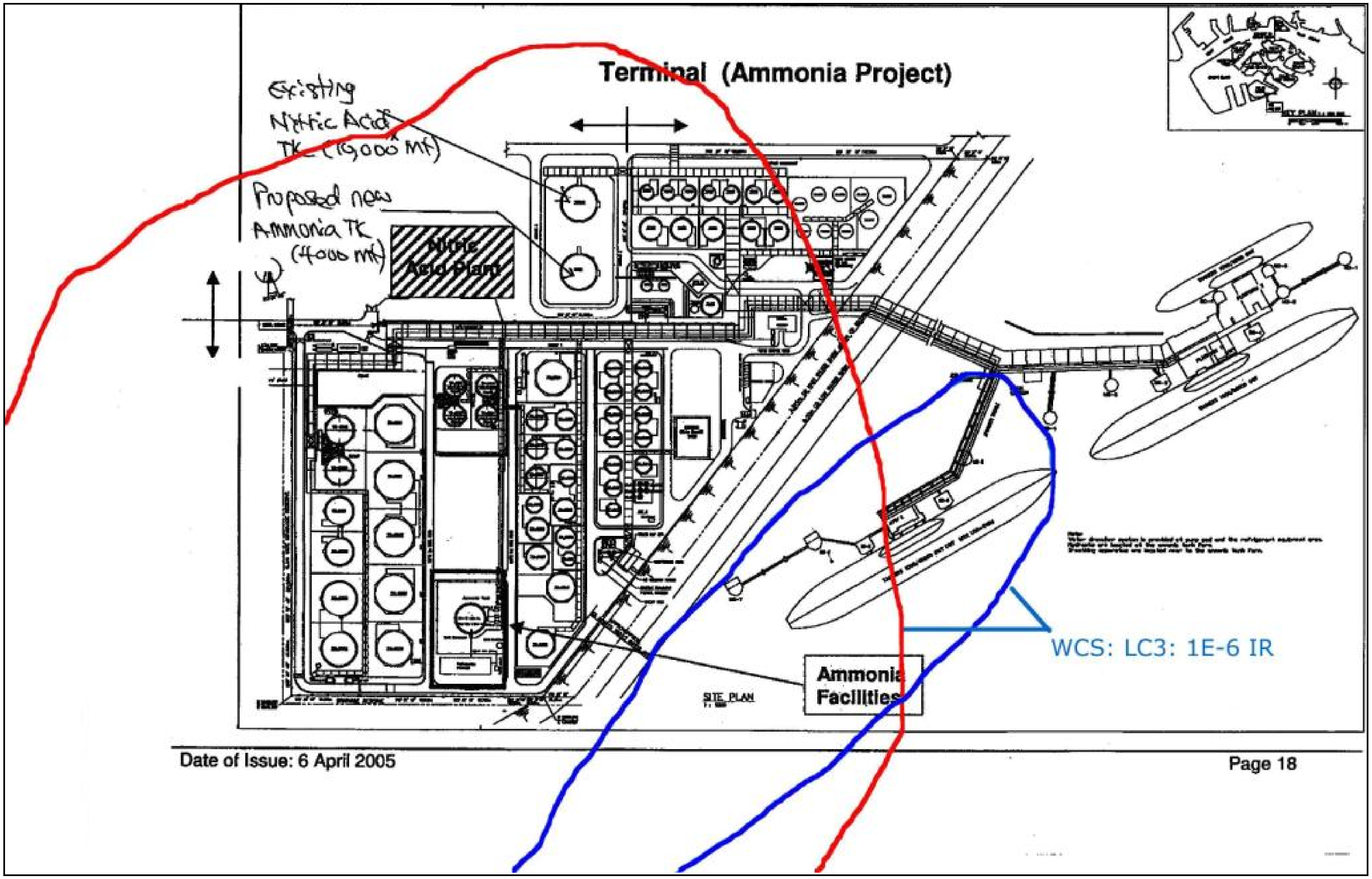
Results Summary…



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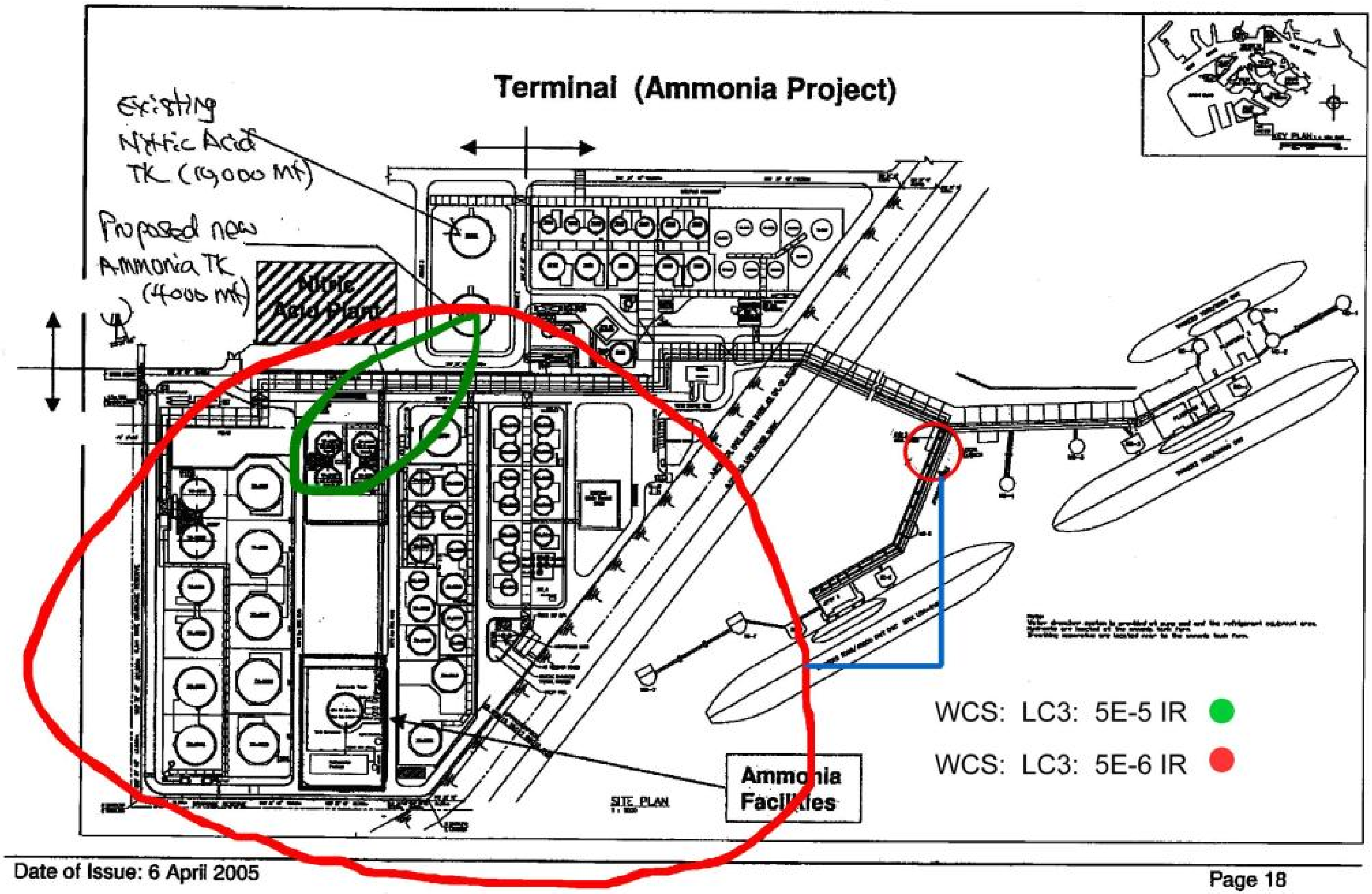
Results Summary…



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Case Study II…

Pharmaceutical Facility, US:

- Various toxic and flammable materials

Purpose of study:

- Assess onsite and offsite risks through Quantitative Risk Analysis
- Develop risk-reduction opportunities for client

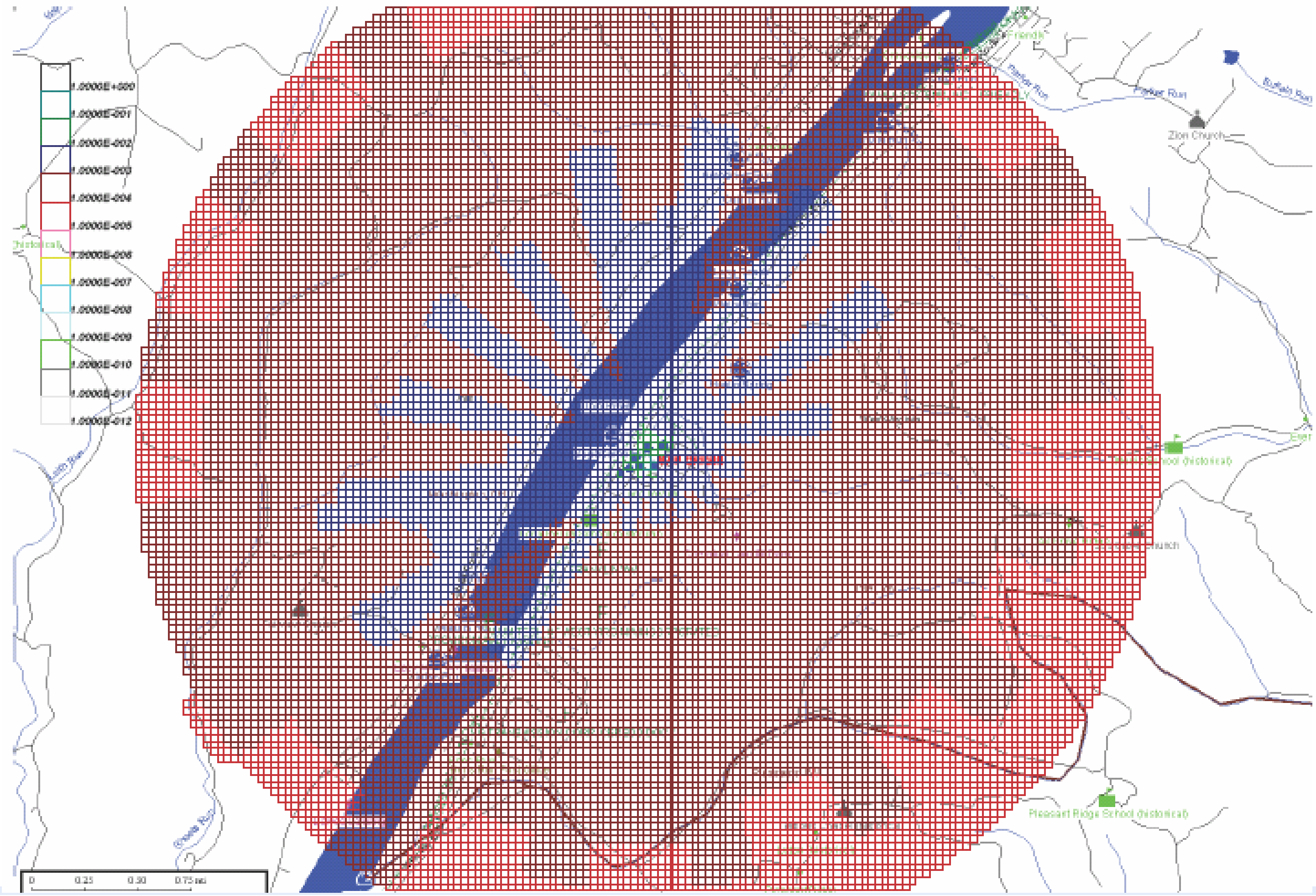
Case Study II…

Scenarios identified:

- **Vessel failure**
- **Line failure due to external impact or corrosion**
- **Relief device premature failure**
- **Overfilling**
- **Hose failure**
- **External Fire**
- **Contamination**
- **Mischarge**
- **Failure of Heating or Cooling Medium**
- **Loss of Nitrogen, allowing Air into Equipment**

Case Study II…

Offsite Risk Profiles, >10-5 individual risk contours:



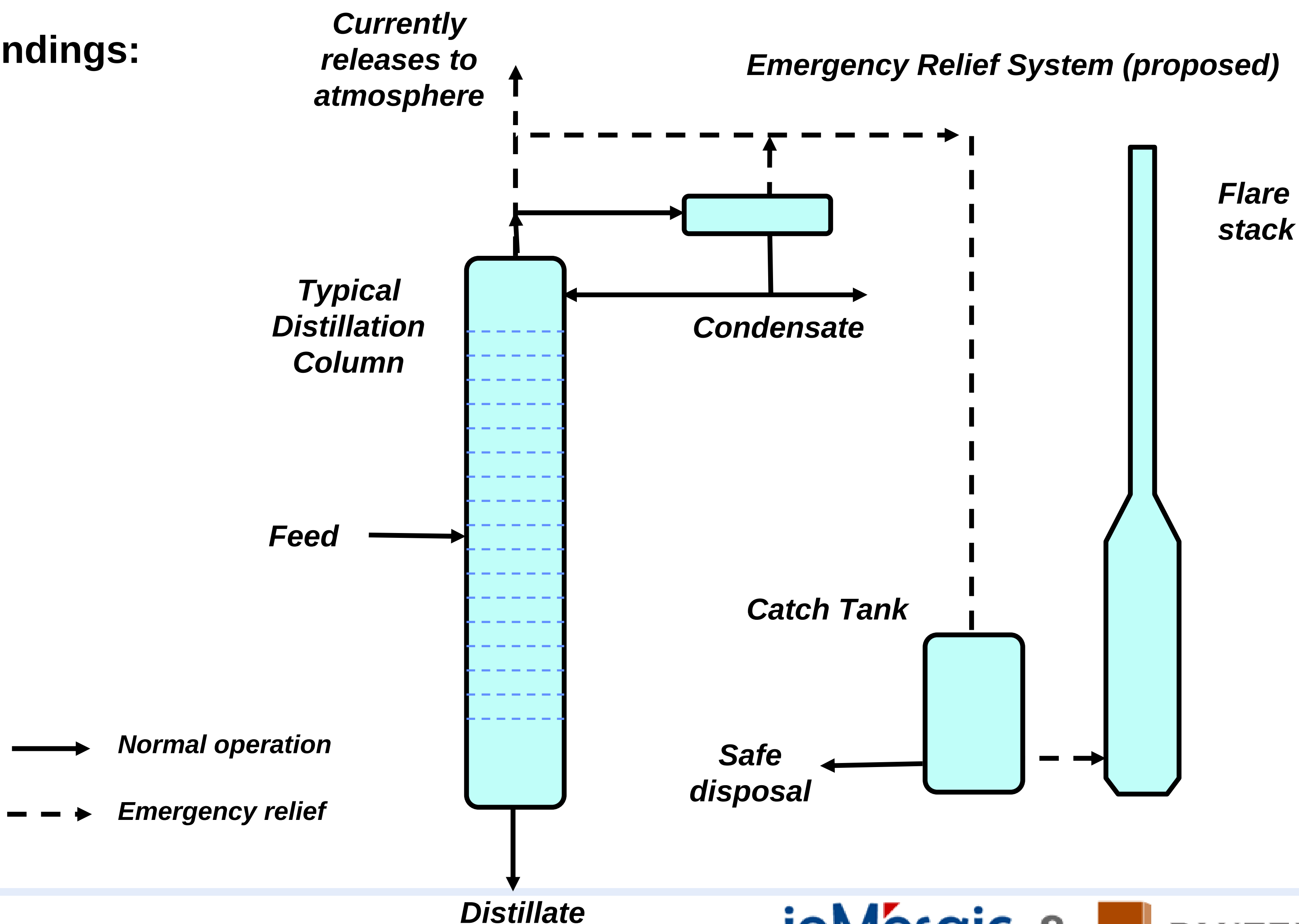
Case Study II…

Findings:

- Main risks are dominated by toxic releases through pressure safety valves, due to runaway reactions or external fires
- If these scenarios are eliminated / mitigated, by using an effluent handling system consisting of a catch tank and an associated flare stack, the offsite risks can be reduced significantly
- Ongoing process with client….currently in Cost-Benefit Analysis stage

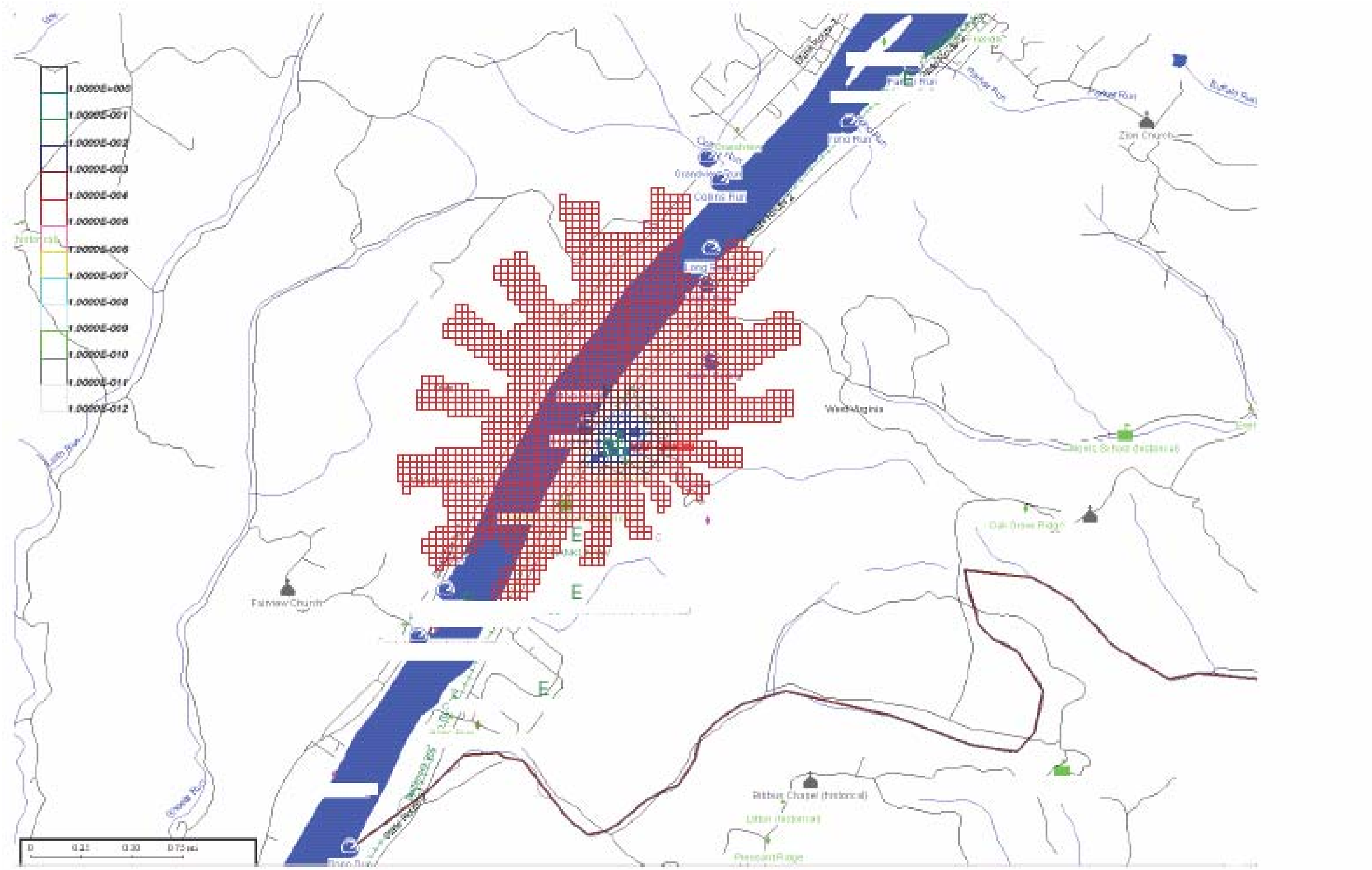
Case Study II…

Findings:



Case Study II…

With Mitigation: Offsite Risk Profiles, >10-5 individual risk contours:



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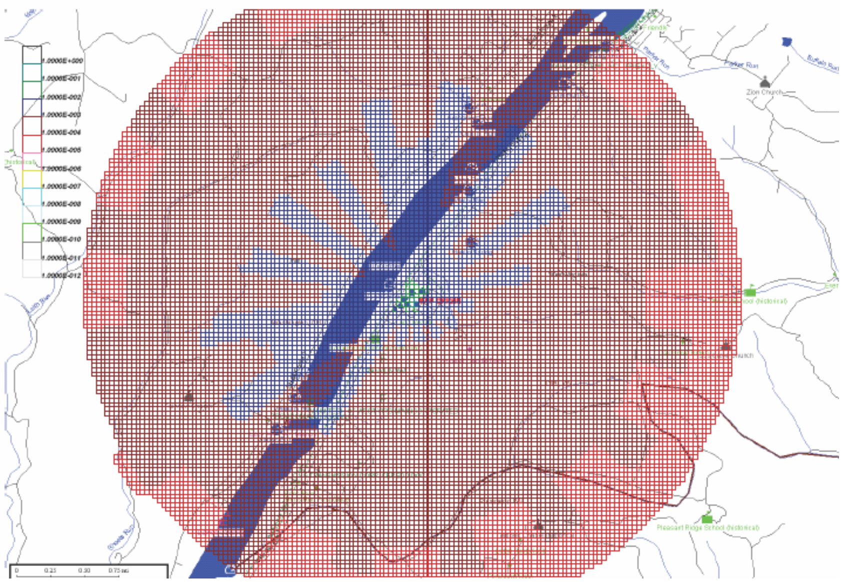
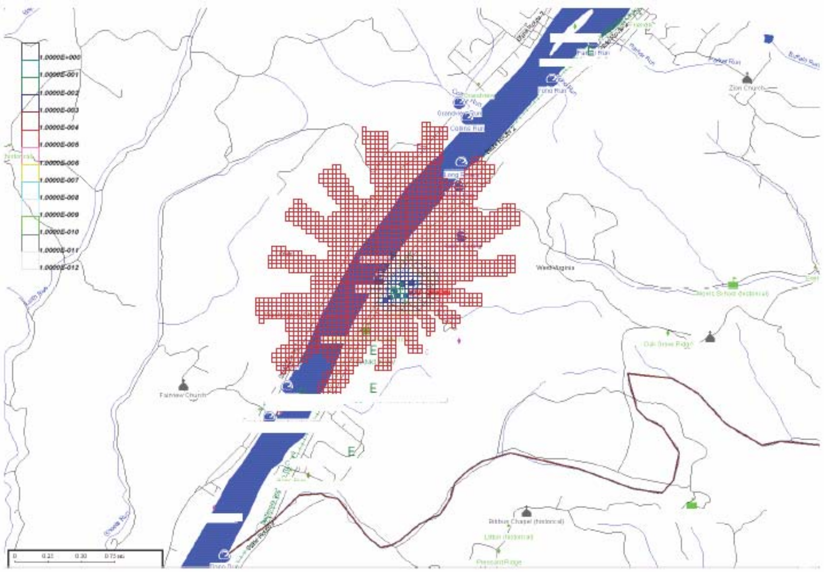
Case Study II…

Offsite Risk Profiles, >10-5 individual risk contours:

Without Mitigation

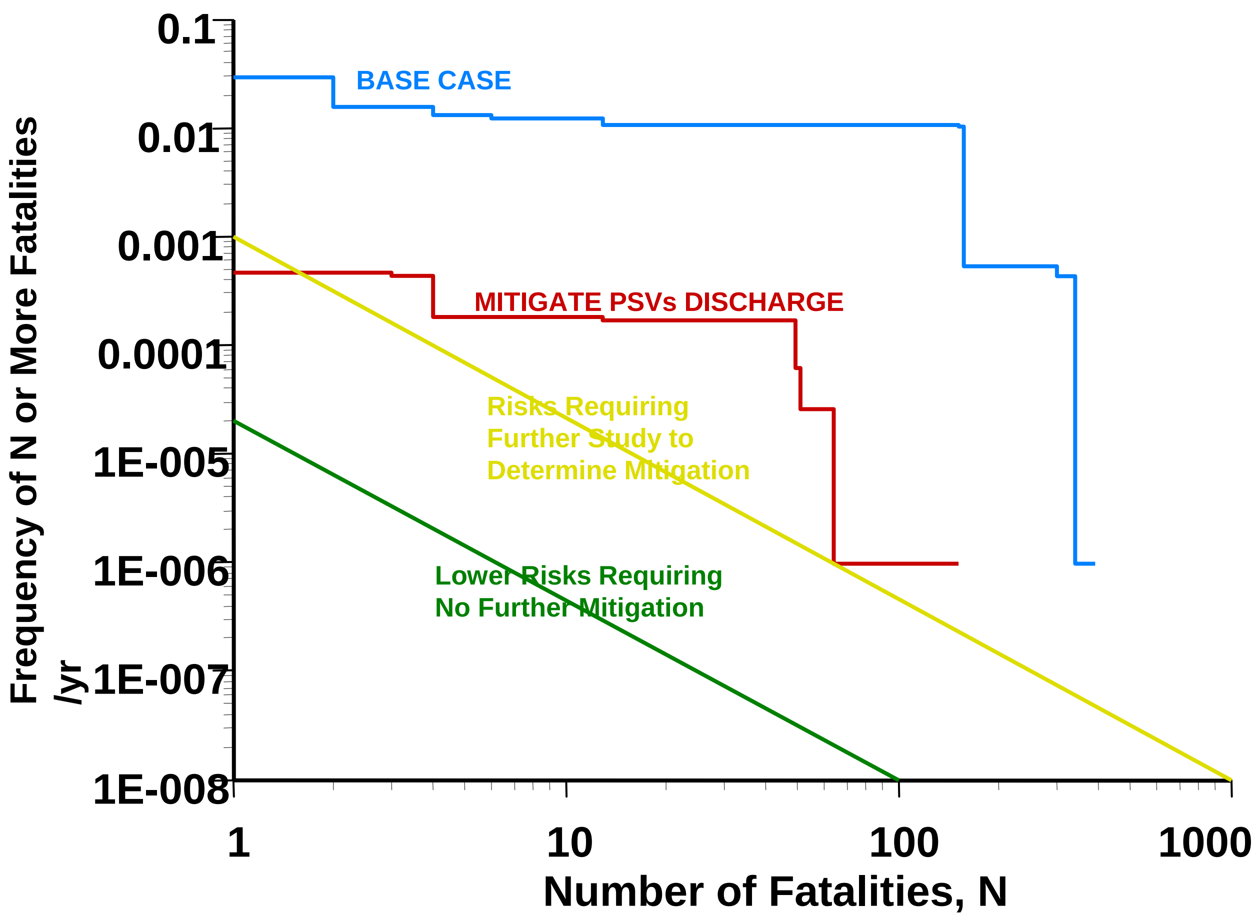


With Mitigation



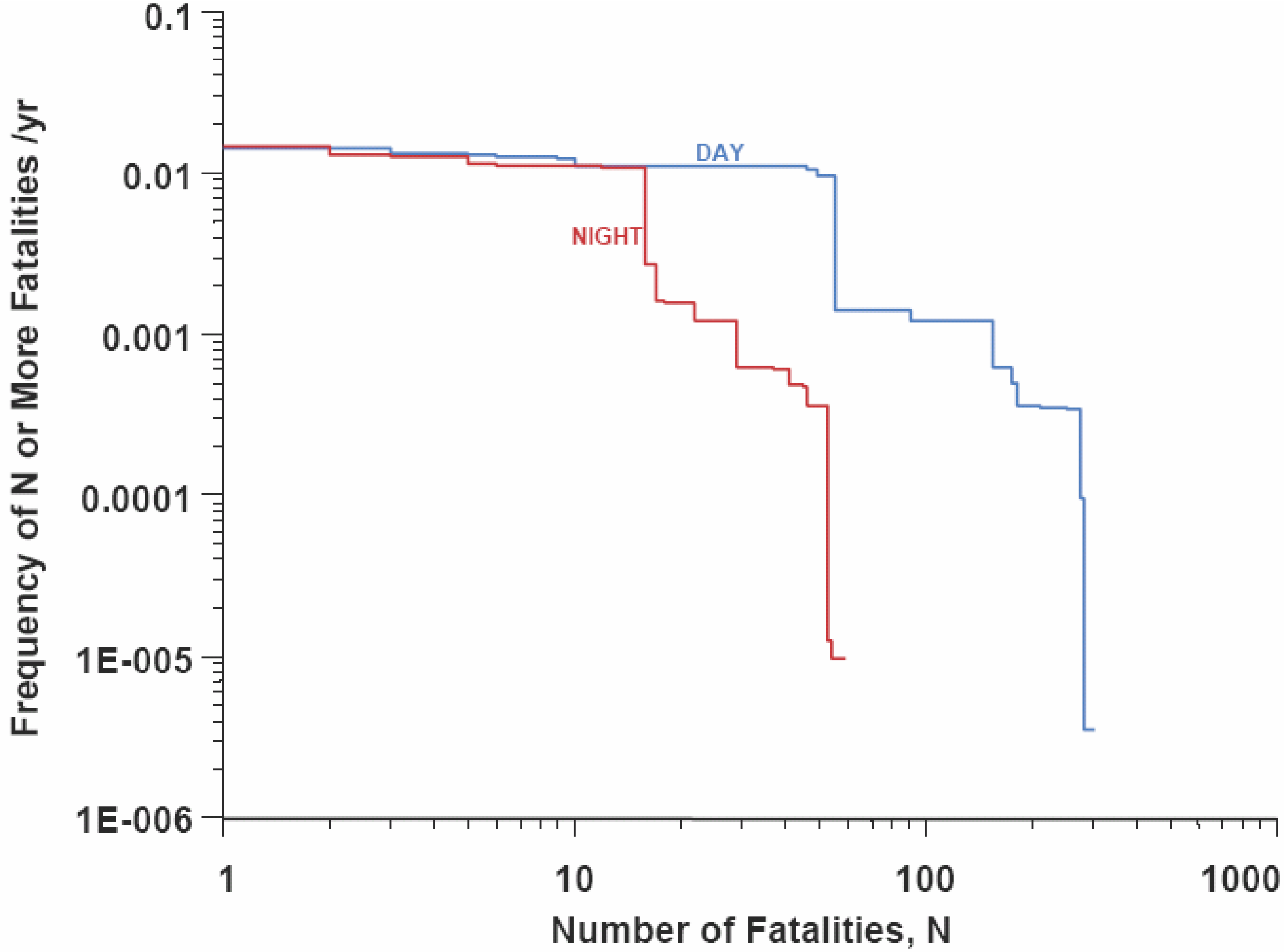
Case Study II…

Offsite Risk Profiles, Societal Risk:



Case Study II…

Offsite Risk Profiles, Societal Risk, Further Analysis:



Conclusions…

Quantitative Risk Analysis:

- Most rigorous method of analysing hazards and risk within the chemical and process industries
- Assists with facility siting, planning, and cost-benefit decision-making
- Still has many uncertainties
- Benefits from use of software tools such as @RISK
- Requires a consistent approach, and assumptions to be stated explicitly
- Forms only a small part of a successful Process Safety Management program

References…

- Lees, F. P; 'Loss Prevention in the Process Industries', (2005)
- Center for Chemical Process Safety; 'Guidelines for Process Safety Documentation', (1995)
- Health & Safety Executive; 'The Buncefield Investigation: Progress Report', (2006)
- Det Norske Veritas; 'Introduction to Hazard Analysis and Risk Assessment', (1997)
- Health & Safety Executive; 'Application of QRA in operational safety issues', (2002)