STAG 6442 Environmental Risk Assessment

Lecture #5: Quantitative Risk Assessment (QRA)

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Content

- **Acts & Regulations**
- **Introduction to Risk Assessment methodologies**
- **Hazard Identification – HAZID, HAZOP**
- **Risk Analysis – Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Bow-Tie Analysis**
- **Risk assessment**

Laws & Regulations

- **Department of Occupational Safety and Health, Ministry of Human Resources, Malaysia.**

- **Petroleum Act (Safety Measures) 1984 (Act 302)**
  - Petroleum (Safety Measures) (Transportation Of Petroleum By Pipelines) Regulations 1985

- **Occupational Safety And Health Act 1994 (Act 514)**
  - Occupational Safety And Health (Employers' Safety And Health General Policy Statements) (Exception) Regulations 1995
  - Occupational Safety And Health (Control of Industrial Major Accident Hazards) Regulations 1996
  - Occupational Safety And Health (Safety And Health Committee) Regulations 1996
  - Occupational Safety And Health (Classification, Packaging And Labelling of Hazardous' Chemicals) Regulations 1997
  - Occupational Safety And Health (Safety And Health Officer) Regulations 1997
  - Occupational Safety And Health (Use And Standards Of Exposure Of Chemicals Hazardous To Health) Regulations 2000 (Malay Version)
  - Occupational Safety And Health (Use And Standards Of Exposure Of Chemicals Hazardous To Health) Regulations 2000 (English Version)
  - Occupational Safety And Health (Notification of Accident, Dangerous Occurrence, Occupational Poisoning and Occupational Disease) Regulations 2004

- **http://www.dosh.gov.my/**

Codes of Practice

- **Department of Occupational Safety and Health, Ministry of Human Resources, Malaysia.**

- Code Of Practice For Road Transport Activities 2010
- **Industry Code of Practice for Safe Working in a Confined Space 2010**
- Industry Code of Practice On Indoor Air Quality 2010
- Code Of Practice On Indoor Air Quality, 2005
- **Code Of Practice For Safe Working In A Confined Space, 2001**
- Code Of Practice On Prevention And Management Of HIV/AIDS At The Work Place, 2001
- Code Of Practice On Prevention And Eradication of Drug, Alcohol And Substance Abuse in the Workplace, 2005
- **Code of Practice On Safety Health And Environment For Transportation Sector (SHE Code), 2007**

http://www.dosh.gov.my/

Guidelines

http://www.dosh.gov.my/

- **Guidelines On Occupational Safety And Health In The Office - 1996**
- Guidelines On Method Of Sampling And Analysis For Airborne Lead - 1997
- Guidelines For The Formulation Of A Chemical Safety Datasheet - 1997
- Guidelines For The Classification Of Hazardous Chemicals - 1997
- Guidelines For Labelling Of Hazardous Chemicals - 1997
- Guidelines On Occupational Safety And Health In Tunnel Construction - 1998
- Guidelines On Trenching For Construction Safety - 2000
- **Assessment Of The Health Risks Arising From Use Of Hazardous Chemical In The Workplace (2nd Edition) - 2000**
- **Guidelines On the Control Of Chemicals Hazardous To Health - 2001**
- Guidelines for Preparation of Demonstration of Safe Operation Document (Storage of Liquified Petroleum Gas In Cylinder) - 2001
- **Guidelines On Monitoring Of Airbone Contaminant For Chemicals Hazardous To Health - 2002**
- **Guidelines On Occupational Safety And Health For Standing At Work - 2002**
- **Guidelines On The Use of Personal Protective Equipment Against Chemicals Hazards – 2005**
- **Guidelines On Occupational Safety and Health (Notification Of Accident, Dangerous Occurance, Occupational Poisoning And Occupational Disease) Regulations 2004 (NADOPOD) – 2005**
- Guidelines For The Prevention of Falls at Workplaces - 2007
- Guidelines For Public Safety And Health At Construction Sites - 2007
- **Guidelines for Hazard Identification, Risk Assessment and Risk Control (HIRARC) - 2008 (English Version)**
- Guidelines on Storage of Hazardous Chemicals: A Guide for Safe Warehousing of Packaged Hazardous Chemicals - 2005

RISK

(PROBABILITY OF EVENT OCCURRING)

- Likelihood of event / Based of failure frequency of process components

X

(IMPACT OF EVENT OCCURRING)

- Extent of Damage Fatality Injuries Losses

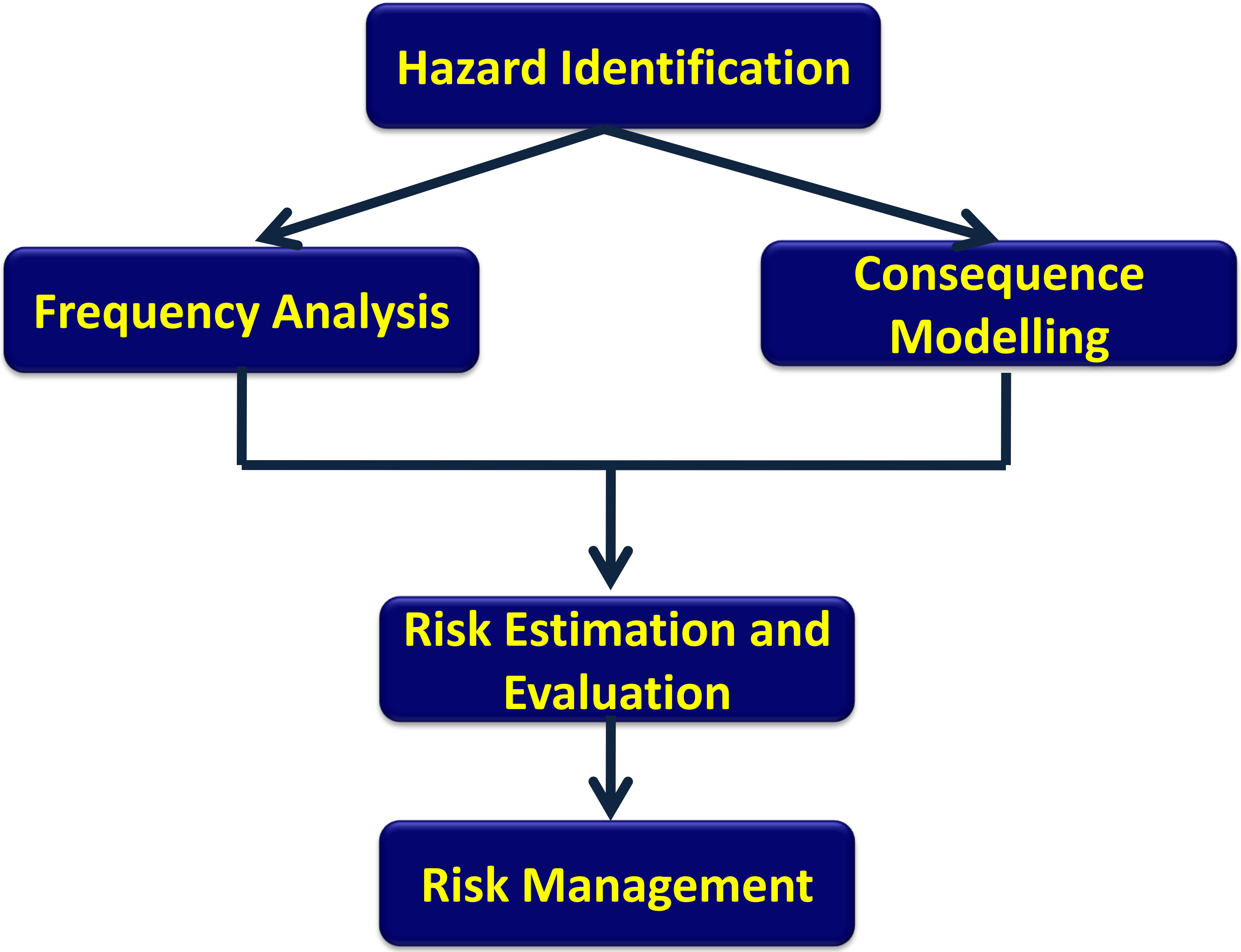
Types of Risk Assessment

Type of Risk	Description
Qualitative	•Easiest to apply (least resource demands and least additional skill sets required) •Use words to describe severity and likelihood
Semi-Quantitative	•Lie between these extremes •Give values for qualitative scales
Quantitative (QRA)	•Most demanding on resources and skill, but potentially deliver the most detailed understanding. •Use numerical values for severity and probability •Data from past accident and scientific research

What is QRA

- Systematic methodology to assess risks associated any installation
  - Taking into consideration all forms of hazards
  - Uses design information and historical data to estimate frequency of failure
  - Uses modelling software to assess consequence

QRA Procedure



Hazard Identification

Purpose: to identify plausible hazard conditions

Hazard identification tools:

- Check-list
- HAZID – **HAZ**id **ID**entification
- HAZOP - **HAZ**ard and **OP**erability Study.
- FMEA – **F**ailure **M**odes and **E**ffects **A**nalysis
- SWIFT – **S**tructured **W**hat-**If** Checklist **T**echnique

HAZID

- A process of **identifying hazards**
- **Qualitative** exercise based primarily on **expert judgement**
- Performed by a team: a group of experts + HAZID leader
- Guidewords are defined in advance
- The discussion proceeds through the installation's modules or operations using guidewords to identify potential hazards, its **causes** and the possible **consequences**

Example of HAZID Guide words

Generic Hazard	Cause	Consequence
Loss of containment	Design/construction	Gas & smoke ingress
Fire/explosion	Operation/maintenance	Fire/explosion
Mechanical impact	Simultaneous operations	Pollution
Structural failure	Human error	Structural collapse
Transport	Hardware failure	Safety systems impaired
Natural/environmental	Control system failure	
Simultaneous operations	Structural failure	
Human error	Dropped load etc.	

Example HAZID Worksheet

Area: TR emergency evacuation systems				
Generic Hazard	**Event**	**Consequence**	**Mitigating Factors**	**Recommendations**
Fire/explosion	Fire on deck blocks escape route	Personnel trapped in TR	Water spray over key routes	Assess vulnerability of escape routes
Environment	Evacuation by lifeboat in severe weather	Unable to move clear of installation		Check lifeboat speed against current speed

HAZOP

- Performed by a team + HAZOP leader
  - A team approach to hazard working together will identify more problems than working individually and combine results.
- A HAZOP is similar to a HAZID but is a **more detailed study**
- The process is divided into distinct sub-sections or "nodes"
- use a standard list of **guidewords**

HAZOP Guide Words

Guidewords	Meaning	Example deviation
NO or NOT	No part of the intentions is achieved	No flow, no signal
MORE	Increase in quantities such as flow rates, temperatures, etc	High pressure Excess temperature
LESS	Decrease in quantities such as flow rates, temperatures, etc	Low temperature Less flow Less cooling
AS WELL AS	All the design and operating intentions are achieved together with some additional activity	Impurities present in product
REVERSE	The logical opposite of the intention	Reverse flow
OTHER THAN	Something completely different than intended is achieved	Leakage Heating instead of pumping

Figure 2.2 Example EER HAZOP (Boyle & Smith 2000)

Stage Number	EER Stage	Property Words
1	Alarm and detection /communication	Alarm system Communication system Response
2/4	Access/ Egress	Escape route Decision Movement
3	Muster	Muster point Communication Registration Survival equipment
5	Helicopter evacuation	Availability Approach Landing Take off Helideck Boarding Communication Equipment
5	Lifeboat evacuation	Boat availability Launch system Crew Communicatio Navigation Drop zone Survival equipn
6	Escape directly to sea	Escape devices Decision Movement Survival equipn Drop zone
7	Rescue and subsequent recovery	Availability Search Recover Sustain life

1. Each stage of the EER is considered in turn.

Guideword
Failed
Impaired/damaged
Fails during
Not done
Inadequate/ Insufficient
Incorrect/inappropriate
Too late/soon
Congested/overloaded

2. Combinations of property words and guidewords are used to identify hazards.

3. Possible causes and consequences are considered to clarify the hazard.

4. Recommendations are made where the available safeguards appear inadequate.

Large Turret Fire/Explosion

Property word/ Guideword	Causes	Consequences	Safeguards	Recommendations
Alarm/ detection inadequate	Inaudible (e.g. during flaring, or through being close to the release)	Delays in personnel mustering. Increased exposure to hazards	Designated noisy areas have visible alarm signals. Human perception/ visualisation of the hazard.	Action 6. Areas of high noise potential, arising from normal or emergency conditions, should be re-examined throughout the installation to ensure that sufficient visual alarms are provided so enabling an appropriate emergency response.

EER - Escape, Evacuation,.Rescue

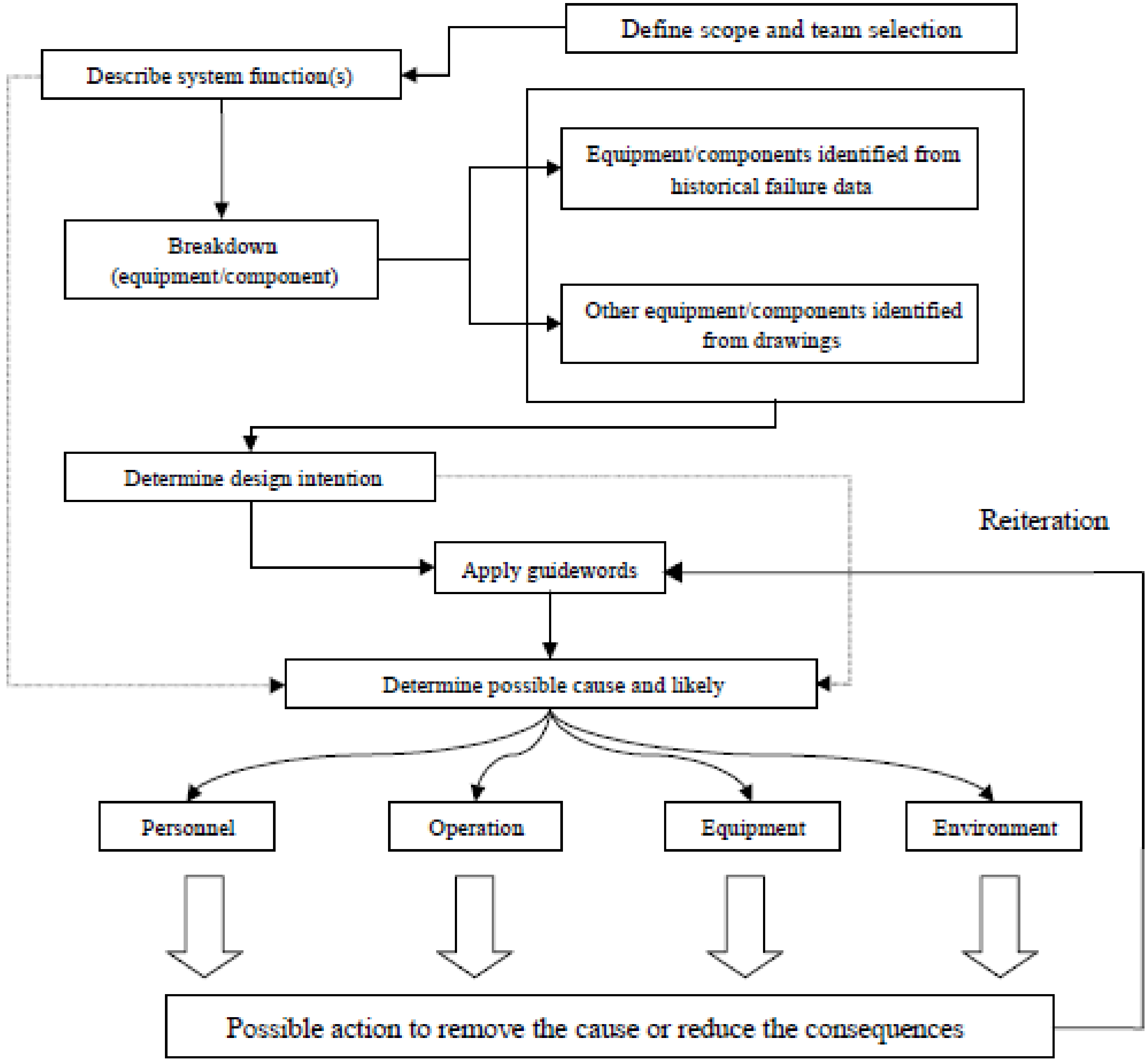


Figure 1.4 Flowchart of HAZOP process applied to fishing vessels

Qualitative Risk Assessment

- **Likelihood of an occurrence**
- "How many times has this event happened in the past?"

LIKELIHOOD (L)	EXAMPLE	RATING
Most likely	The most likely result of the hazard / event being realized	5
Possible	Has a good chance of occurring and is not unusual	4
Conceivable	Might be occur at sometime in future	3
Remote	Has not been known to occur after many years	2
Inconceivable	Is practically impossible and has never occurred	1

Table A

Department of Occupational Safety and Health, Ministry of Human Resources, Malaysia
Guidelines for Hazard Identification, Risk Assessment and Risk Control (HIRARC), 2008

Qualitative Risk Assessment

- **Severity of hazard**
- Severity are based upon an increasing level of severity to an individual's health, the environment, or to property.

SEVERITY (S)	EXAMPLE	RATING
Catastrophic	Numerous fatalities, irrecoverable property damage and productivity	5
Fatal	Approximately one single fatality major property damage if hazard is realized	4
Serious	Non-fatal injury, permanent disability	3
Minor	Disabling but not permanent injury	2
Negligible	Minor abrasions, bruises, cuts, first aid type injury	1

Table B

Risk Matrix

- **Risk Assessment**

Risk can be calculated using the following formula:

L x S = Relative Risk

L = Likelihood

S = Severity

High
Medium
Low

An example of risk matrix (Table C) is shown below:

	Severity (S)				
Likelihood (L)	1	2	3	4	5
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5

Table C

Qualitative Risk Assessment

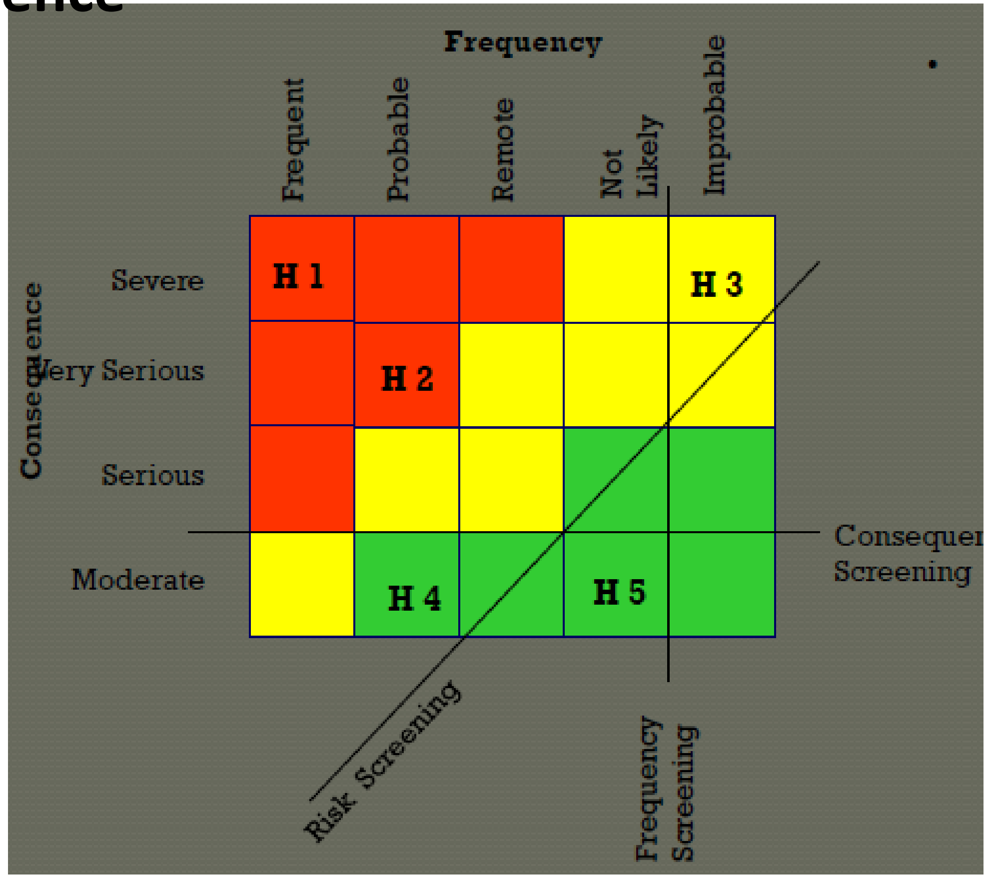
The relative risk value can be used to prioritize necessary actions to effectively manage work place hazards. Table D determines priority based on the following ranges:

RISK	DESCRIPTION	ACTION
15 - 25	HIGH	A HIGH risk requires **immediate** action to control the hazard as detailed in the hierarchy of control. Actions taken must be documented on the risk assessment form including date for completion.
5 - 12	MEDIUM	A MEDIUM risk requires a planned approach to controlling the hazard and applies temporary measure if required. Actions taken must be documented on the risk assessment form including date for completion.
1 - 4	LOW	A risk identified as LOW may be considered as acceptable and further reduction may not be necessary. However, if the risk can be resolved quickly and efficiently, control measures should be implemented and recorded.

Table D

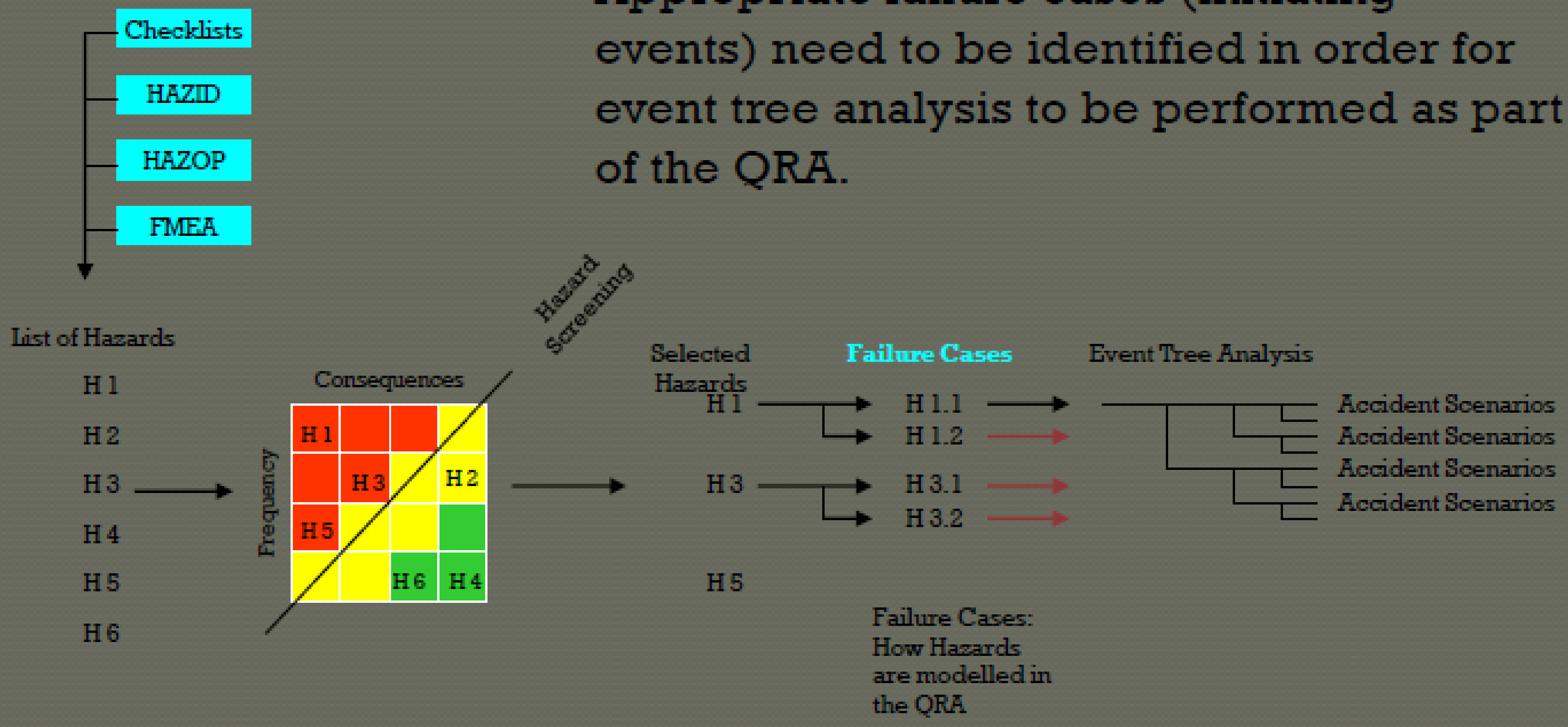
Hazard Screening

- Rank the hazards and screen out ones that pose minor risk
  - Screening based on Risk
  - Screening based on Frequency
  - Screening based on Consequence



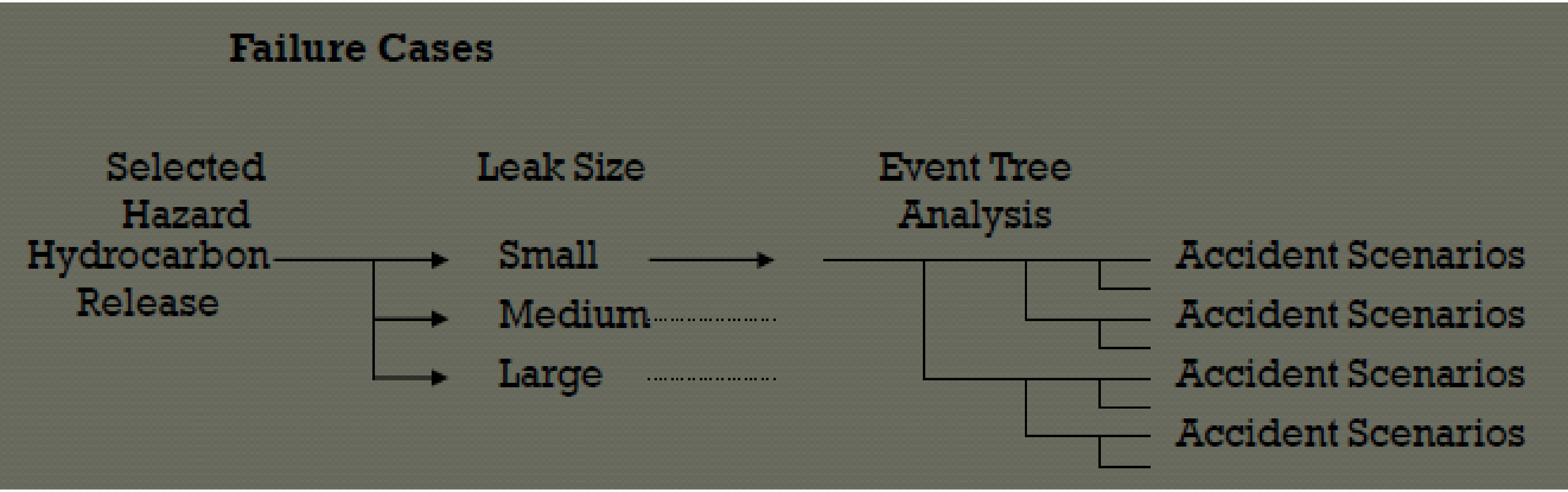
Failure Case Selection

- Appropriate failure cases (initiating events) need to be identified in order for event tree analysis to be performed as part of the QRA.



Failure Case Selection (Example)

- Offshore Safety Assessment
- Hazard: Hydrocarbon release
  - Size of release
    - Small – local long lasting fire
    - Large – Severe, short lived fire



History of Safety Related QRA

- QRA first used in chemical industry in 1960s
- Has since been used in other industries including nuclear and petrochemical industries
- In 1981, QRA for offshore installations became a requirement of the Norwegian Petroleum Directorate (NPD) regulations.

QRA- Risks Evaluated

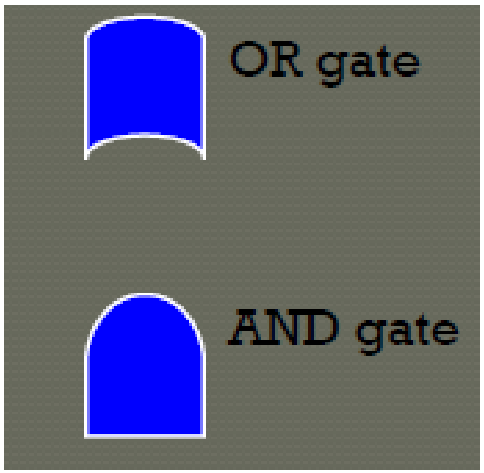
- **Different types of risk can be evaluated:**
  - Loss of life
  - Property damage
  - Business interruption
  - Environmental pollution

Fault Tree Analysis (FTA)

- **It is a diagrammatic method used to evaluate the probability of an accident**
- **It uses logic diagrams and Boolean Algebra to identify single events and combinations of events that could cause the top event**
- **Probability of occurrence values are assigned to the lowest events in the tree in order to obtain the probability of occurrence of the top event.**

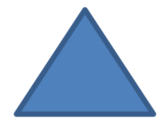
Fault Tree Main Symbols

Commonly Used Symbols:

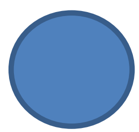


The event symbols are rectangle, circle, diamond and triangle.

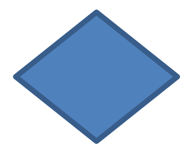
Fault /events



to indicate a **transfer** from one part of an FT to another

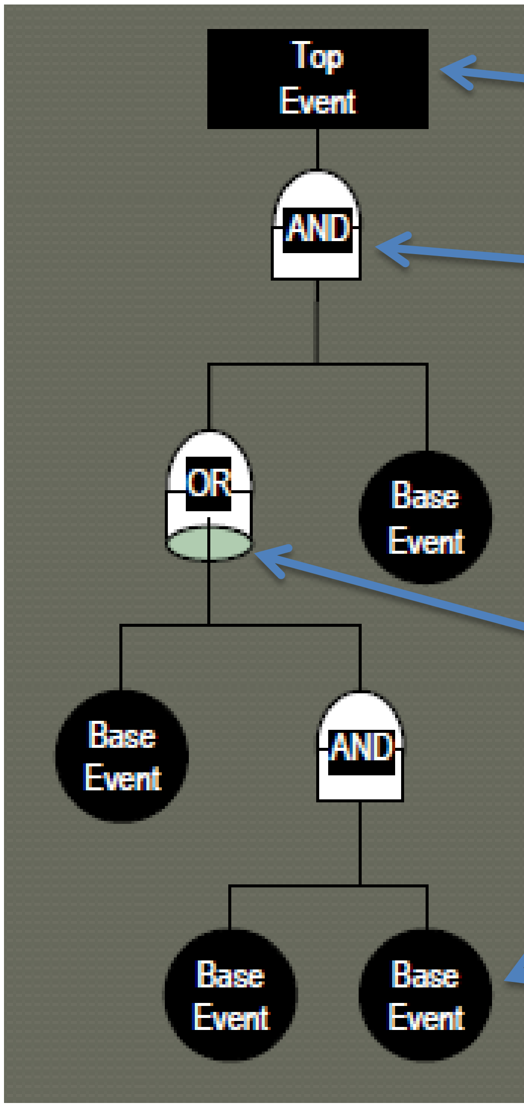


Basic event



Incomplete event (**not develop event**)

Principles of Fault Tree Construction



- Top Event
  - System Failure
- **AND** Gate
  - produces an output if all input events occur simultaneously. produces an output if all input events occur simultaneously.
- **OR** Gate
  - yields output events if one or more of the input events are present.
- Base Event

Quantitative Fault Tree Evaluation

- In **Boolean algebra**, binary states 1 and 0 are used to represent the two states of each event (i.e. occurrence and non-occurrence). Any event has an associated Boolean variable. Events A and B can be described as follows using Boolean algebra:

$$A = \begin{cases} 1 \_\_\_ event\ occurs \_\_\_\_\_\_ \\ 0 \quad event \quad does \quad not\ occur \end{cases}$$

$$B = \begin{cases} 1 \_\_\_ event\ occurs \_\_\_\_\_\_ \\ 0 \quad event \quad does \quad not\ occur \end{cases}$$

Suppose *"+" stands for "OR" and "·" for "AND". Suppose " Â " stands for "not A". Then the typical Boolean algebra rules are described as follows: A*

Quantitative Fault Tree Evaluation

Typical Boolean algebra rules

Identity laws

$$A + 0 = A$$

$$A + 1 = 1$$

$$A \cdot 0 = 0$$

$$A \cdot 1 = A$$

Indempotent laws

$$A + A = A$$

$$A \cdot A = A$$

Complementative laws

$$A \cdot \overline{A} = 0$$

$$A + \overline{A} = 1$$

Commutative laws

$$A + B = B + A$$

$$A \cdot B = B \cdot A$$

Associative laws

$$(A + B) + C = A + (B + C)$$

$$(A \cdot B) \cdot C = A \cdot (B \cdot C)$$

Distributive laws

$$A \cdot (B + C) = A \cdot B + A \cdot C$$

$$A + (B \cdot C) = (A + B) \cdot (A + C)$$

Absorption laws

$$A + A \cdot B = A$$

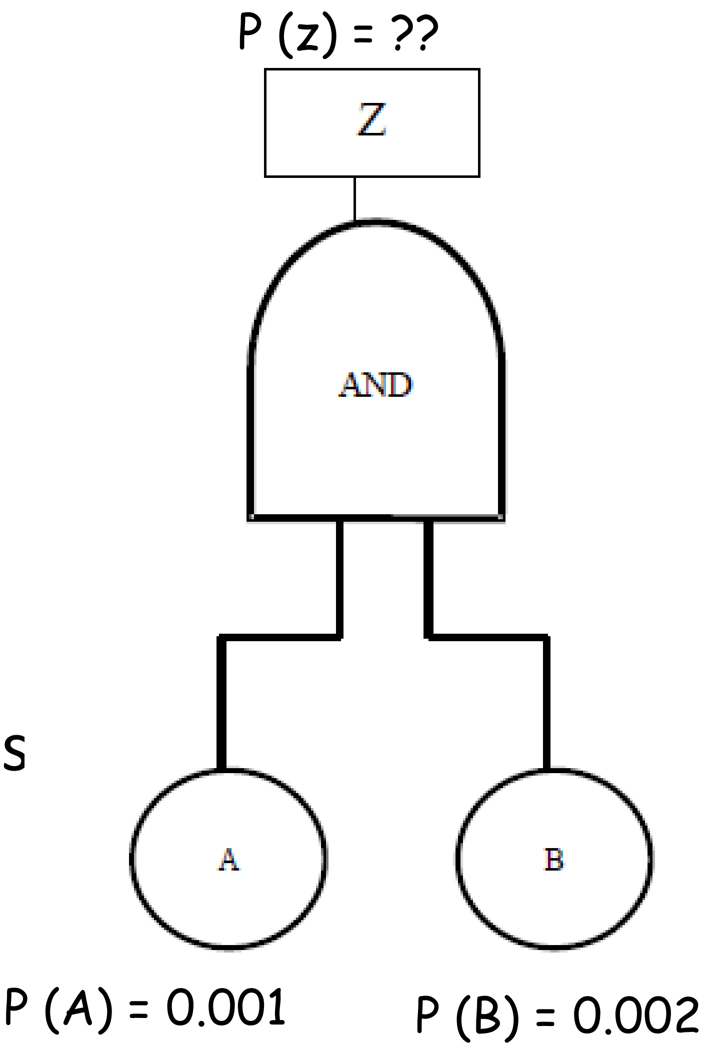
$$A \cdot (A + B) = A$$

Quantitative Fault Tree Evaluation

- Obviously the minimum cut set for the mini-tree is A.B.
- If one event is independent from the other, the occurrence probability of top event Z is

$$\mathbf{P(Z) = P(A \cdot B) = P(A) \times P(B)}$$

where P(A) and P(B) are the occurrence probabilities of events A and B.



Quantitative Fault Tree Evaluation

- Obviously the minimum cut set for the mini-tree is A + B.
- If one event is independent from the other, the occurrence probability of top event Z is

P(Z) = P(A + B) = P(A) + P(B) - P(A · B) = P(A) + P(B) – P(A) × P(B)

where P(A) and P(B) are the occurrence probabilities of events A and B.

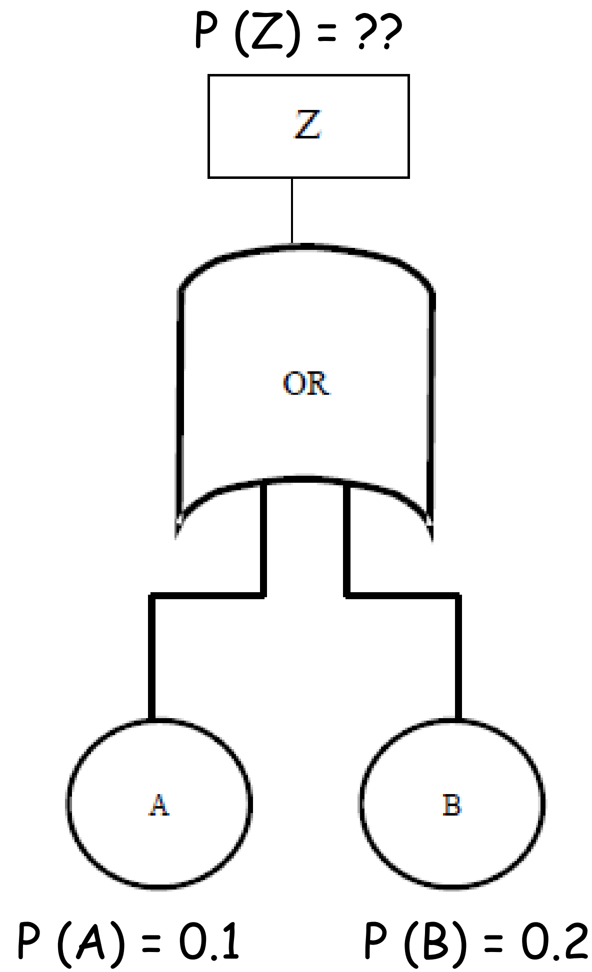
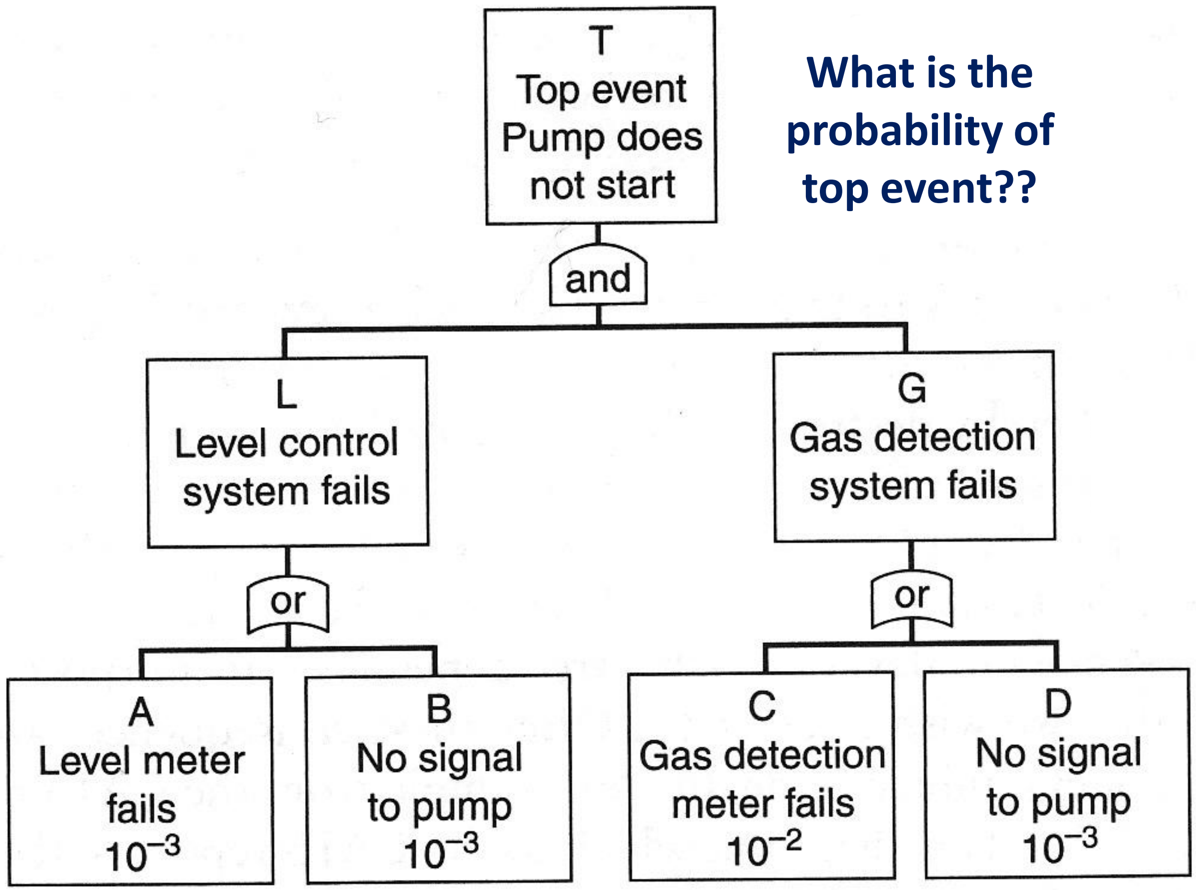


Figure 3.8 Simple fault tree



What is the probability of top event??

Failure rate

- Failure is defined as non-conformance to some defined performance criterion
- If failures occur randomly, they can be measured in terms of a constant **failure rate (λ)**
- **failure rate (λ) is a average number of failures per unit time**
- Failures ‘per year’ or ‘per million hours’

Failure Probability

$$P(A) = 1 - e^{-\lambda t}$$

Where,

λ= the failure rates (1/hour)

t = time (hour)

P(A) = Probability of event A

Example

- A car manufacturer finds that each of their cars breaks down, on average, once every 5 years. Assuming the failures occur randomly (constant failure rate):

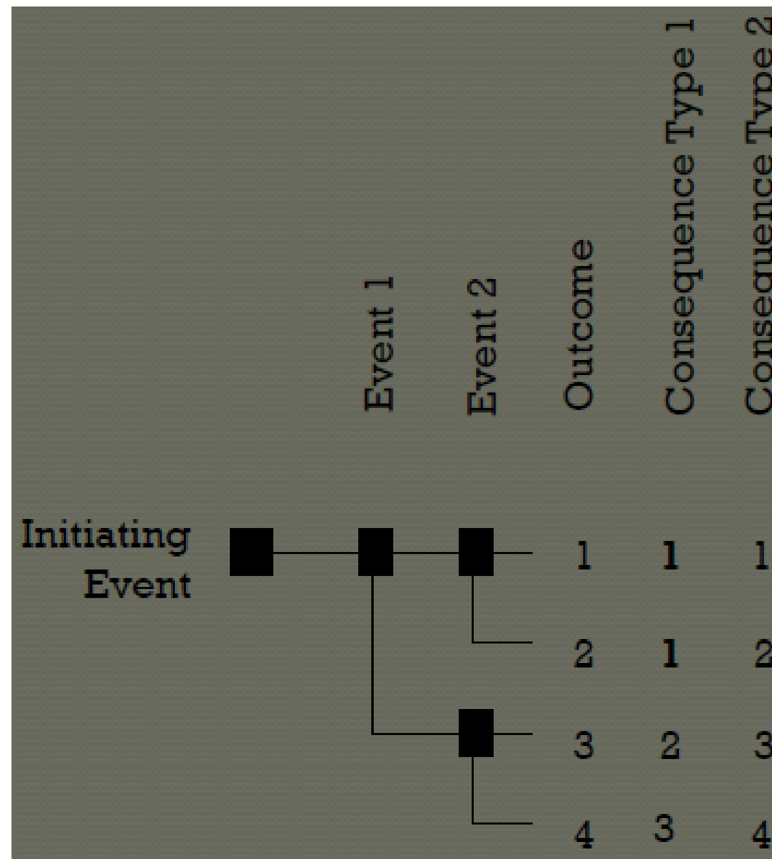
a. What is the probability that one of their cars will break down in a 10-year period?

Answer

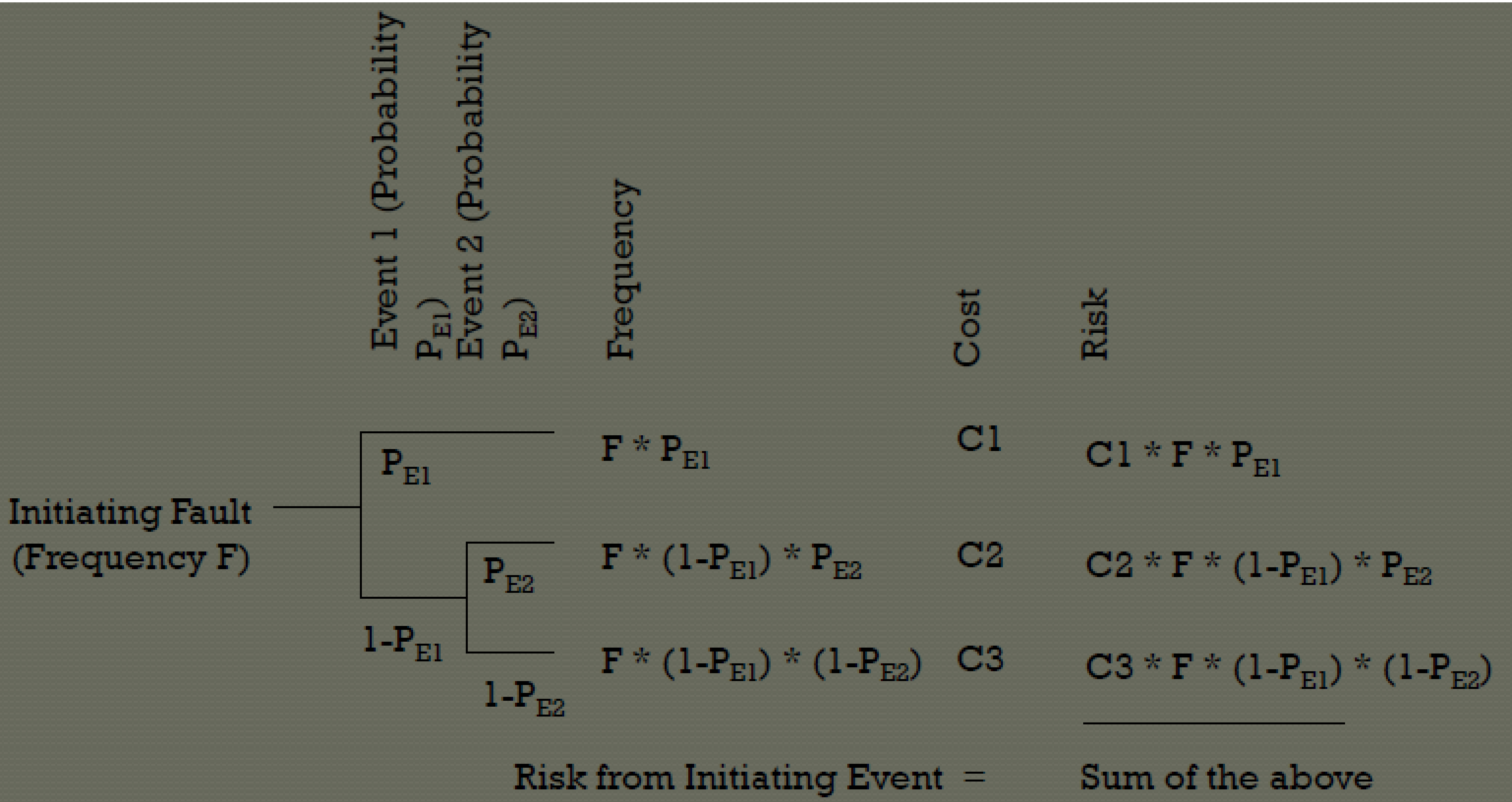
Introduction to Event Trees

- **History**
  - Developed from the concept of decision trees
  - First applied to nuclear power stations

- **Event Tree Terms**
  - Initiating Event (from Hazard Identification)
  - Events
  - Outcome
  - Consequence Types
    - Monetary
    - Safety
      - Fatalities
      - Injury

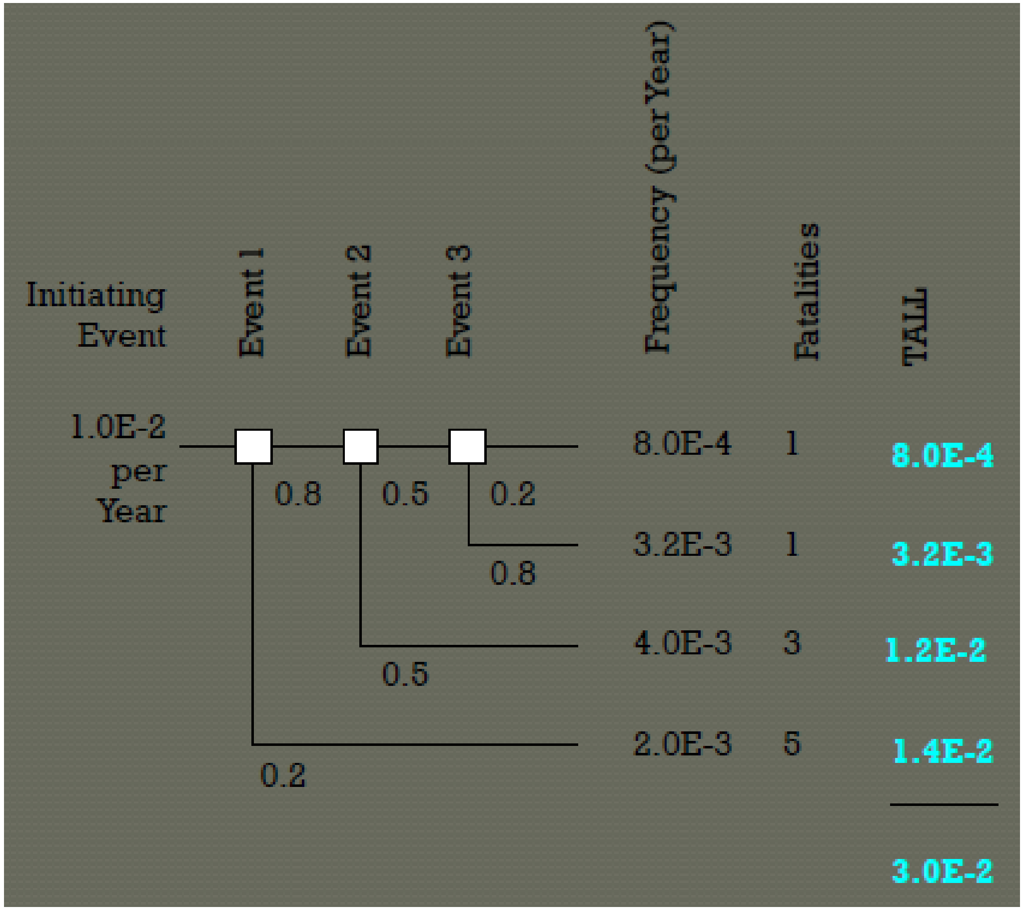


Event Tree Analysis (ETA)



Use of Event Trees in QRA

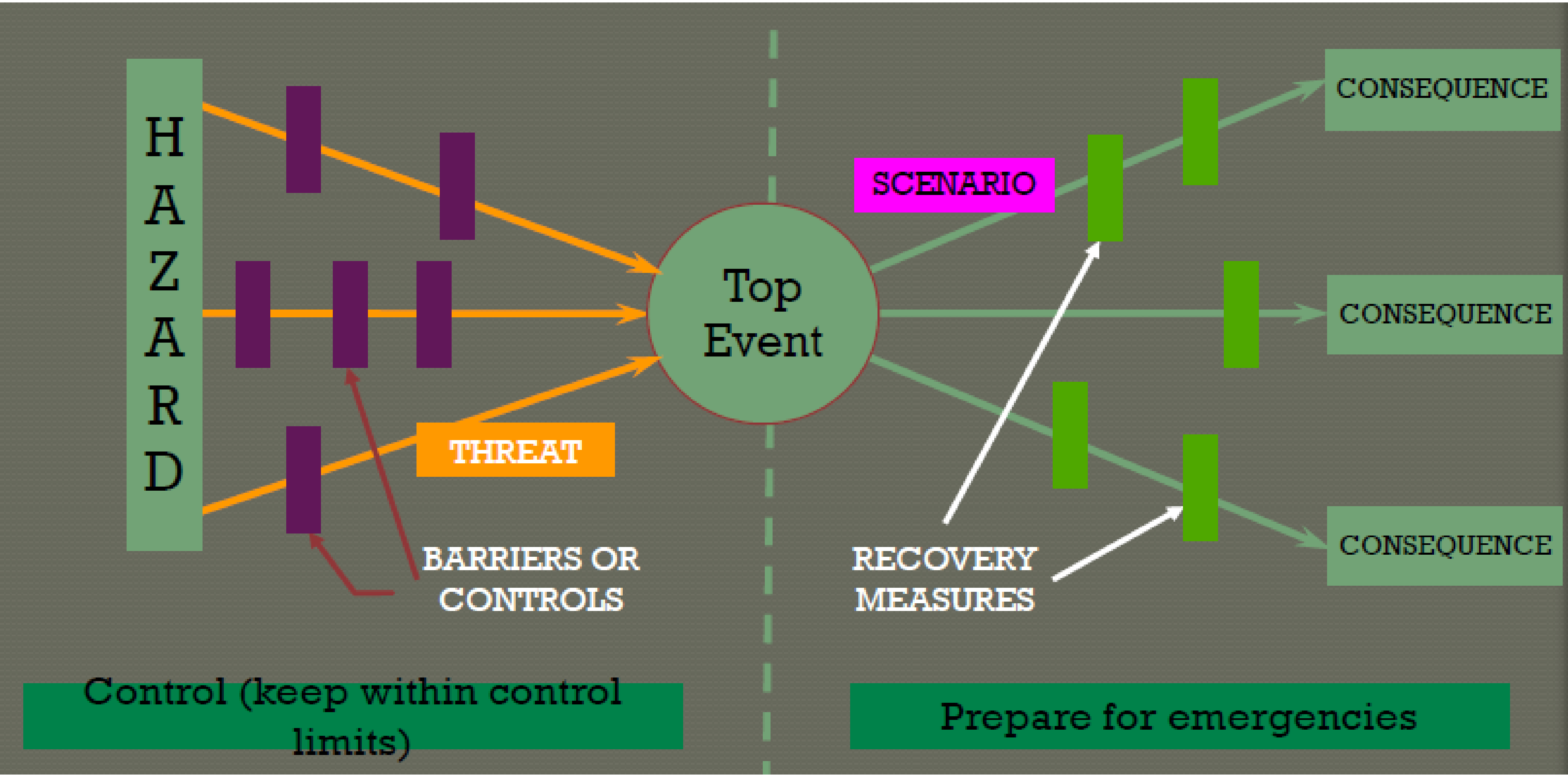
- **Risk Analysis**
  - Outcome Risk
    - Frequency x Consequence
  - Initiating Event Risk
    - Sum of outcome Risks
- **Total Risk**
  - Sum all Initiating Event Risks
  - Interpretation of Risk
  - Presentation of Risk
    - Tables
    - Graphs



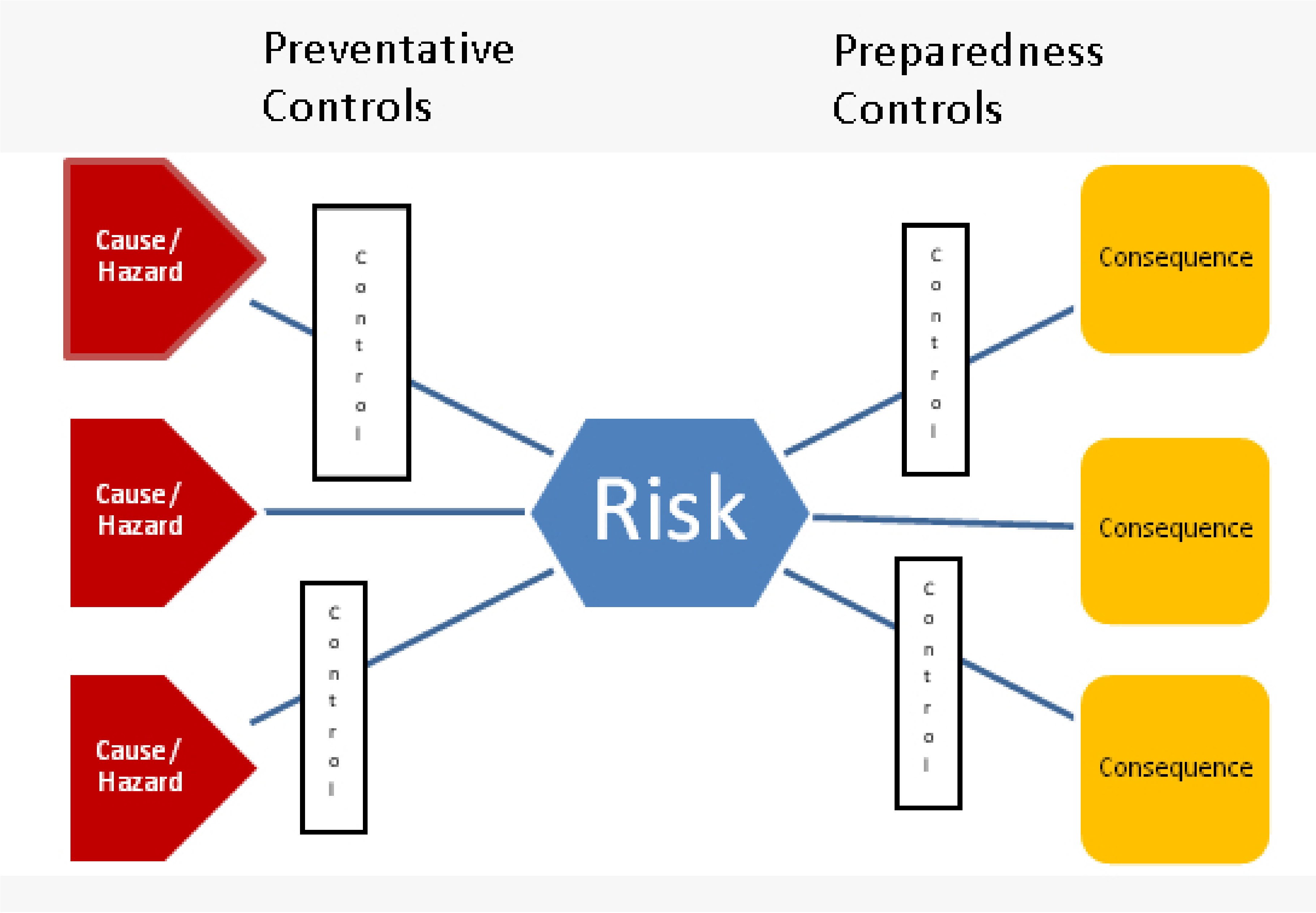
BOW-TIE Analysis

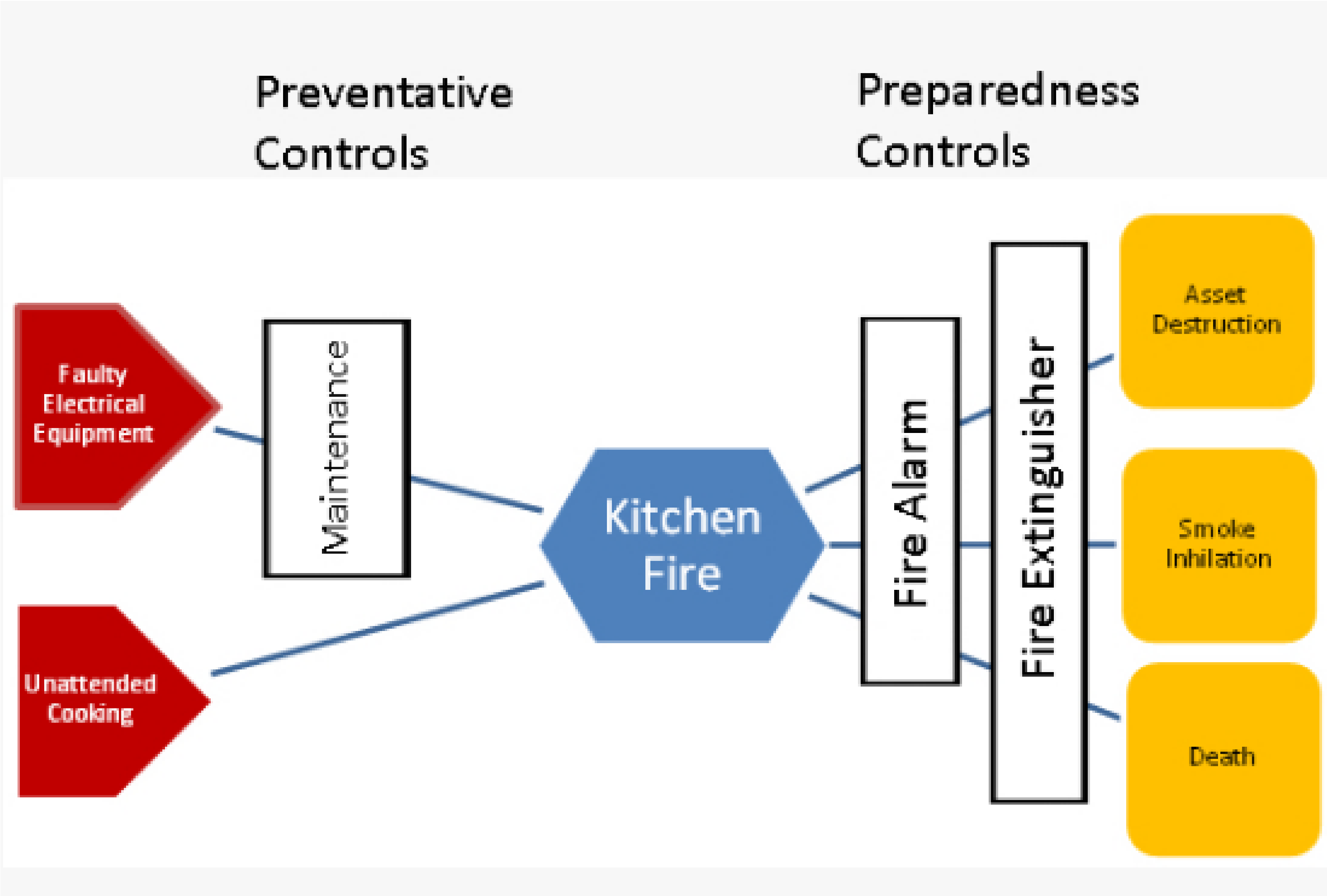
- structured approach for risk analysis within safety cases where quantification is not possible or desirable.
- combine the **cause** and **consequence** analyses into a single diagram with the **Fault Tree** plotted sideways on the left and the **Event Tree** plotted sideways on the right
- the **Major Accident** is plotted as a large circle in the middle – looks like a Bow Tie.

BOW-TIE



Reduce Likelihood **Mitigate consequences**

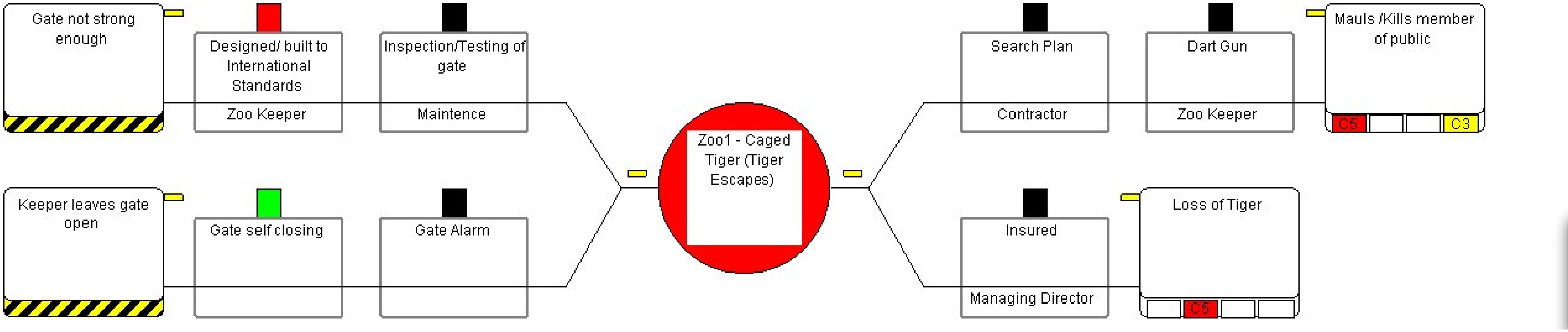

Preventative Controls
Preparedness Controls
Cause / Hazard
Cause / Hazard
Cause / Hazard
control
control
Risk
control
control
Consequence
Consequence
Consequence


Preventative Controls
Preparedness Controls
Faulty Electrical Equipment
Unattended Cooking
Maintenance
Kitchen Fire
Fire Alarm
Fire Extinguisher
Asset Destruction
Smoke Inhilation
Death

[Slide Presentation (link)]

Tiger Bowtie

This is the bowtie diagram for the causes and consequences of a tiger escaping from a cage. The diagram can be extended further to identify the reasons why a control may fail and in turn the controls that will prevent this control from failing.



Overall Risk Evaluation

- Expected consequence value per unit time

$$= \sum_{all\ j} F(A_j)\,x_j = F \sum_{all\ j} P(A_j)\,x_j$$

$P(A_j)$ = **Probability** of outcome j
F = Initiating event frequency
$F(A_j)$ = **Frequency** of outcome j
X_j = Consequence value of outcome j

Risk Presentation

- The results from a QRA may be expressed as:
- **Individual risks**
  - Risk experienced by individuals on the installation.
  - Refers to the risk of death, and may be expressed as an **individual risk per annum (IRPA)** or a **fatal accident rate (FAR)** per 100 million exposed hours
- **Group risks**
  - risk experienced by the whole group of personnel working on the installation or otherwise affected by it.
  - This usually refers to the risk of death, and is usually expressed as an average number of fatalities per installation-year, known variously as **annual fatality rate**, **potential loss of life (PLL),** it may be expressed as an **FN curve**, showing the cumulative **frequency (F) of events involving N** or more fatalities.

Potential Loss of Life (PLL)

- PLL = Statistical Annual Number of Fatalities

$$\mathbf{PLL = \sum_{i=1,NS} f_i \times N_i}$$

Where:

NS = Number of Scenarios

f_i = Frequency of scenario 'i' (per year)

N_i = No. of fatalities estimated for scenario i

Individual Risk

- **Individual Risk Per Annum (IRPA)**
  - **IRPA is the frequency with which as individual may be expected to sustain fatal due to exposure to specific hazards in a year.**

$$IR = \frac{PLL \times Exposure}{POB}$$

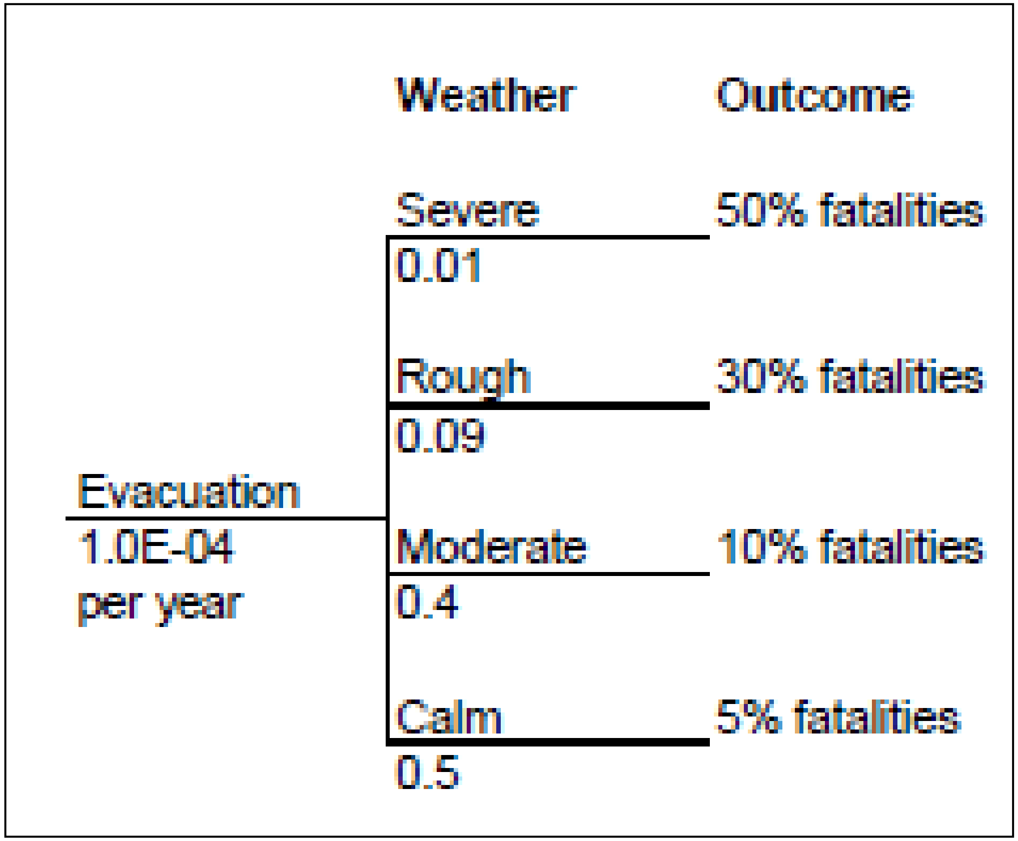
Where,

Exposure = Percentage of time exposed to hazard

POB = Number of workers exposed

Example Risk Calculation

- This example presents the risks in evacuation from an accident whose frequency is 10^{-4} per installation year. Four different weather cases are considered, with different probabilities of occurrence and outcomes ranging from 5% to 50% fatalities among the 30 people on board, as shown in the **event tree**.



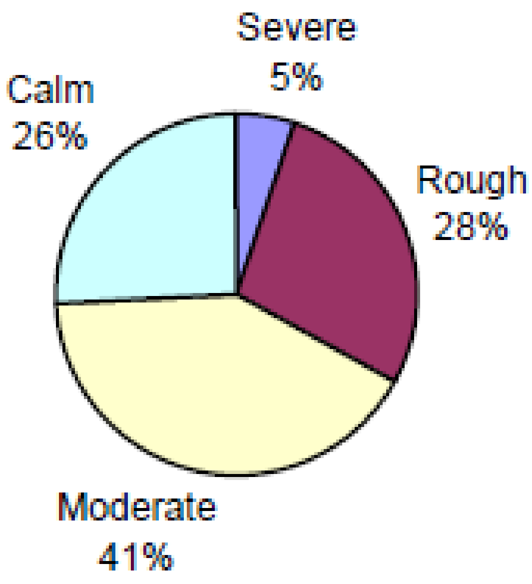
Example Risk Calculation

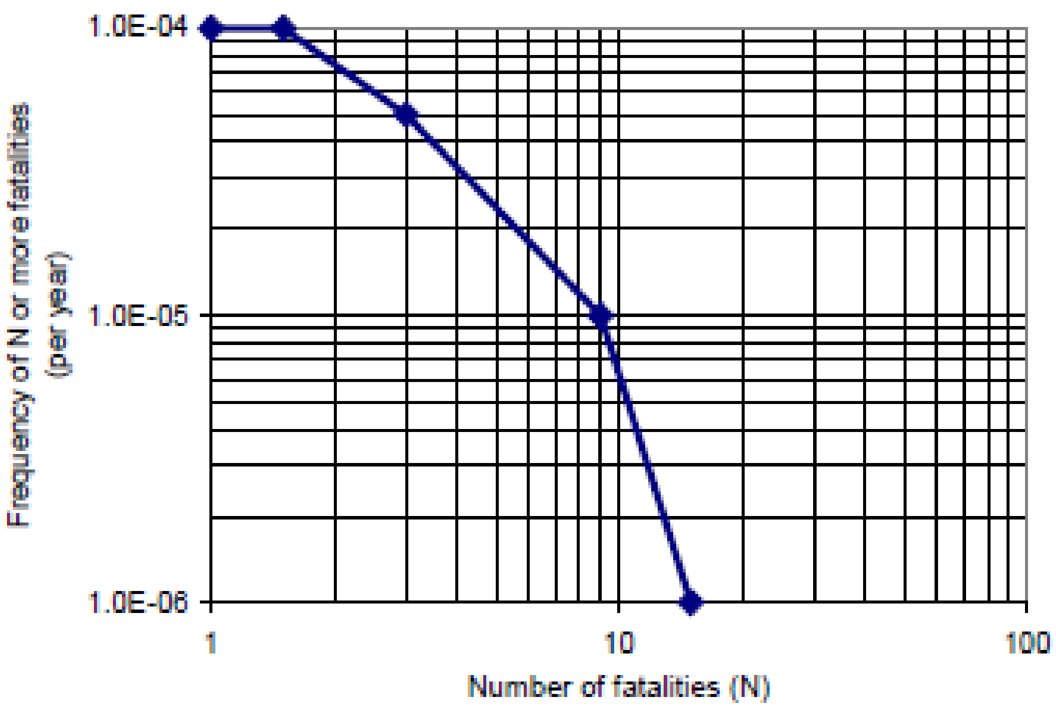
- The spreadsheet calculates the individual risk for a person continuously on board (LSIR = 9.7×10^{-6} per person year), the group risk (GR = 2.9×10^{-4} per installation year) and the cumulative frequencies (F) for the FN curve.

Event frequency		1.0E-04	per year				
POB		30					
Weather	Weather prob	Fatality fraction	Fatalities (N)	Outcome freq	LSIR	GR	F
Severe	0.01	0.5	15	1.0E-06	5.0E-07	1.5E-05	1.0E-06
Rough	0.09	0.3	9	9.0E-06	2.7E-06	8.1E-05	1.0E-05
Moderate	0.4	0.1	3	4.0E-05	4.0E-06	1.2E-04	5.0E-05
Calm	0.5	0.05	1.5	5.0E-05	2.5E-06	7.5E-05	1.0E-04
Total	1.0			1.0E-04	9.7E-06	2.9E-04	

Example Risk Calculation

- The pie chart (below left) shows the distribution of group risk by weather category. In this case, fatalities in moderate weather dominate the result. The FN curve is shown (below right).





DECISION MAKING

- **The ALARP Principle - *A*s *L*ow *A*s *R*easonably *P*racticable** *@* ALARA (***R**easonably **A**chievable*)

Part of the philosophy of the UK Health and Safety at Work etc. Act 1974, which requires **“*every employer to ensure, so far as is reasonably practicable, the health, safety and welfare of all his employees*”.**

- Intolerable is greater than 1 in 10,000 (10^{-4}) per year

- Acceptable is no greater than 1 in 1,000,000 (10^{-6}) per year

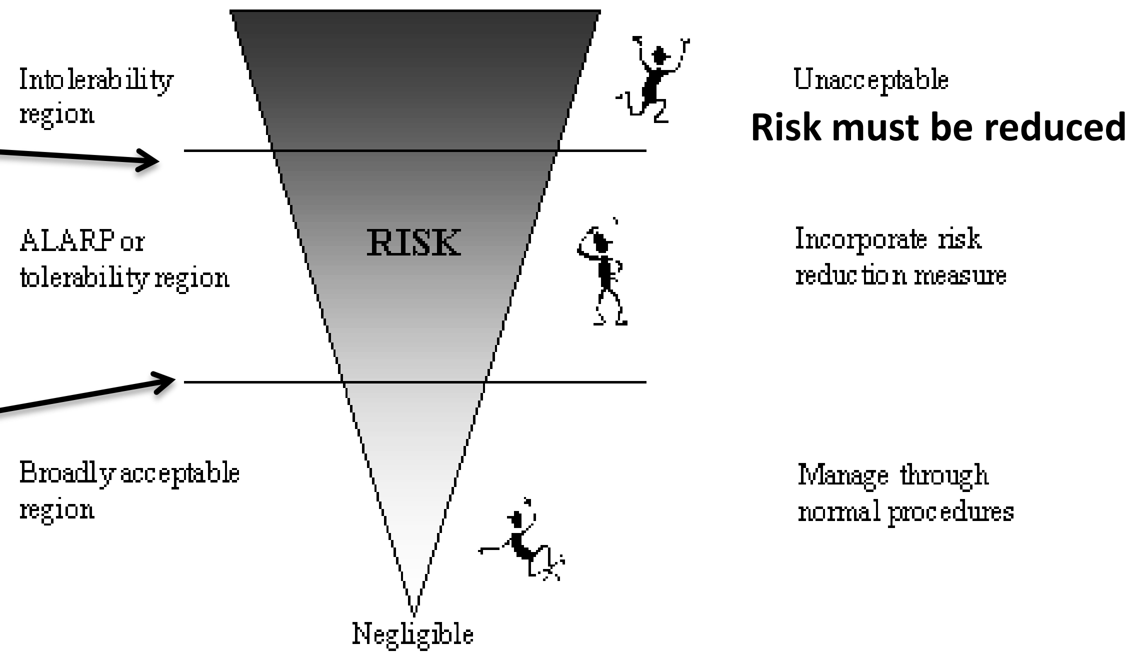
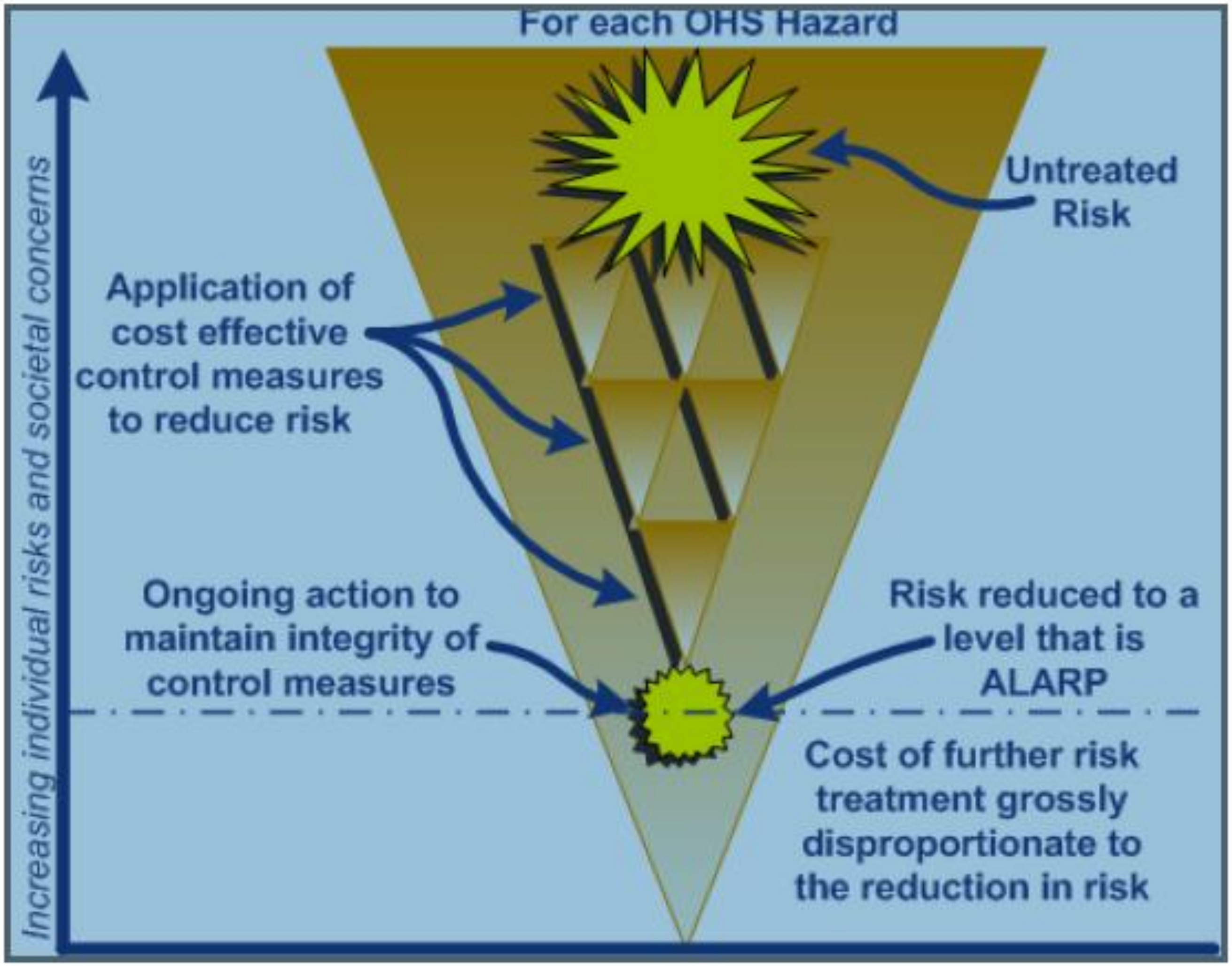


Figure 4 – OPGGS(S) ALARP triangle diagram



CONCLUSION