Risk Assessment

Components

- Identify hazards using PHA methods
- Identify scenarios for hazards to cause incidents, e.g., using HAZOP
- Assess consequences of events
- Estimate probabilities of events using failure rate data
- Risk comparisons, reductions, and risk management

The Problem

Example

You have a very important appointment tomorrow at 9:00 a.m. The distance between your house and the interview location is 10 miles and under best conditions it would take you 15 minutes to get there by car.

What time will you leave your house?

Risk Table

Example

Scenario	Likelihood	Consequence

Risk Table

Example

Scenario	Likelihood	Consequence (minutes delayed)
1. Car does not start	Low	5
2. Car breaks down enroute	Very low	30
3. Minor traffic congestion	High	10
4. Severe traffic congestion	Moderate	20
5. Police stops you	Low	15
6. Minor accident	Low	30
7. Major accident	Very low	2 hours

Calibrating the Likelihood Example

- *High* - Minor traffic congestion
  - Three days in a week = 3/5 = 0.6
- *Moderate* - Severe traffic congestion
  - Once every 2 weeks = $1/(2\times5)$ = 0.1
- *Low* - Car does not start
  - Once in 3 years = $1/(3\times250$ days) = 1/750 = 0.001
  - Police stops you
  - Minor traffic accident
- *Very Low* - Car breaks down enroute
  - Once in 15 years = $1/(15\times250)$ = 0.0003
  - Major traffic accident

Risk Quantification

Example

Scenario	Likelihood	Delay Minutes	Departure Time
0	$1-\Sigma\ \pi$	0	8:45
1	0.001	5	8:40
2	0.0003	30	8:15
3	0.6	10	8:35
4	0.1	20	8:25
5	0.001	15	8:30
6	0.001	30	8:15
7	0.0003	120	6:45

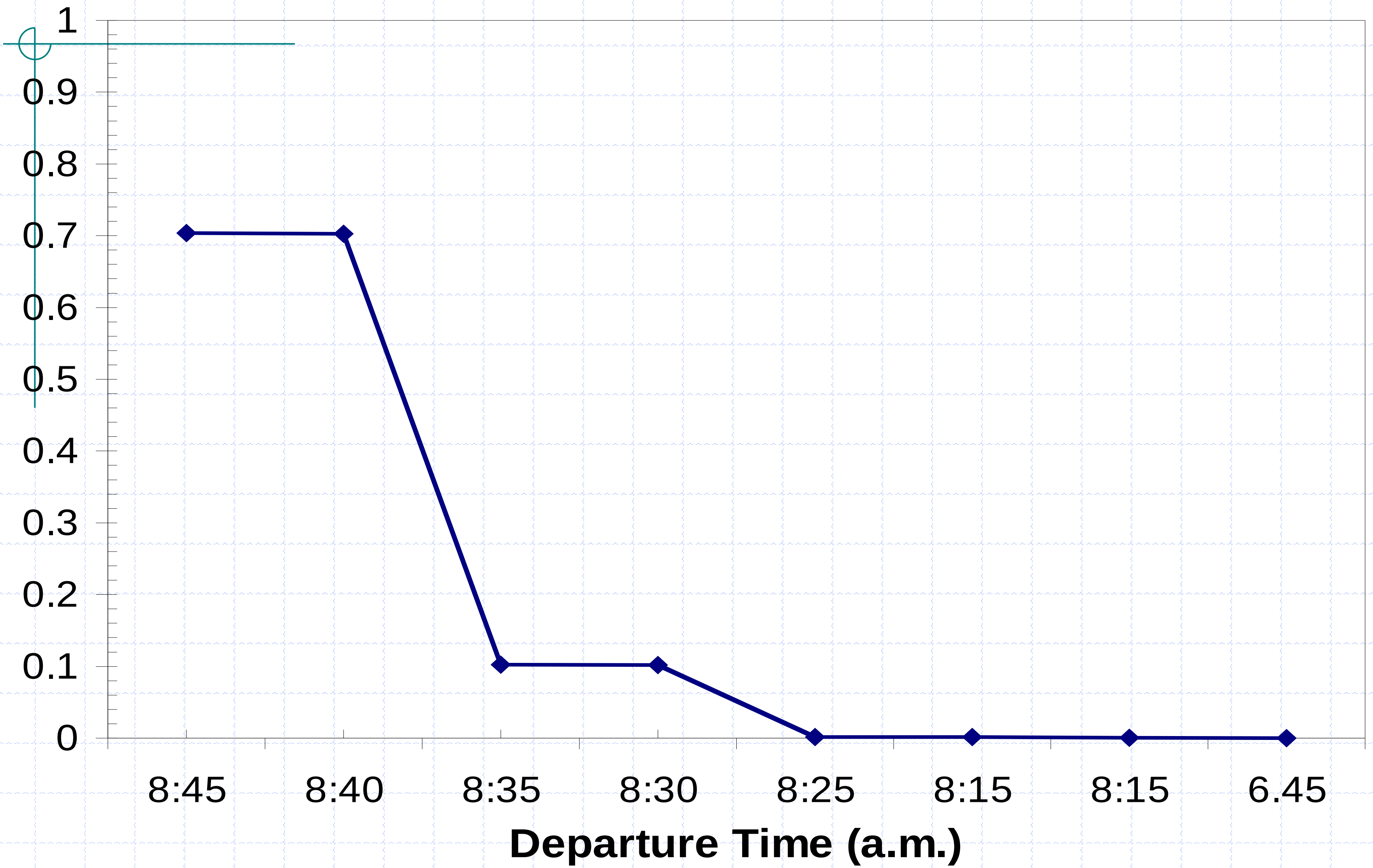
Risk Quantification

Example

Scenario	Delay Minutes	Departure Time	Probability	Probability of Missing Appointment	Probability of On Time Arrival
0	0	8:45	0.2964	0.7036	0.2964
1	5	8:40	0.001	0.7026	0.2974
2	30	8:15	0.0003	0.0013	0.9987
3	10	8:35	0.6	0.1026	0.8974
4	20	8:25	0.1	0.0016	0.9984
5	15	8:30	0.001	0.1016	0.8984
6	30	8:15	0.001	0.0003	0.9997
7	120	6:45	0.0003	0.0000	1.000

Risk Curve

Example



Other Risk Parameters

Example

- **Average Travel Time**

  = 15 + Σ (Delay in Minutes) X (Probability)

  = 15 + (5X0.001) + (30X0.0003) + (10X0.6) + (20X0.1)

  + (15X0.001) + (30X0.001) + (120X0.0003)

  = 23.1 minutes

- **Minimum Travel Time = 15 minutes**
- **Maximum Travel Time = 135 minutes**

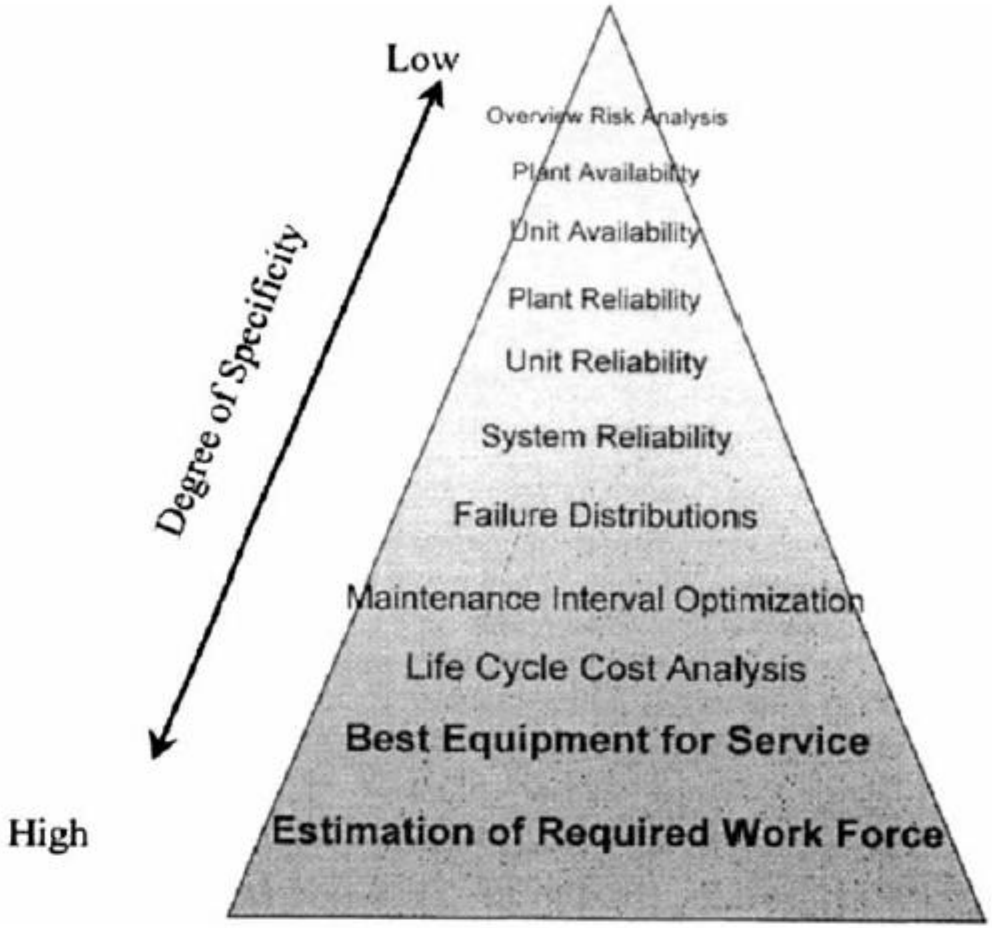


FIGURE 1.3. ***Detail of data required for complexity of analysis.***

Fault Tree Analysis

Fault tree analysis (FTA) is a deductive technique that focuses on one particular incident and then constructs a logic diagram of all conceivable event sequence that could lead to the incident.

FTA identifies ways that hazards can lead to incidents.

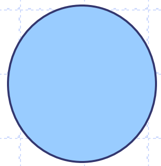
Fault Tree Analysis

- Purpose
  - To identify failure pathways, both mechanical and human that could lead to an incident.
- Applications
  - Can be used during design, modification, or operation of a facility
- Results
  - A set of logic diagrams that illustrate how certain combination failures and/or errors can result in specific incidents

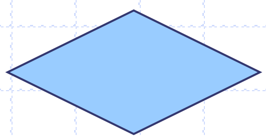
Fault Tree Analysis

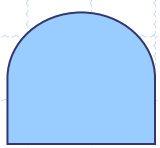
- Data
  - P&IDs, equipment drawings and specifications, operating procedures, knowledge of failure modes, and failure rate data
- Staff
  - Normally, one person is assigned to prepare a single fault tree for a given incident
- Time
  - Preparation of fault trees can be very time consuming for large or complex facilities

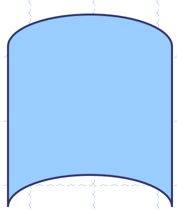
Basic Components

Basic Event  A basic initiating fault (e.g., component failure)

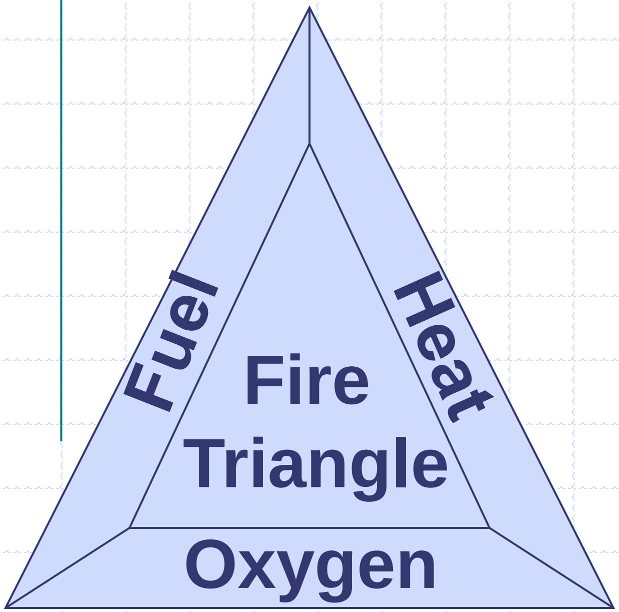
Intermediate Event  Occurs as a result of events at a lower level acting through logic gates

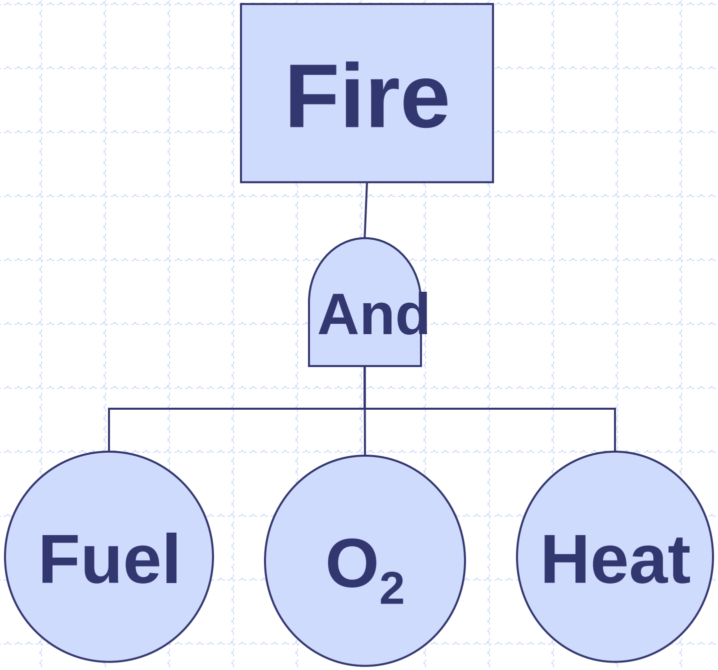
Undeveloped  Undeveloped event due to lack of information or significance

“And” Gate  Output occurs if all input events occur

“Or” Gate  Output occurs if any input event occurs

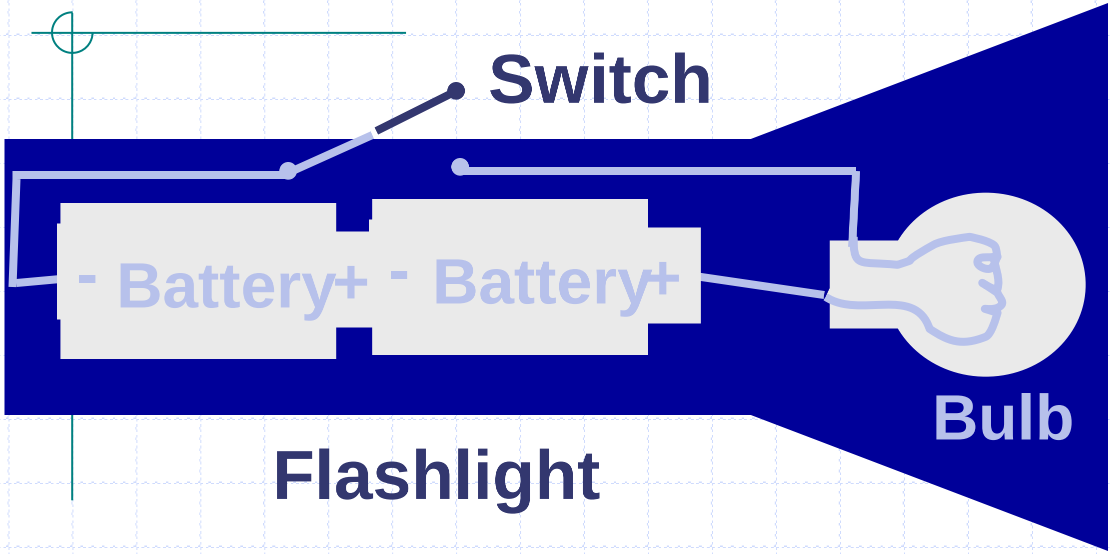
Logic Diagram for Fire Triangle

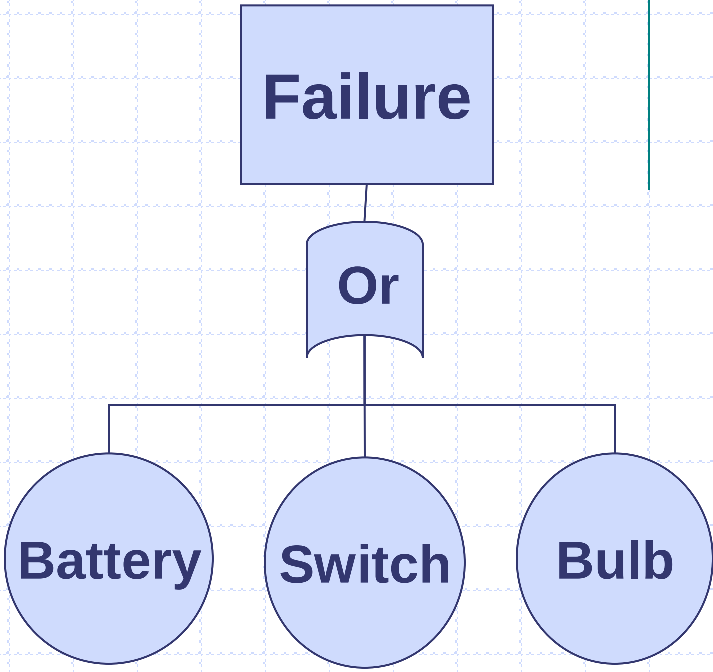




Probability (parallel): $P = \prod_{i=1}^{n} P_i$

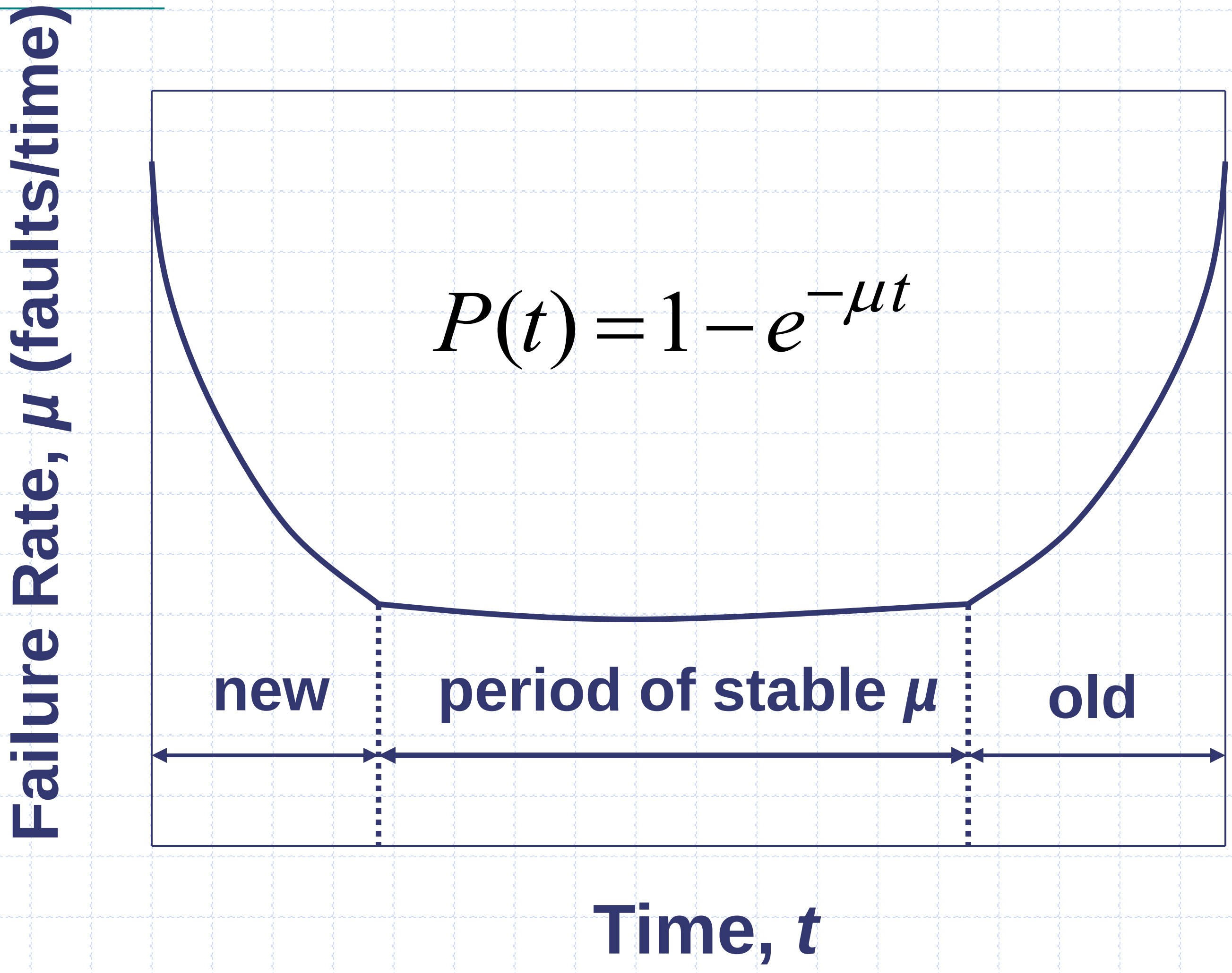
Fault Tree for a Flashlight



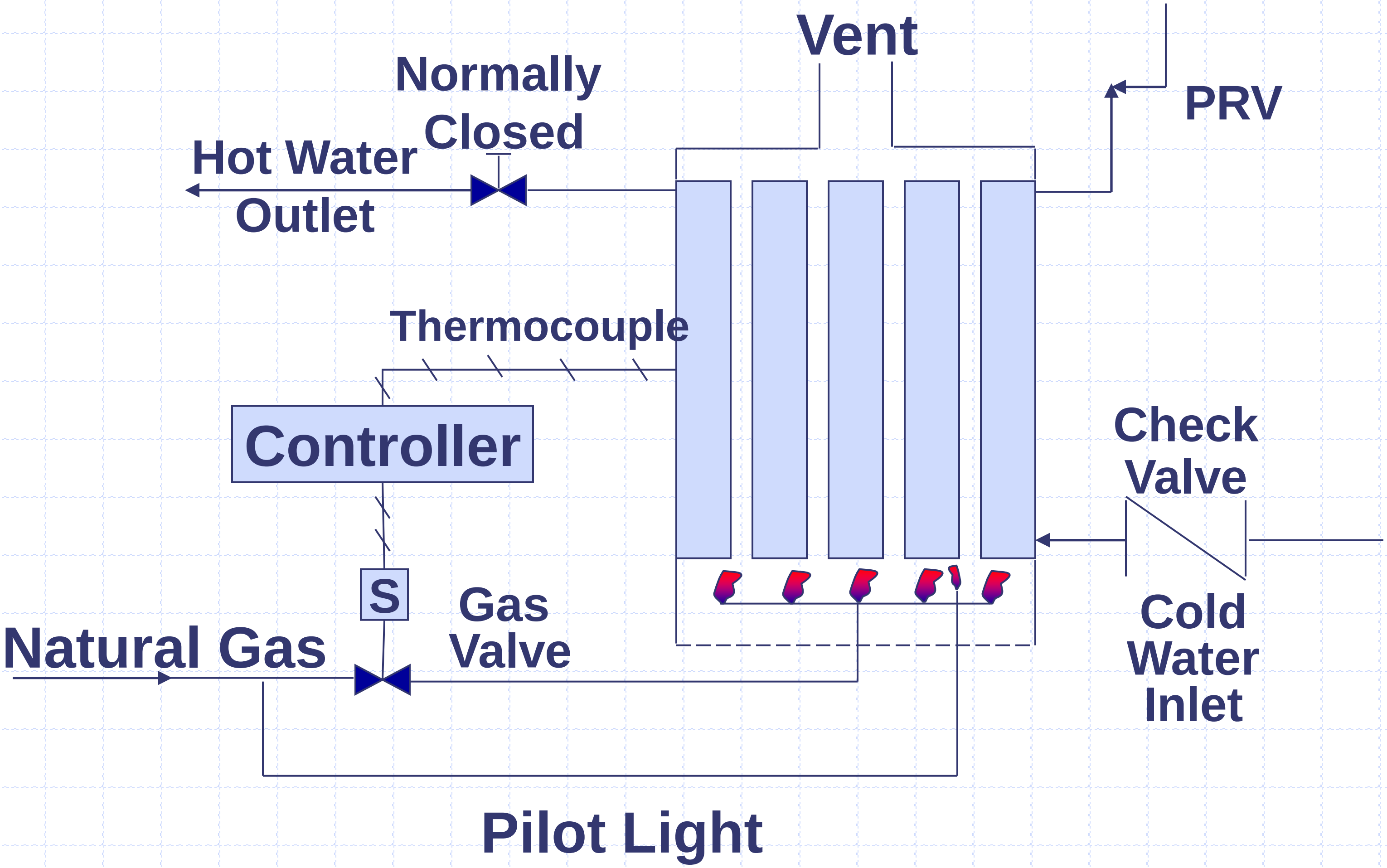


Probability (series): $P = \sum_{i=1}^{n} P_i$

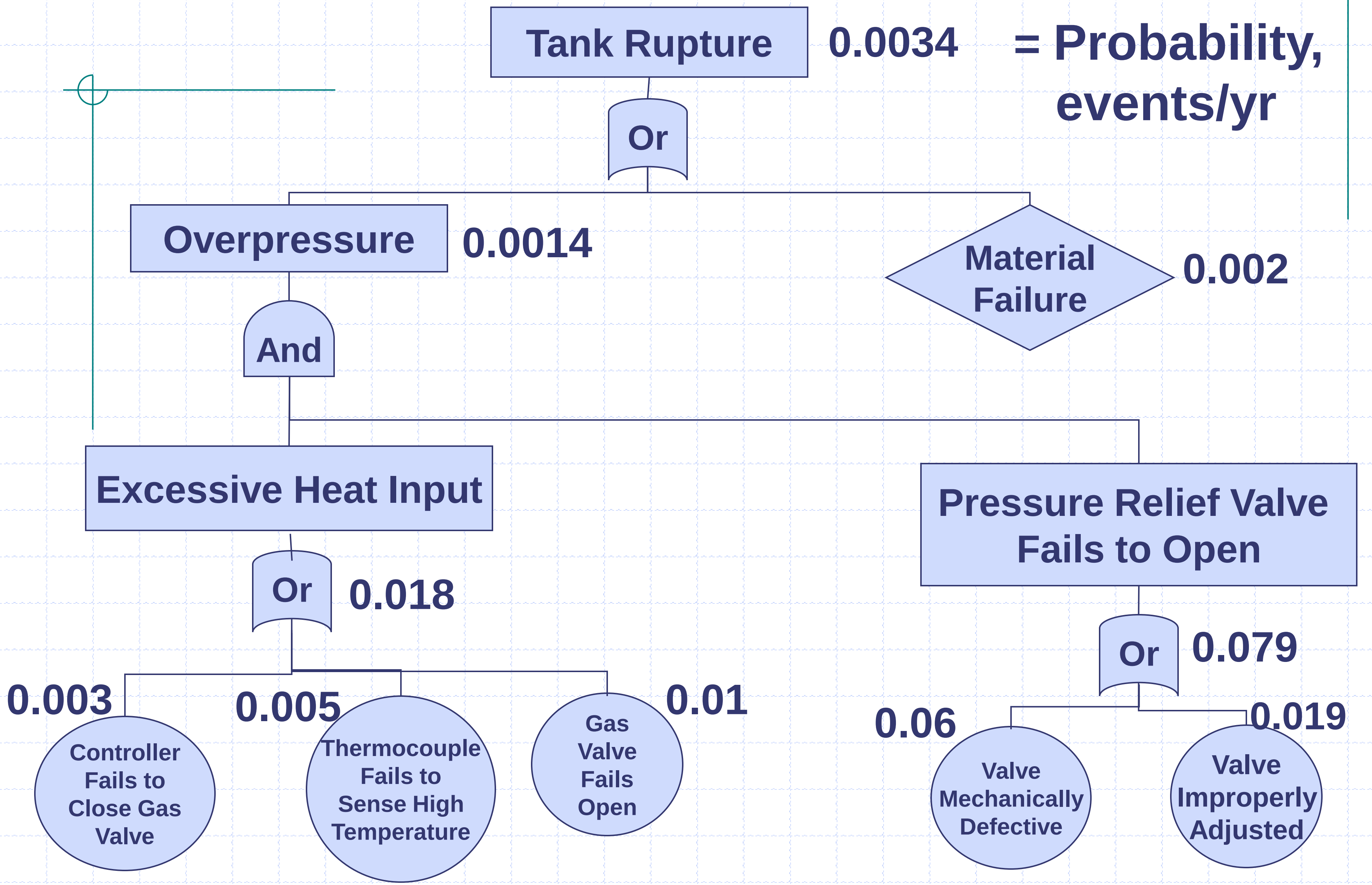
Process Hardware Failure Rate and Probability of Failure During (0, *t*)



Schematic of Hot Water Heater



Fault Tree Rupture of Hot Water Tank



Acceptability of Risk

- Acceptability of risks is judged by comparing the average individual risks with risks associated with some common activities and incidents.
- Two categories of risk are:
  - Voluntary
  - Involuntary
- Industrial workers are voluntary risk recipients.
- Persons living in residential areas near the plant are involuntary risk recipients.

Comparison of Voluntary and Involuntary Risks

Voluntary		Involuntary	
Activity	Risk of Death per Person per Year (x 10^{-6})	Activity	Risk of Death per Person per Year (x 10^{-6})
Smoking (20 cigarettes/ day)	5,000	Influenza	200
		Leukemia	80
Motorcycling	2,000	Run over by road vehicle (UK)	60
Car racing	1,200		
Drinking (1 bottle wine/ day	750	Run over by road vehicle (USA)	50
Car driving	170	Floods (USA)	2.2
Rock climbing	40	Tornadoes (Mid-West USA)	2.2
Football	40	Earthquakes (California)	1.7
Operation of PDSB's LPG Terminal	33	Storms (USA)	0.8
Taking contraceptive pills	20	Bites of venomous creatures (UK)	0.2
		Lightning (UK)	0.1
		Falling aircraft (USA)	0.1
		Release from atomic power station (at site boundary) (USA)	0.1
		(at 1 km) (UK)	0.1
		Flooding of dikes (Holland)	0.1
		Transport of petrol and chemicals (USA)	0.05
		Falling aircraft (UK)	0.02
		Transport of petrol and chemicals (UK)	0.02

Acceptability of Risk

- Voluntary Risk
  - Society's acceptance of voluntary risk is about the same as acceptance of death by disease.
    - 1×10^{-6} fatalities per person hour of exposure, or
    - 8.76×10^{-3} fatalities per person year with continuous exposure (8,760 hours)
  - A risk of 1×10^{-3} fatalities per person year is generally acceptable to industrial workers.
- Involuntary Risk
  - Acceptable level of risk is about one one-thousandth of the value for voluntary exposure, i.e., about 1×10^{-6} fatalities per person year.

Acceptability of Risk I

- Each individual in the population has a different perception of risk, a different opinion as to the level of risk posed by various activities, and a different opinion on how much risk is acceptable
- Factors influence individual perceptions of risk:
  - Cultural and educational background,
  - how much benefit the individual feels that will be received from the activity; i.e., the benefit received is sufficient to justify the risk.

Acceptability of Risk II

- Public's lack of understanding of risk indicators.
  - Accidents that result in multiple fatalities cause more public concern than accidents that cause only one or two fatalities but occur more often.
- Some members of the public may never be convinced that a hazardous materials facility is safe enough.
  - Most regulatory agencies take a realistic approach and are willing to license or approve facilities that satisfy their risk criteria.

Case Study

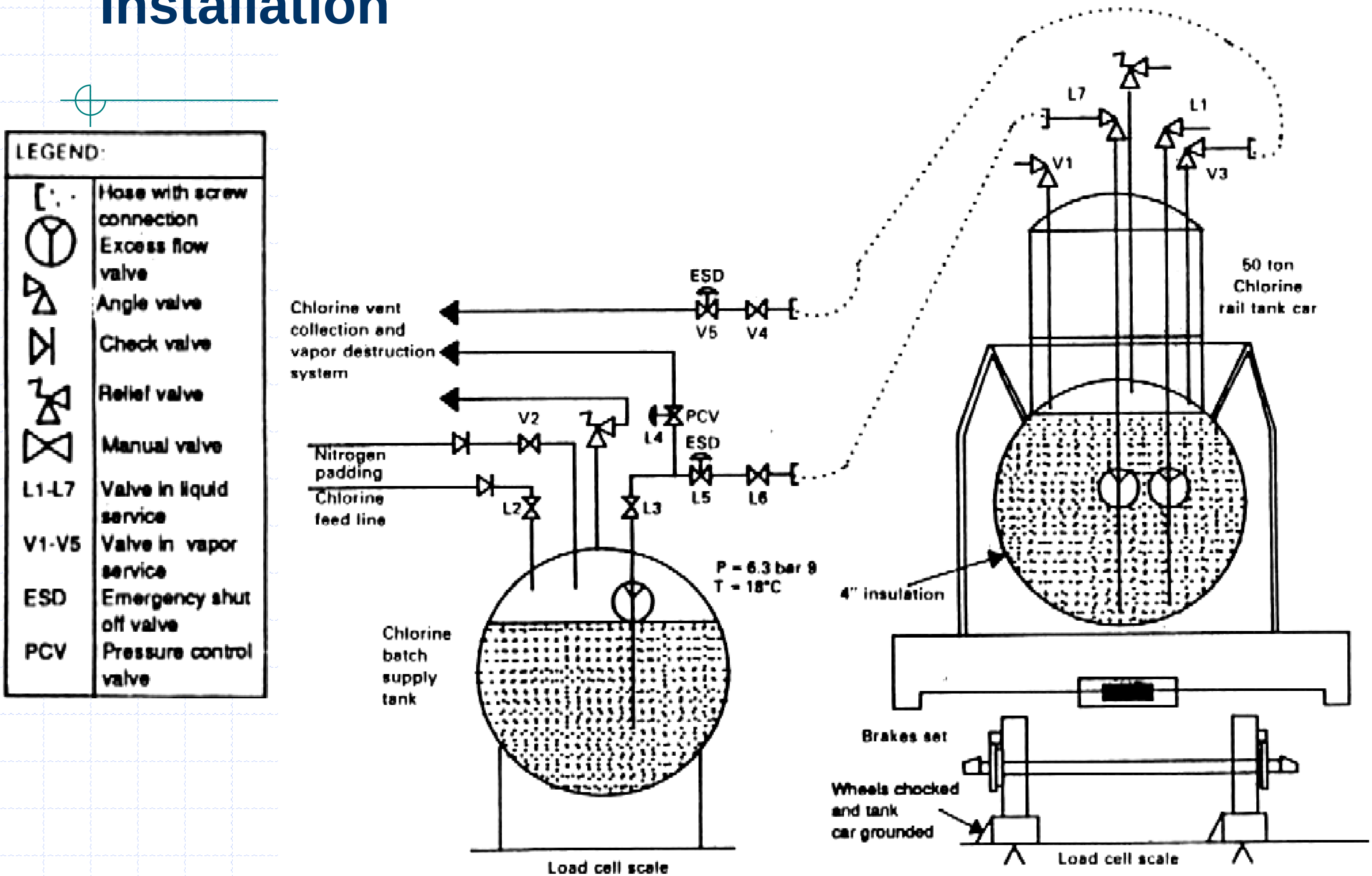
CHLORINE RAIL TANK CAR LOADING FACILITY

Source: Chemical Process Quantitative Risk Analysis, CCPS, AIChE, New York (1989)

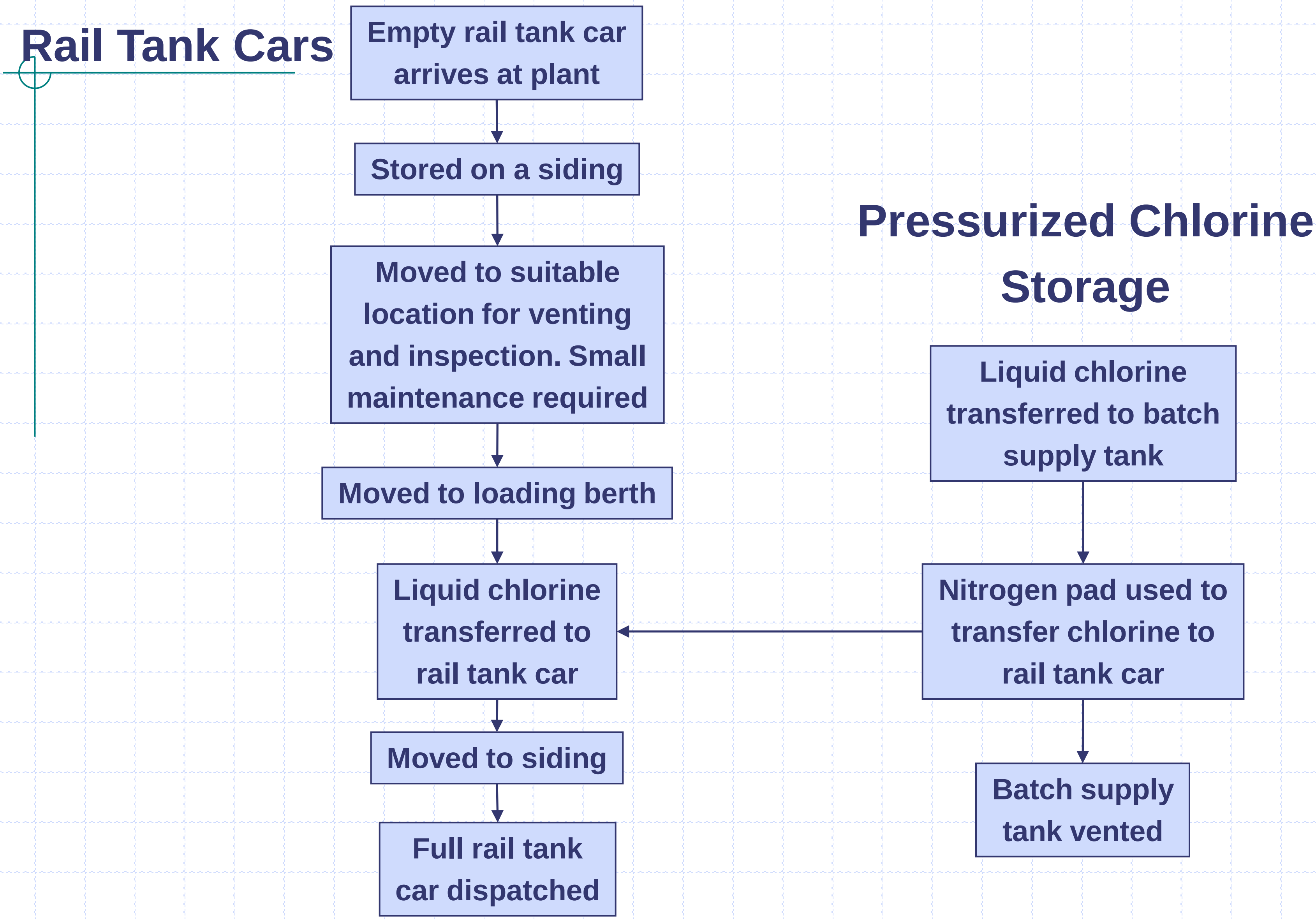
Chlorine Rail Tank Car Loading Facility

- Steps involved in the risk assessment:
- Data gathering
- Hazard scenario development
- Consequence analysis
- Probability of occurrence
- Risk estimation

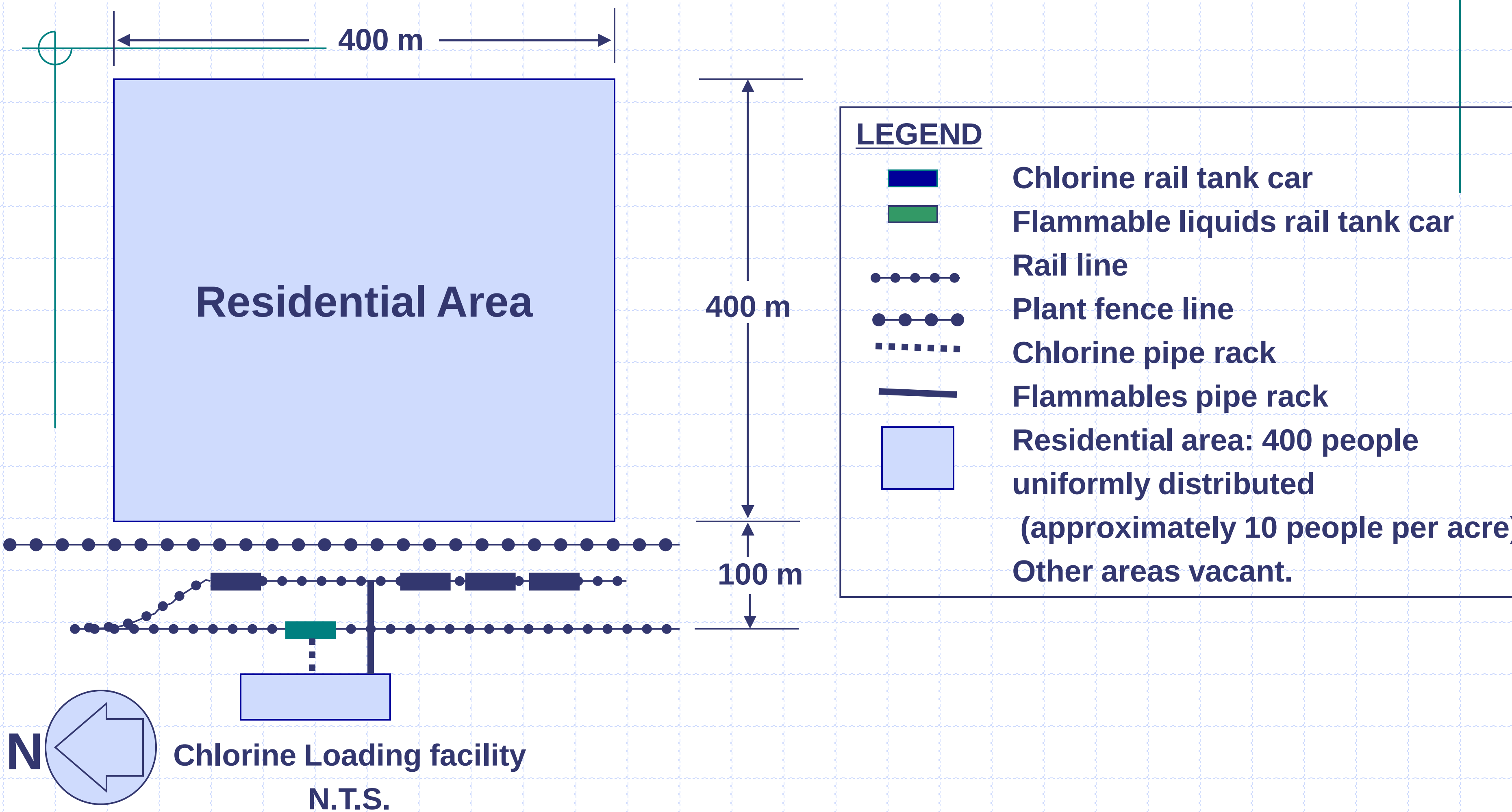
Diagram of Liquid Cl_2 Rail Tank Car Loading Installation



Simplified Chlorine Rail Car Loading Procedures



Layout of Chlorine Rail Loading Facility



Hazard Identification

The risk assessment is based on specific chlorine release incidents.

- To estimate public risk, localized incidents with consequences that do not extend beyond the boundary fence are not evaluated.
- Major incidents of similar scale are grouped and represented as single incidents with frequency determined from contributions of all individual incidents in each group.

Representative Set of Incidents

INCIDENT NUMBER	INCIDENT DESCRIPTION
1	Small liquid leakage (equivalent to 1/2-in., 12 mm hole) Duration = 10 min (estimated) Causes: Valve leak (7 valves and associated flanges) Hose leak Impact failure of liquid connecting pipe
2	Small vapor leakage (equivalent to 1/2-in., 12 mm hole) Duration = 10 min (estimated) Causes: Valve leak (5 valves and associated flanges) Hose leak Impact failure of vapor connecting pipe Relief valve leak
3	Large vapor leakage Duration = 60 min (estimated time for fire fighting measure to cool chlorine car and stop release) Cause External fire lifts relief valve

Summary of Representative Release Rate Estimates

INCIDENT	DESCRIPTION	ESTIMATED RELEASE RATE (kg/s)
1	Liquid leak	2.7
2	Vapor leak	0.26
3	Relief, vapor discharge	2.4

Downwind Center Line Ground Level Chlorine Concentrations for the Three Representative Incidents

INCIDENT 1 LIQUID LEAK (2.7 kg/s 10 min)		INCIDENT 2 VAPOR LEAK (0.26 kg/s 10 min)		INCIDENT 3 RELIEF VALVE DISCHARGE (2.4 kg/s 60 min)	
x(m)	C(ppm)	x(m)	C(ppm)	x(m)	C(ppm)
100	2000	50	690	100	1700
200	550	64	430	150	830
230	430	100	190	200	490
250	370			250	330
300	270			300	240
				360	175
				400	145

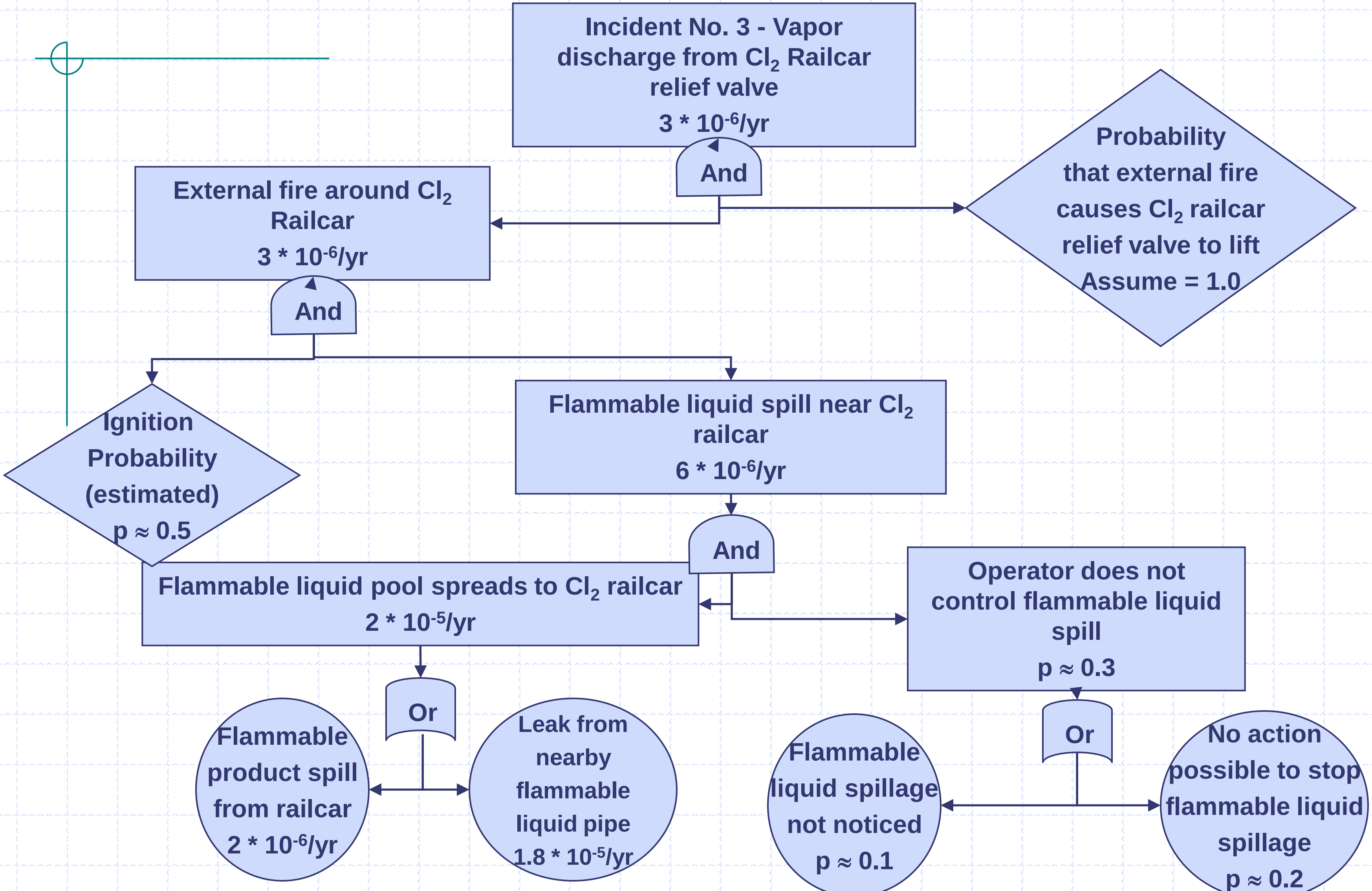
Distance at Which Chlorine Concentration Reaches LC_{50}

INCIDENT	DESCRIPTION	DURATION (min)	DOWNWIND DISTANCE AT WHICH CONCENTRATION = LC_{50} (m)
1	Liquid leak	10	230
2	Vapor leak	10	64
3	Relief valve discharge	60	360

Estimated Failure Frequency for Chlorine System Components

FAILURE DESCRIPTION	FAILURE FREQUENCY, AVERAGE SERVICE (events/year)
Valve leak	1×10^{-5}
Hose leak	5×10^{-4}
Impact failure of pipe[a]	1×10^{-5}
Relief valve leak at normal operating pressure	1×10^{-4}

Fault Tree for External Fire Around Chlorine Loading Facility Leading to Relief Valve Discharge of Chlorine (Incident No. 3)



Summary of Representative Incident Frequency Estimates

INCIDENT	DESCRIPTION	ESTIMATED FREQUENCY (yr^{-1})
1	Liquid leak	5.8×10^{-4}
2	Vapor leak	6.6×10^{-4}
3	Relief valve discharge	3.0×10^{-6}

Summary of Representative Incidents with Associated Effect Zones and Frequencies

INCIDENT	DESCRIPTION	Cl_2 DISCHARGE RATE (kg/s)	LEAK DURATION (min)	EFFECT ZONE DISTANCE TO LC_{50} (m)	FREQUENCY OF OCCURRENCE (yr^{-1})
1	Liquid leak -- 1/2-in. equivalent hole	2.7	10	230	$5.8 * 10^{-4}$
2	Vapor leak -- 1/2-in. equivalent hole	0.26	10	64	$6.6 * 10^{-4}$
3	Vapor discharge from relief valve due to fire	2.4	60	360	$3.0 * 10^{-6}$

List of Incident Outcome Cases Assuming an 8-point Wind Rose, 1

INCIDENT	INCIDENT FREQUENCY (yr^{-1})	INCIDENT OUTCOME CASE NO.	WIND DIRECTION PROBABILITY	FREQUENCY (yr^{-1})	COMMENTS[a]
1	5.8×10^{-4}	1SW	0.125	7.3×10^{-5}	A
		1W	0.125	7.3×10^{-5}	A
		1NW	0.125	7.3×10^{-5}	A
		1N	0.125	7.3×10^{-5}	B
		1NE	0.125	7.3×10^{-5}	B
		1E	0.125	7.3×10^{-5}	B
		1SE	0.125	7.3×10^{-5}	B
		1S	0.125	7.3×10^{-5}	B

[a] A, Effect zone affects populated area; B, effect zone does not affect populated area.

where N_i = number of fatalities resulting from incident outcome case i

P_i = the total number of people within the effect zone for incidnet outcome case i

$P_{f,i}$ = the probability of fatality within the effect zone for incident outcome case i

List of Incident Outcome Cases Assuming an 8-point Wind Rose, 2

INCIDENT	INCIDENT FREQUENCY (yr^{-1})	INCIDENT OUTCOME CASE NO.	WIND DIRECTION PROBABILITY	FREQUENCY (yr^{-1})	COMMENTS[a]
2	6.6×10^{-4}	2SW	0.125	8.2×10^{-5}	B
		2W	0.125	8.2×10^{-5}	B
		2NW	0.125	8.2×10^{-5}	B
		2N	0.125	8.2×10^{-5}	B
		2NE	0.125	8.2×10^{-5}	B
		2E	0.125	8.2×10^{-5}	B
		2SE	0.125	8.2×10^{-5}	B
		2S	0.125	8.2×10^{-5}	B

[a] A, Effect zone affects populated area; B, effect zone does not affect populated area.

where N_i = number of fatalities resulting from incident outcome case i

P_i = the total number of people within the effect zone for incidnet outcome case i

$P_{f,i}$ = the probability of fatality within the effect zone for incident outcome case i

List of Incident Outcome Cases Assuming an 8-point Wind Rose, 3

INCIDENT	INCIDENT FREQUENCY (yr^{-1})	INCIDENT OUTCOME CASE NO.	WIND DIRECTION PROBABILITY	FREQUENCY (yr^{-1})	COMMENTS[a]
3	3.0×10^{-6}	3SW	0.125	3.8×10^{-7}	A
		3W	0.125	3.8×10^{-7}	A
		3NW	0.125	3.8×10^{-7}	A
		3N	0.125	3.8×10^{-7}	B
		3NE	0.125	3.8×10^{-7}	B
		3E	0.125	3.8×10^{-7}	B
		3SE	0.125	3.8×10^{-7}	B
		3S	0.125	3.8×10^{-7}	B

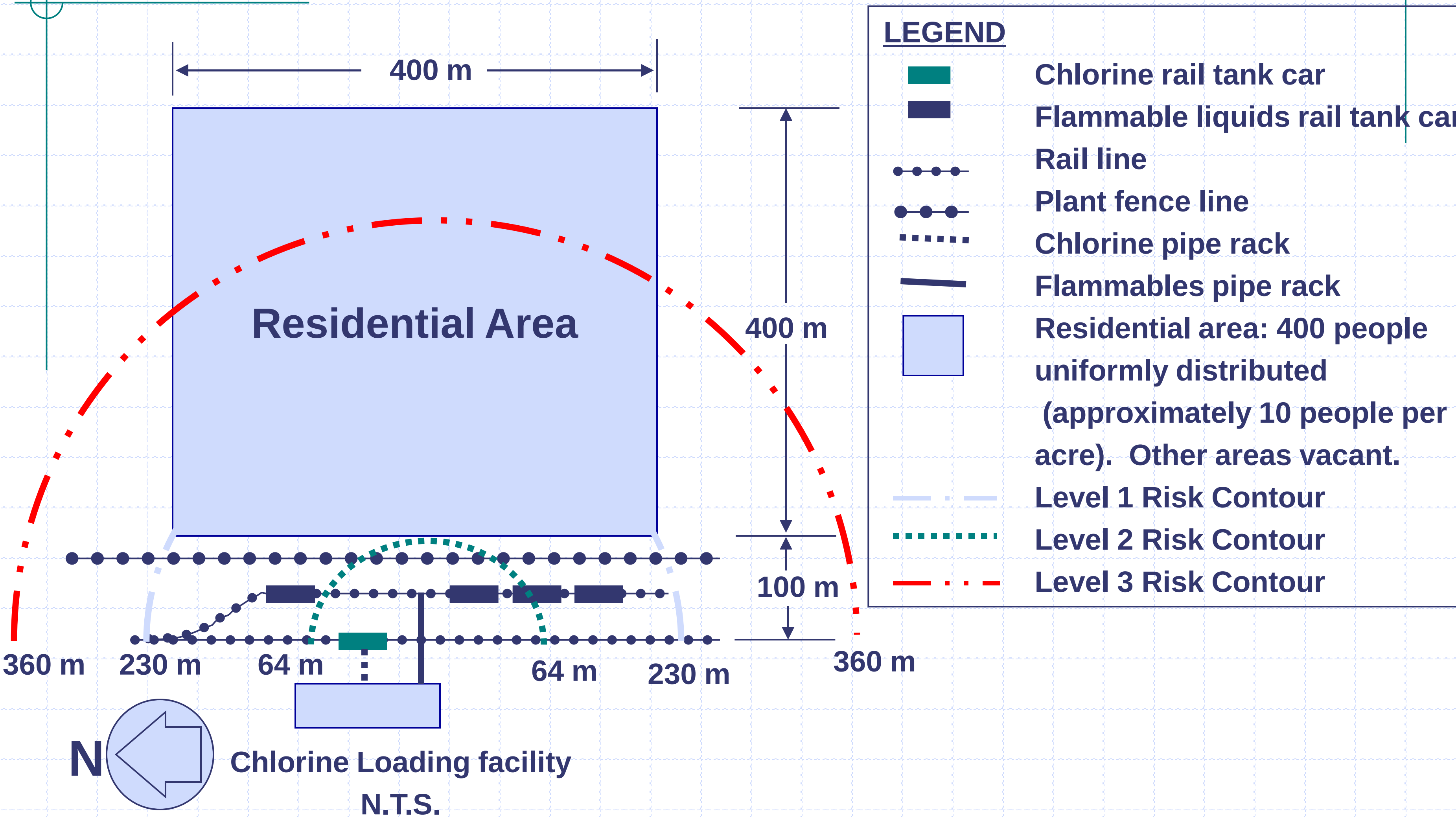
[a] A, Effect zone affects populated area; B, effect zone does not affect populated area.

where N_i = number of fatalities resulting from incident outcome case i

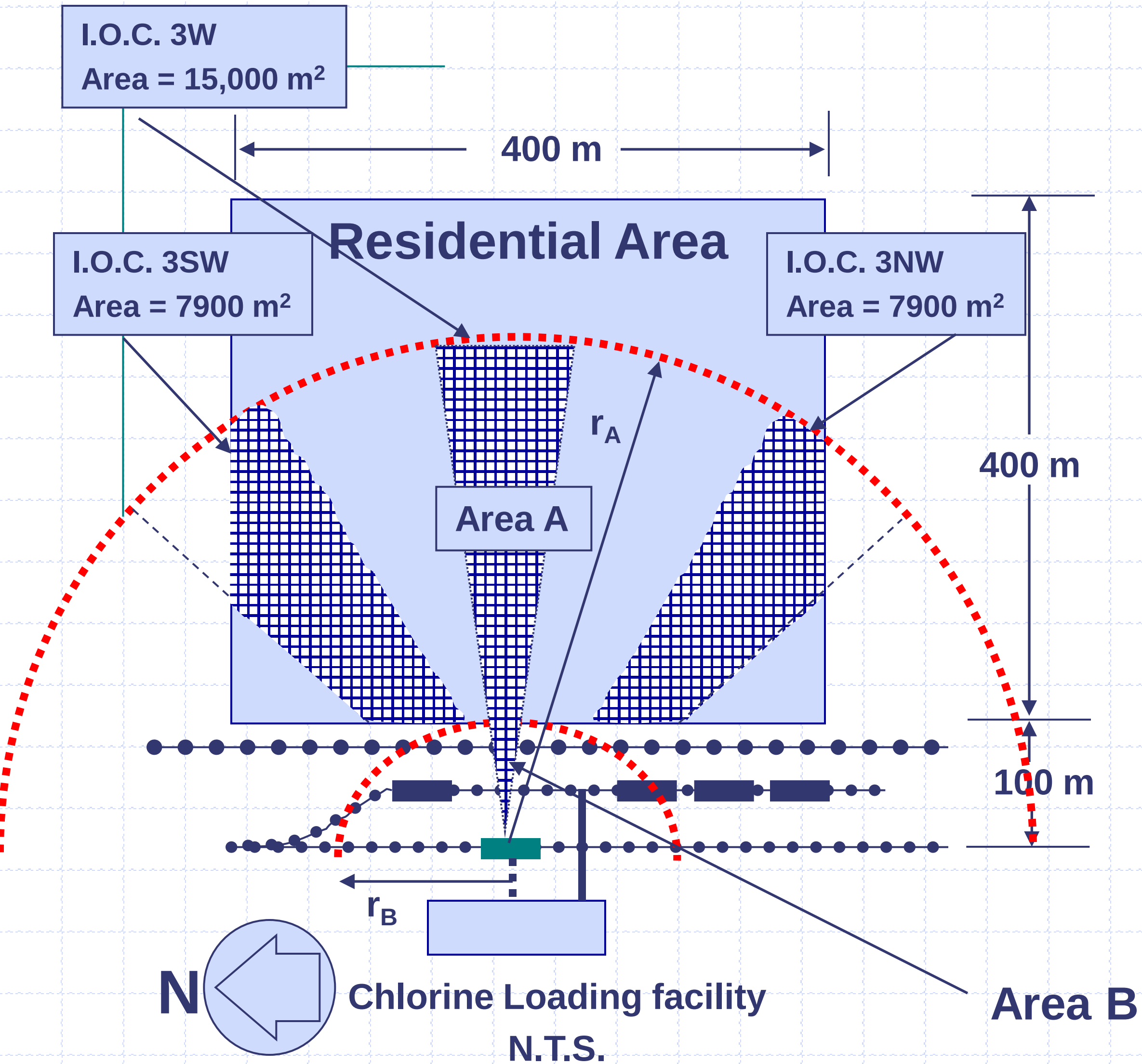
P_i = the total number of people within the effect zone for incidnet outcome case i

$P_{f,i}$ = the probability of fatality within the effect zone for incident outcome case i

Individual Risk Contours around Cl_2 Loading Facility



Effect Zones for Incident No. 3



LEGEND

- Chlorine rail tank car
- Flammable liquids rail tank car
- Rail line
- Plant fence line
- Chlorine pipe rack
- Flammables pipe rack
- I.O.C. — Incident Outcome Case
- Residential area: 400 people uniformly distributed (approximately 10 people per acre). Other areas vacant.

$r_A = 360$ m $\quad r_B = 100$ m

Example area calculations

$$Area\ A = \prod r_A^2 \frac{\theta}{360} = \prod (360)^2 \frac{(15^\circ)}{360^\circ} = 16.964\, m^2$$

$$Area\ B = \prod r_B^2 \frac{\theta}{360} = \prod (100)^2 \frac{(15^\circ)}{360^\circ} = 1.308\, m^2$$

Area Impacted = Area A - Area B ≈ 15,656 m²

Estimated Number of Fatalities for Incident Outcomes Cases Affecting the Populated Area

INCIDENT OUTCOME CASE	FREQUENCY F (yr^{-1})	ESTIMATED NUMBER OF FATALITIES
1SW	7.3×10^{-5}	13
1W	7.3×10^{-5}	14
1NW	7.3×10^{-5}	13
3SW	3.8×10^{-7}	20
3W	3.8×10^{-7}	38
3NW	3.8×10^{-7}	20
All others	------	0

Societal Risk Calculation and F-N Curve Data

ESTIMATED NUMBER OF FATALITIES [a]	CUMULATIVE FREQUENCY OF N OR MORE FATALITIES, F_N (yr^{-1})	INCIDENT OUTCOME CASES INCLUDED
$N > 38$	0	None
$20 < N \leq 38$	3.8×10^{-7}	3W
$14 < N \leq 20$	1.1×10^{-6}	3W, 3SW, 3NW
$N \leq 14$	7.4×10^{-5}	3W, 3SW, 3NW, 1W
$N \geq 13$	2.2×10^{-4}	3W, 3SW, 3NW, 1W, 1SW, 1NW

[a] N must be an integer value.

Summary of Single Number Risk Measures and Risk Indices

RISK MEASURE	VALUE
Maximum individual risk	2.4×10^{-5}/yr R_I
Average individual risk	
Exposed population	1.2×10^{-5}/yr R_I
Total population	7.5×10^{-6}/yr R_I
Fatal accident rate (FAR)	0.14 fatalities/10^8 man-hr exposure
Average rate of death	3×10^{-3} fatalities/yr
Equivalent social cost	
Okrent	4.9×10^{-3}
Netherlands	3.7×10^{-2}