Special Topics, Future Development and Case Practice

2009_2nd semester

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Special Topics

- Domino effects
  - Predict the occurrence of such incidents that affect nearby items by thermal, blast or fragment impact
  - Domino analysis is also used to evaluate equipment separation to minimize the potential for incident propagation
- Unavailability analysis of protective systems
  - Determine the probability that a protective system will be in a failed state when a demand on that system occurs
- Reliability analysis of programmable electronic systems
  - Determine the probability of electronic system and quantitative methods for the analysis of a system

Future Development

- Hazard identification
  - Continued improvement and ongoing development in process hazard analysis methodologies;
  - Increased industry sharing of incident and potential incident data;
  - Continued development of expert systems, checklists, failure libraries, and other tools to leverage the effectiveness of PHA teams;
  - Improved access to existing data on industry experience and history, so past incidents can be more effectively prevented from recurring;
  - Use of modern tools for searching and screening data to extract relevant incident data from a large mass of diverse data.

- Source and Dispersion Models
  - Better methods for defining source terms including hole size and release rates;
  - Better methods to deal with two phase flashing flow through holes;
  - Performance evaluation of newly released dispersion models based on actual experiments and field data
  - Better methods to estimate the plume or puff width for the dispersion of dense clouds;
  - Continued improvements in understanding of aerosol formation, including better methods for determining the mass fraction of aerosol formed, and the particle size distribution;

- Consequence Models
  - Improved determination of the flammable mass in a vapor cloud, including a better fundamental understanding and experimental verification;
  - Increased understanding of the factors which impact the transaction from ignition to explosion for flammable liquid and gas releases;
  - Better experimental data, and data on more materials, for short chemical exposures (in the range of a few minutes up to one hour);
  - Continued improvement in toxicity modeling and dose-response modeling, particular for single, very short exposures (in the range of a few minutes up to one hour)

- Frequency Models
  - Continued improvements in models for incorporating human factors into a CPQRA study;
  - Improved capability of understanding the likelihood of failure of complex electronic systems such as digital control systems, programmable logic controllers, and other such equipment.
  - A generalized method to estimate the probability that one or more of the software bugs or errors will occur within a specified mission time.
- Real time fault diagnosis

Case Practice

Chlorine Rail Tank Car Loading Facility

- System description
  - The supply tank is mounted on weigh scales and liquid chlorine is transferred to a rail car using pressurized nitrogen
  - Two remotely actuated emergency shutoff valves are located, and the storage tank has a emergency vent
  - 10,000 gal(50 ton) ambient temperature rail tank car is fitted with pressurized valves
  - Use typical weather condition
    - Wind speed of 4 m/s(13 ft/s) and D atmospheric stability
  - The chlorine loading facility is located 100 m west of a populated area 400 meters(1/4 miles) square with a uniformly distributed population of 400 people

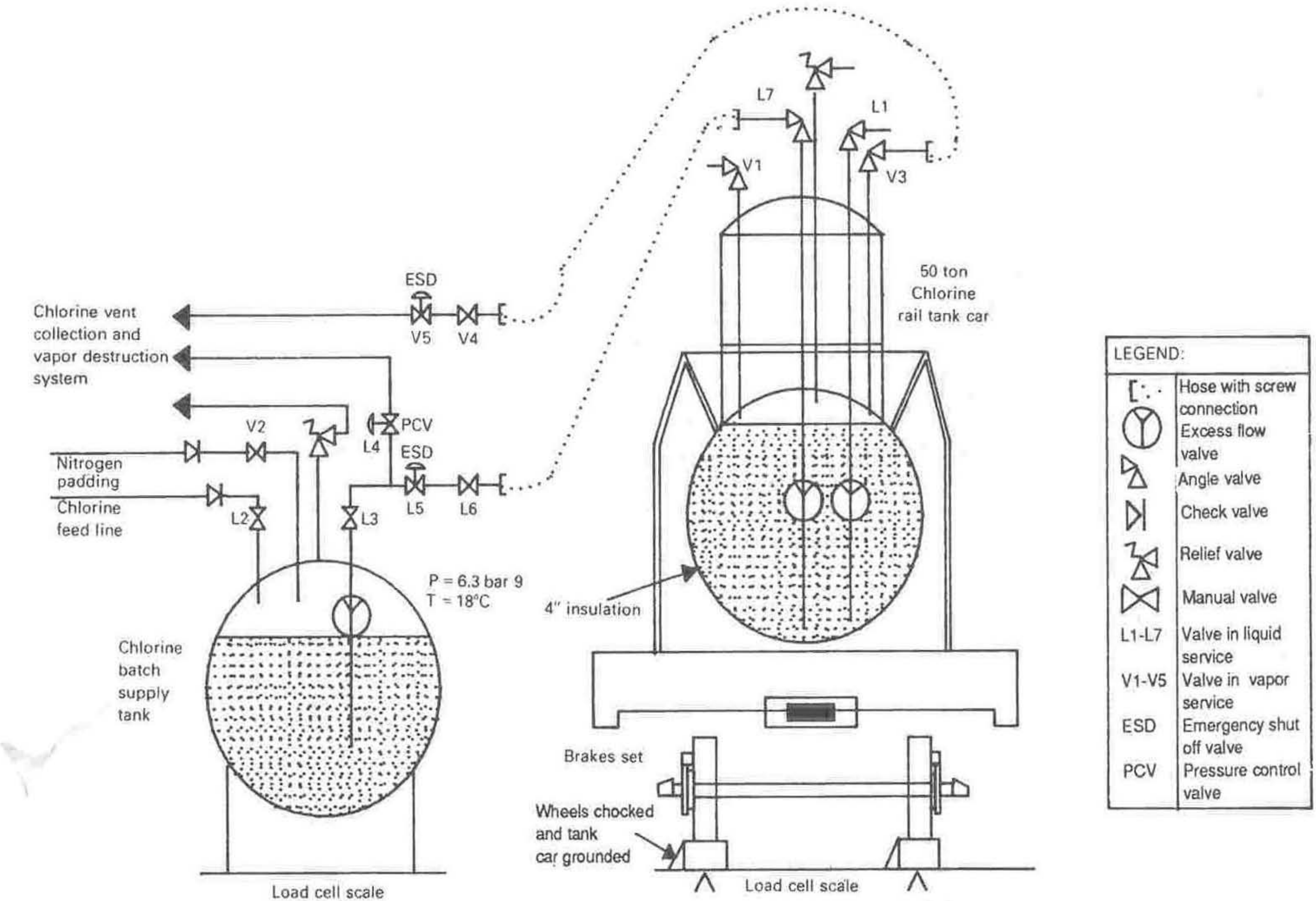


FIGURE 8.2. Diagram of liquid chlorine rail tank car loading installation.

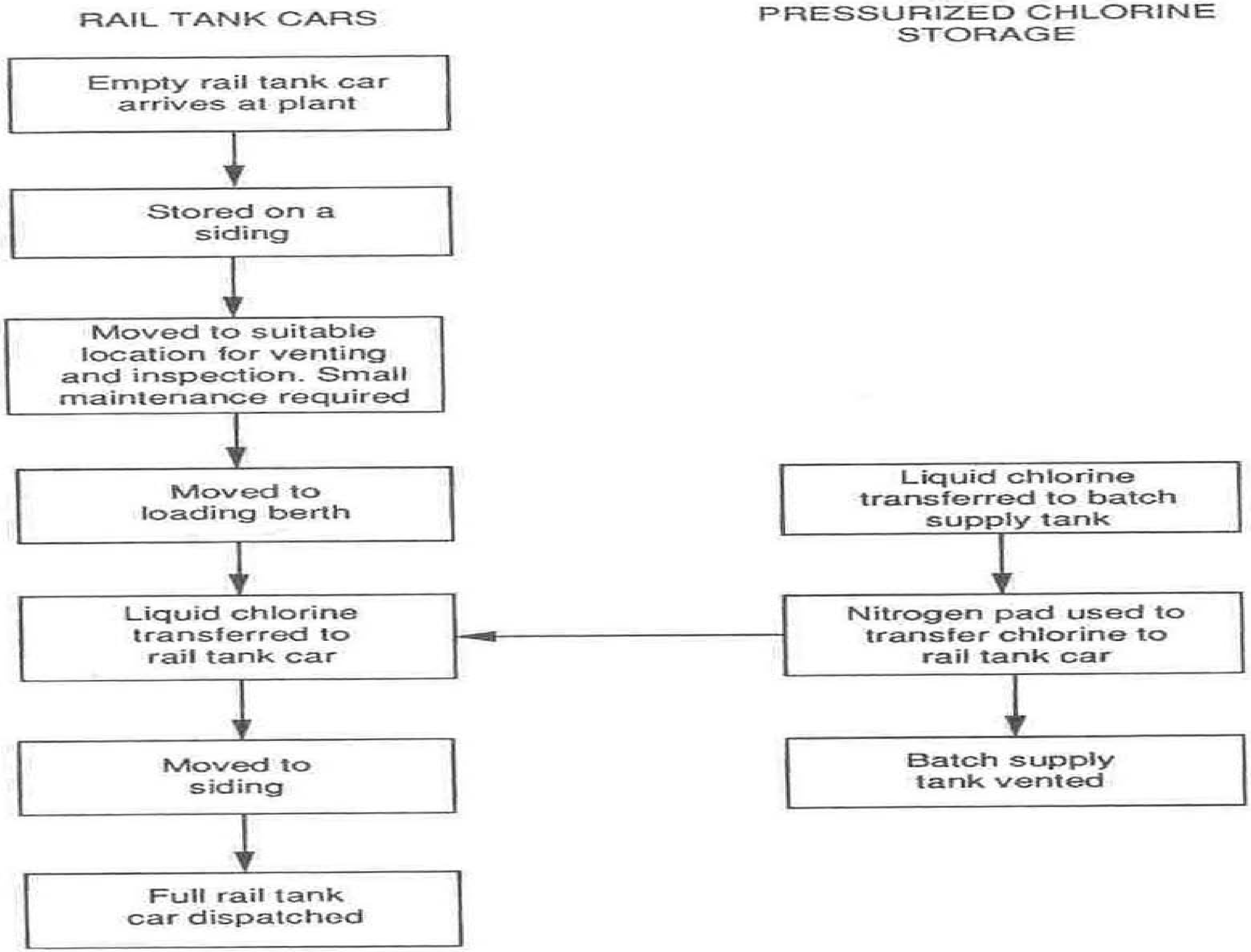


FIGURE 8.3. Simplified chlorine rail car loading procedure.

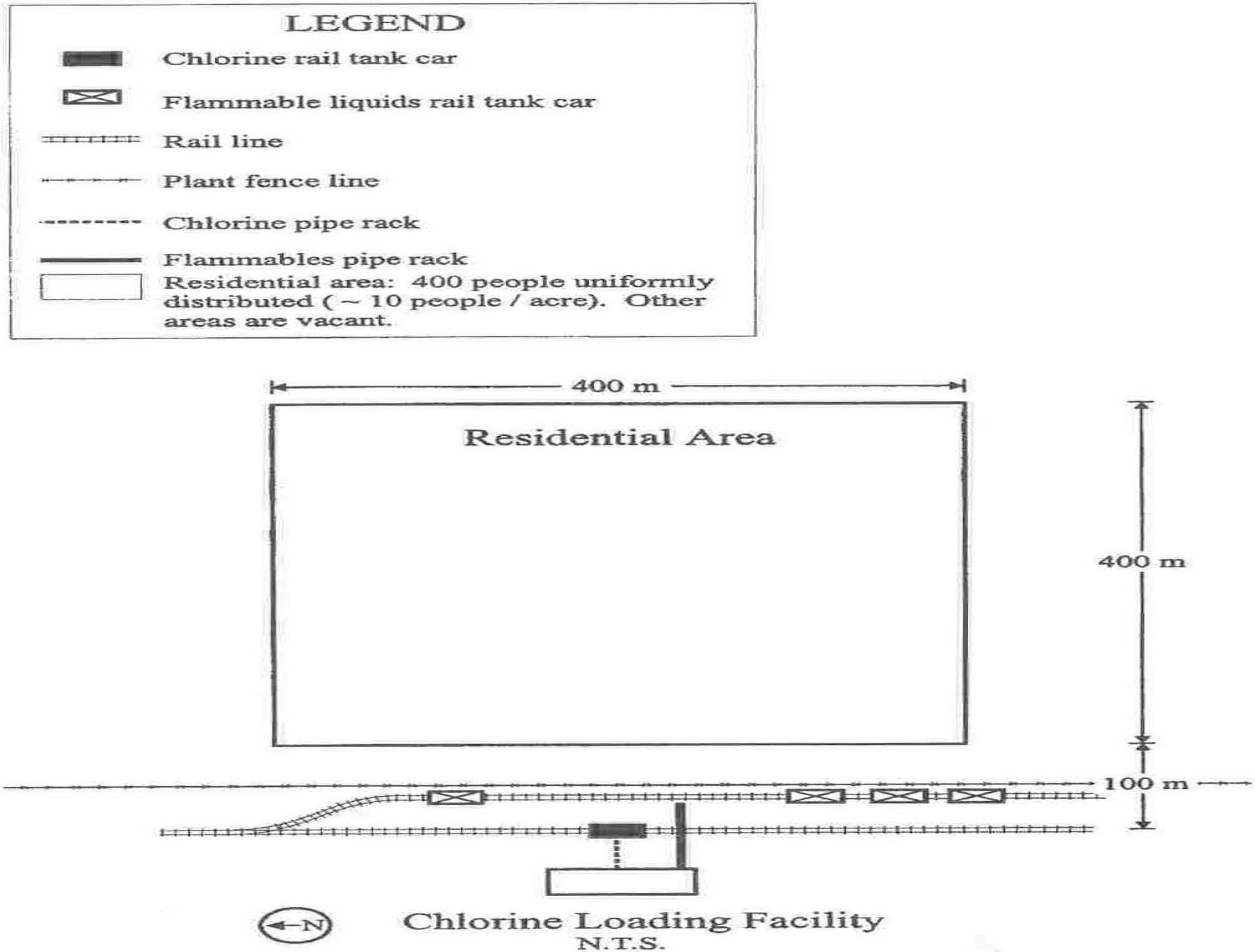


FIGURE 8.4. Layout of chlorine rail loading facility.

Identification, Enumeration and Selection of Incident

- Incident should be screened based on the criteria
  - Localized incidents whose consequences do not extend beyond the boundary fence need not be evaluated for purposes of estimating public risk
  - Major and catastrophic incident of similar scale can be grouped and represented by single incident with frequencies determined from contributions of all individual incident in each group
- Hazards and specific incidents in the chlorine loading facility can be identified in a number of ways (HAZAOP, PHA, What-if and so on)
- The representative set of incidents should cover a range of incident outcome capable of causing consequences in the community

TABLE 8.1. Output from a HAZOP Review of Chlorine Rail Car Loading Facility Flowsheet (Extract Only)

FLOWSHEET: CHLORINE LOADING SYSTEM

Guide word	Deviation	Possible causes	Consequences	Action required
I. No	Flow	A. Manual valves shut B. ESD valve shut C. Hose blocked D. Pipe blocked	A–D Operational delay	A–D Confirm operation instructions suitable for safe corrections of all No Flow cases
II. High	Flow	A. Flange leak	A. Toxic hazard	A.1. Minimize flange connections A.2. Check suitability of gasket specification A.3. Ensure ESD activation point is at convenient location, consider 2 actuation points A.4. Check location of breathing apparatus
		B. Valve leak	B. Toxic hazard	B. Similar to flange leak
		C. Pipe leak due to impact	C. Toxic hazard	C. Minimize activities near chlorine line
		D. RV malfunction on rail car	D. Toxic hazard	D. Inspect RV before loading.
		E. Hose leak	E. Toxic hazard	E. Develop preventive maintenance program for hoses
III. High	Level	A. Weigh scale error	A. Chlorine passes through relief valve-toxic hazard	A. Unlikely, existing design and weigh scale system considered adequate
IV. High	Temperature	A. External fire from neighboring (1) rail line handling flammable material; (2) elevated pipeline with flammable material	A.1 Relief valve lifts passes large vapor flow A.2 Shell failure catastrophic rupture-toxic hazard	A. Fire protection facilities adequate, approximately 60 min to control pool fire. Catastrophic rupture unlikely before fire brought under control
V. High	Pressure	A. Nitrogen supply overpressure	A. Relief valve lifts and emergency vent-toxic hazard	A. No action required; pressure control system on nitrogen supply and PCV to emergency vent adequate
VI. Other	Corrosion	A. Internal corrosion of tanks or pipe fittings	A. Liquid or vapor leak; toxic hazard	A. Periodic internal inspections (1–5 year intervals) should detect any incipient corrosion

TABLE 8.2. Representative Set of Incidents Extracted from Table 8.1

Incident No.	Incident description	Reference from Table 8.1
1	Small liquid leakage (equivalent to ½", 12.7 mm hole)	IIA, IIB
	Duration = 10 min (estimated)	IIE
	Causes	IIC
	Valve leak (7 valves and associated flanges)	
	Hose leak	
	Impact failure of liquid connecting pipe	
2	Small vapor leakage (equivalent to ½", 12.7 mm hole)	IIA, IIB
	Duration = 10 min (estimated)	IIE
	Causes	IIC
	Valve leak (5 valves and associated flanges)	IID
	Hose leak	
	Impact failure of vapor connecting pipe	
	Relief valve leak	
3	Large vapor leakage	IVA
	Duration = 60 min (estimated time for fire fighting measures to cool chlorine car and stop release)	
	Cause	
	External fire lifts relief valve	

Incident Consequence Estimation

- Incident No. 1 : Liquid discharge, ½-in(12.7 mm) hole
  - The liquid chlorine system is specified to be under slight nitrogen pressure at 6.3 bar(6.3 X 10^5 N/m^2 abs)

$$\dot{m}_L = \rho v A = \rho A C_D \sqrt{2\left(\frac{g_c P_q}{\rho} + g h_L\right)}$$

- m_L is the mass discharge rate (kg/s)
- v is the fluid velocity
- A is the area of the hole(for 12.7 mm, 1.27 X 10^{-4} m^2)
- C_D is the mass discharge coefficient(for liquids use 0.61, dimensionless)
- g_c is the gravitational constant(force/mass acceleration)
- P_g is the upstream pressure(5.3 X 10^5 N/m^2 gauge)
- ϱ is the liquid density (1420 kg/m^3)
- g is the acceleration due to gravity(9.8 m/s)
- h_L is the height of liquid above the hole(assume 0 m)

- So m_L = 3.0 kg/s

Equation for flash fraction

$$F_V = C_P \frac{(T - T_b)}{h_{fg}}$$

- C_P is the average heat capacity over the range T to Tb(0.950 kJ/kg ℃)
- T is the initial temperature(19 ℃)
- T_b is the final temperature = atmospheric boiling point(-34 ℃)
- h_{fg} is the heat of vaporization(at –34 C, 285 kJ/kg)
- F_V is the mass fraction of released liquid vaporized(unitless)

- With this data, the flash fraction is calculated to be 0.17
- So the cloud is 34%(17% vapor and 17% aerosol)of the release and 66% rains out on contacting warm ground

Incident No. 2 : Vapor discharge, ½-in.(12.7 mm) Hole

- If the pressure difference between the chlorine system and the atmosphere exceeds the critical pressure ratio, the flow through the orifice will be limited by the sonic or critical velocity

$$\frac{P_{choked}}{P_1} = \left(\frac{2}{k+1}\right)^{(k/(k-1))}$$

  - P_{choked} is the maximum down stream pressure resulting in maximum flow
  - P_1 is the upstream pressure(6.3 bar abs.)
  - P_2 is the downstream pressure(1.01 bar abs., atmospheric)
  - k is the heat capacity ratio(1.32 for chlorine)
- So the choked pressure P_{choked} = (6.3 bar)(0.542) = 3.42bar
- The discharge downstream is to atmospheric pressure which is less than the calculated choked flow, thus sonic flow is expected through the hole

The equation for sonic or choked flow through the hole

$$\dot{m}_{choked} = C_D A P_1 \sqrt{\frac{2g_C}{R_q}\frac{M}{T_1}\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}$$

- m_{choked} is the gas discharge rate, choked flow(kg/s)
- C_D is the discharge coefficient(approximately 1.0 for gases)
- A is the area of the hole(for 12.7 mm, $1.27\ 10^{-4}\ m^2$)
- P_1 is the upstream pressure($6.3 X 10^5\ N/m^2$ abs)
- M is the molecular weight(kg/kg-mol)(for chlorine, 71)
- R is the gas constant(8314 J/kg-mol/K)
- T is the upstream temperature(18 ℃, 291 K)

- So the incident 2 vapor release rate for entry to the dispersion model is 0.29kg/s

Incident No. 3 : Vapor discharge from rail car relief valve

- The vapor generated in a pressure vessel engulfed in an external fire can be estimated using the formula from NFPA 58

$$Q_f = 34{,}500 F A^{0.82}$$

- Q in SI unit

$$Q_f = 34{,}500 F A^{0.82} [2.91 \times 10^{-4} (kJ/s)/(Btu/hr)]$$

  - Q_f =heat input through vessel wall(kJ/s)
  - A = total surface area(approximately 650 ft^2)
  - F = environment factor(from API RP-520 use F=0.3 for insulted tank)
- So $Q_f = (34{,}500)(0.3)(650)^{0.82}(2.93 \text{ X } 10^{-4}) = 614$ kJ/s

- Relief valve discharge rate

$$m = Q_f / h_{fg}$$

  - m = gas discharge rate(kg/s)
  - h_{fg} = latent heat of vaporization at relief pressure(257 kJ/kg)
- m = (614 kJ/s)(257 kJ/kg) = 2.4 kg/s

TABLE 8.3. Summary of Representative Incident Release Rate Estimate

Incident	Description	Estimated release rate (kg/s)
1	Liquid leak	3.0
2	Vapor leak	0.29
3	Relief valve discharge	2.4

Chlorine toxicity calculation

- Determine the toxicity relationship to be used for estimating fatalities from the exposure to chlorine vapor
- Probit method is often used to estimate fatal effects

$$Pr = -8.29 + 0.92 \ln(C^2 t)$$

  - Pr = Probit function value
  - C = chlorine concentration(ppm)
  - t = duration of exposure)

TABLE 8.4. Estimated LC_{50} for Chlorine Exposures

Exposure time (min)	Incident	Estimated LC_{50} (ppm)
10	1,2	433
60	3	177

Dispersion Calculation

$$\langle C\rangle(x,y,x)=\frac{G}{(2\pi)\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\times\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\}$$

- <C> is the average concentration(mass/volume)
- G^* is the continuous release rate(mass/time)
- σ_x σ_y σ_z are the dispersion coefficient in x,y,z direction(length)
- u is the wind speed(length/time)
- y is the cross-wind direction(at the centerline concentration y=0)
- z is the distance above the ground(at ground level, z=0)
- H is the release height above the ground(assume H=0)

$$< C >_{\max} = \frac{G}{\pi\sigma_y\sigma_z u}$$

- To obtain <C> in ppm, use a conversion factor

$$<C>_{\max} = \frac{G}{\pi \sigma_y \sigma_z u}\left[\frac{RT}{MP} * 10^6\right]$$

  - R = gas constant(0.082057 atm-m^3/kg-mol K)
  - T = temperature(K)
  - M = molecular weight(kg/kg-mol)
  - P = pressure(atm)

- Calculation σy, σz for D atmospheric stability

$$\sigma_y = \exp\left[4.23 + 0.9222\ln\left(\frac{x}{1000}\right) - 0.0087\left[\ln\left(\frac{x}{1000}\right)\right]^2\right]$$

$$\sigma_z = \exp\left[3.411 + 0.7371\ln\left(\frac{x}{1000}\right) - 0.0316\left[\ln\left(\frac{x}{1000}\right)\right]^2\right]$$

- So,
  - m_L = 3.0 kg/s (Incident 1)
  - m_v = 0.29 kg/s (Incident 2)
  - m_{rv} = 2.4 kg/s (Incident 3)
  - T = 18C = 291K
  - u = 4 m/s
  - M = 71 kg/kg-mol
  - P = 1 atm

TABLE 8.5. Downwind Center Line Ground Level Chlorine Concentrations for the Three Representative Incidents

Incident 1 Liquid leak (3.0 kg/s 10 min)		Incident 2 Vapor leak (0.29 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	2173	50	769	100	1738
200	617	68	433	150	828
244	433	100	210	200	493
250	415	120	150	250	332
300	301			300	240
				358	177
				400	146

TABLE 8.6. Distance at Which Chlorine Concentration Reaches LC_{50}

Incident	Description	Duration (min)	Chlorine LC_{50} (ppm)	Downwind distance at which concentration = LC_{50} (m)
1	Liquid leak	10	433	244
2	Vapor leak	10	433	68
3	Relief valve discharge	60	177	358

Incident Frequency Estimation

- Failure data for process equipment items(e.g., flanges, valves, hoses) can be obtained from various reliability data bases

$$F_i = \sum_{j=1}^{n} f_j$$

  - F_i = overall frequency of the representative incident i
  - f_i = failure frequency of component j which is included in representative incident i

TABLE 8.7. 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}

[a]It should be noted that among the many factors that must be considered when estimating pipe failure rate are pipe length and pipe size.

- For incident 1, the frequency of the representative vapor leak(7 valves, 1 hose, 1 impact pipe failure)
  - $F1 = (1X10^{-5}) + (1X10^{-5}) + (1X10^{-5}) + (1X10^{-5}) + (1X10^{-5}) + (1X10^{-5}) + (1X10^{-5}) + (5X10^{-4}) + (1X10^{-5}) = 5.8 X 10^{-4}$ per year
- For incident 1, the frequency of the representative vapor leak(5 valves, 1 hose, 1 impact pipe failure and 1 relief valve leak)
  - $F1 = (1X10^{-5}) + (1X10^{-5}) + (1X10^{-5}) + (1X10^{-5}) + (1X10^{-5}) + (5X10^{-4}) + (1X10^{-5}) + (1X10^{-4}) = 6.6 X 10^{-4}$ per year
- For incident 3, historical data are not suitable for frequency estimation
  - A simple fault tree model of the external fire scenario is developed to calculate the frequency from basic causative factors

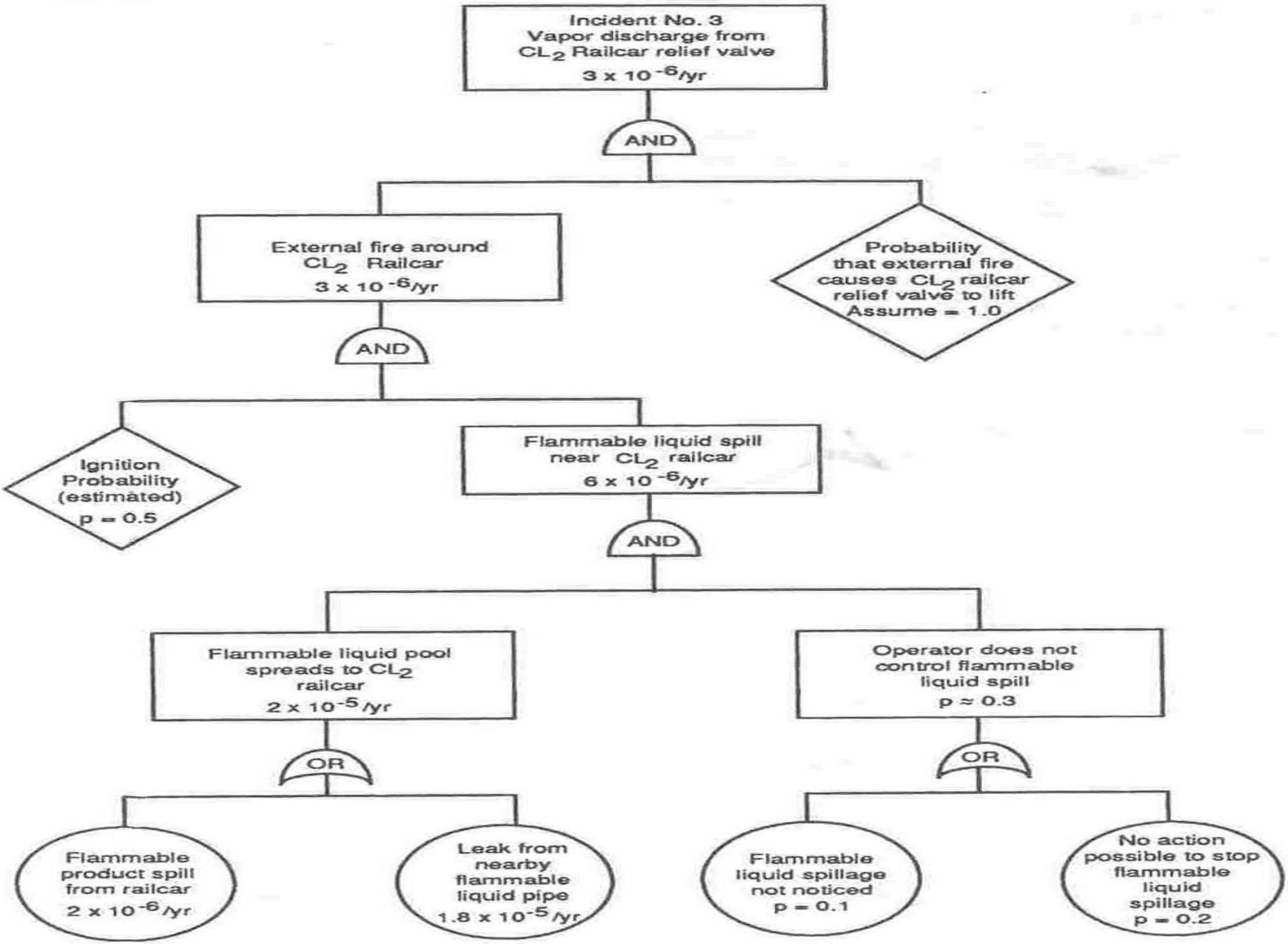


FIGURE 8.5. Fault tree for external fire around chlorine loading facility, leading to relief valve discharge of chlorine (Incident 3).

Summary of frequency estimation

TABLE 8.8. Summary of Representative Incident Frequency Estimates

Incidents	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}

Risk Estimation

- Individual risk
  - Individual risk can be calculated through figure 4.8
  - Frequency in any particular direction assuming a uniform wind direction distribution

$$f_{i,d} = f_i(\theta_i/360)$$

    - $f_{i,d}$ is the frequency at which incident outcome case i affects a point in any particular direction assuming a uniform wind direction distribution(yr^{-1})
    - f_i is the estimated frequency of occurrence of incident outcome case i(yr^{-1})
    - θ_i is the angle enclosed by the effect zone for incident outcome case i (degree)
  - For incident 3, $f_3 = 3 \times 10^{-6}$ and $\theta_3 = 15$
    - $f_{3,d} = (3 \times 10^{-6}\ yr^{-1})(15/360) = 1.2 \times 10^{-7}\ yr^{-1}$

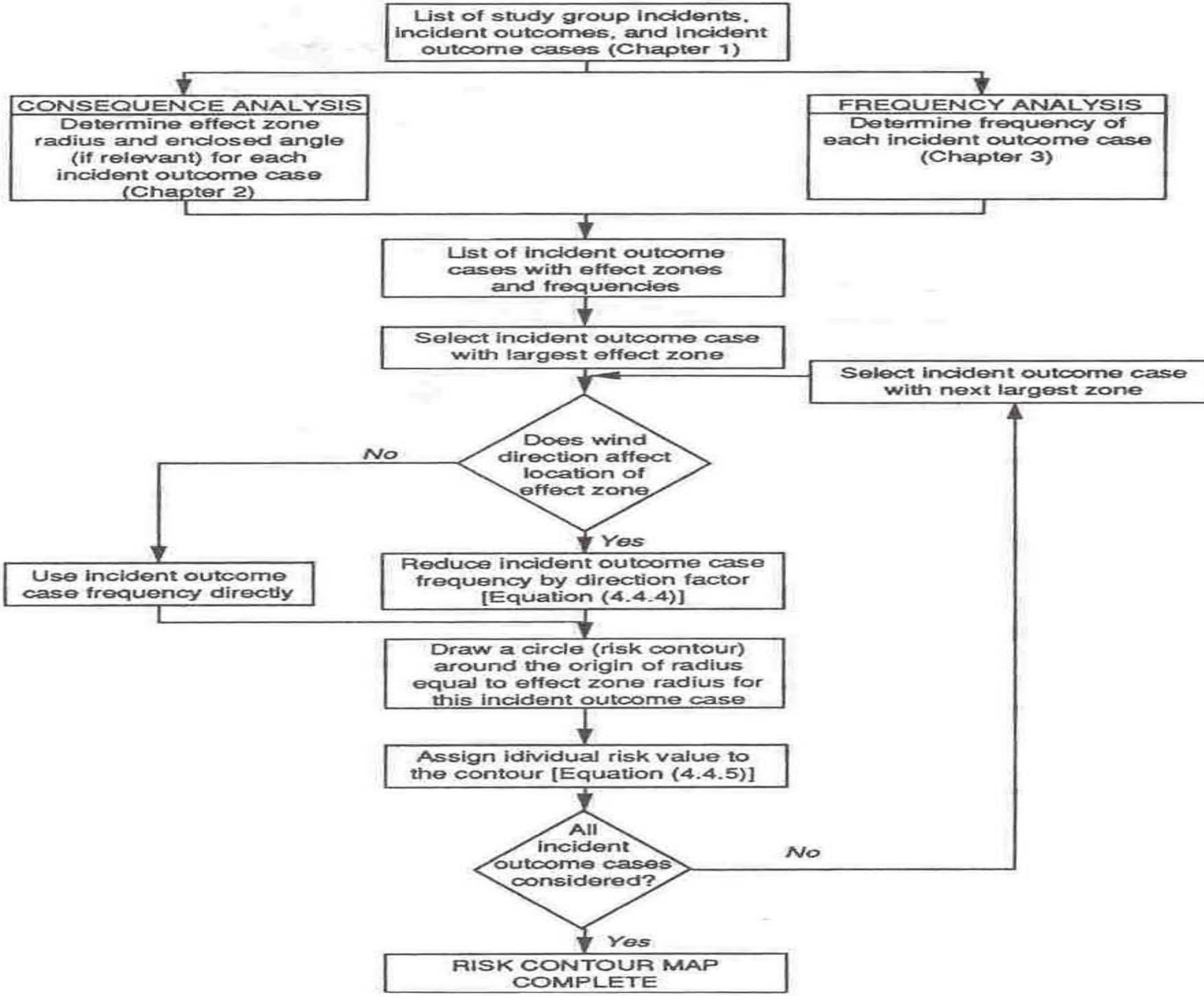


FIGURE 4.8. A simplified procedure for individual risk contours.

TABLE 8.9. Summary of Representative Incidents with Associated Effect Zones and Frequencies

Incident	Description	Cl_2 Discharge rate (kg/s)	Leak duration (min)	LC_{50} (ppm)	Effect zone: Distance to LC_{50} (m)	Effect zone: Plume arc (deg)	Frequency of occurrence (yr^{-1})
1	Liquid leak: ½-in. equivalent hole	3.0	10	433	244	15	5.8×10^{-4}
2	Vapor leak: ½-in. equivalent hole	0.29	10	433	68	15	6.6×10^{-4}
3	Vapor discharge from relief valve due to fire	2.4	60	177	358	15	3.0×10^{-6}

- Draw a circle around the chlorine facility with a radius equal to the effect zone radius(358 m)
- An individual risk value

$$IRC_i = f_i (\text{or } f_{i,d}) + IRC_{i-1}$$

  - IRC_i is the value of individual risk at the contour of the incident outcome case under consideration(yr^{-1})
  - IRC_{i-1} is the value of individual risk at the next further risk contour(yr^{-1})
- $IRC_{\text{Incident 3 Countour}} = f_{3,d} = 1.2 \text{ X } 10^{-7} \text{ yr}^{-1} + 0$

For incident 1

- $f_{1,d} = f_1(\theta_1/360) = (5.8 \text{ X } 10^{-4} \text{ yr}^{-1})(15/360) = 2.4 \text{ X } 10^{-5} \text{ yr}^{-1}$
- $IR_{\text{Incident 1 Countour}} = f_{1,d} + IR_{\text{Incident 3 Countour}}$
- $= 2.4 \text{ X } 10^{-5} \text{ yr}^{-1} + 1.2 \text{ X } 10^{-7} \text{ yr}^{-1}$
- $= 2.4 \text{ X } 10^{-5} \text{ yr}^{-1}$

- For incident 2
  - $f_{2,d} = f_2(\theta_2/360) = (6.6 \text{ X } 10^{-4} \text{ yr}^{-1})(15/360) = 2.8 \text{ X } 10^{-5} \text{ yr}^{-1}$
  - $IR_{\text{Incident 2 Countour}} = f_{2,d} + IR_{\text{Incident 1 Countour}}$
  - $= 2.8 \text{ X } 10^{-5} \text{ yr}^{-1} + 2.4 \text{ X } 10^{-5} \text{ yr}^{-1}$
  - $= 5.2 \text{ X } 10^{-5} \text{ yr}^{-1}$

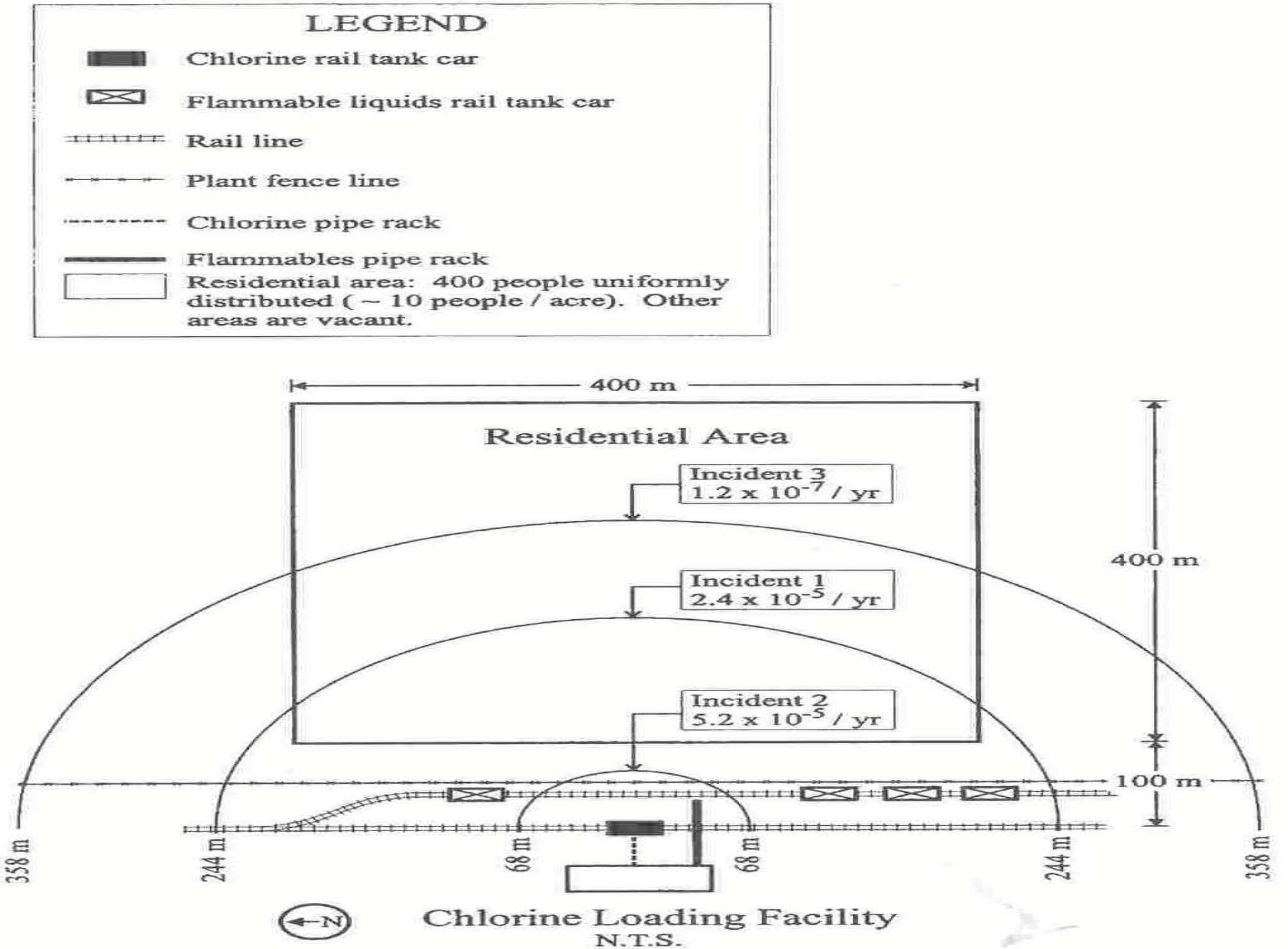


FIGURE 8.6. Individual risk contours around chlorine loading facility.

Societal Risk

- Societal risk calculation
  - Requires an estimate of the number of people killed by each incident outcome case, rather than an estimate of the likelihood of fatality at a particular location
  - Wind direction is divided into an 8-point wind rose
    - N, NE, E, SE, S, SW, W, NW
    - The probability that the wind will blow an any one of the 8 possible direction is 1/8, and the frequency of each incident outcome case is equal to 0.125
    - For example the effect zone from incident outcome case 3W covers an area of about 15,460 m^2 of the populated area, and given the population density of 25 persons per 10,000 m^2, this effect zone affect 39 people (15,460 m^2 X 25 people/10,000 m^2)

TABLE 8.10. List of Incident Outcome Cases Assuming an 8-Point Wind Rose

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
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
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.

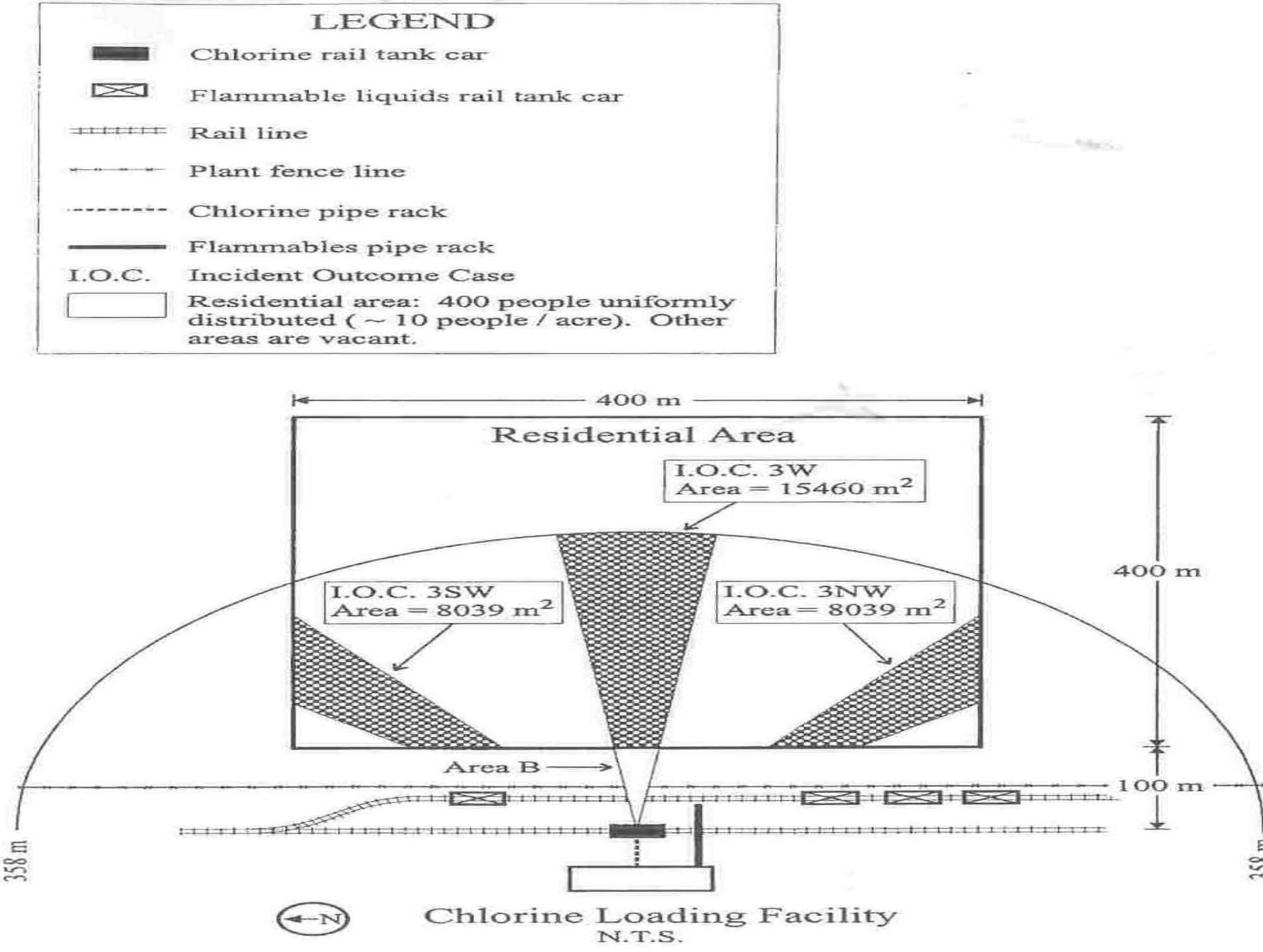


FIGURE 8.7. Effect zones for Incident 3.

- Cumulative frequency (from eq.(4.4.9))

$$F_N = \sum_i F_i$$ **For all incident outcome case i for which N_i>=N**

  - F_i is the frequency of incident outcome case i
  - N_i is the number of people affected by incident outcome case i

TABLE 8.11. Estimated Number of Fatalities for Incident Outcome 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}	16
1NW	7.3×10^{-5}	13
3SW	3.8×10^{-7}	20
3W	3.8×10^{-7}	39
3NW	3.8×10^{-7}	20
All others	—	0

TABLE 8.12. 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
$N > 39$	0	None
$20 < N \leq 39$	3.8×10^{-7}	3W
$16 < N \leq 20$	1.1×10^{-6}	3W, 3SW, 3NW
$N = 16$	7.3×10^{-5}	3W, 3SW, 3NW, 1W
$N \leq 13$	2.2×10^{-4}	3W, 3SW, 3NW, 1W, 1SW, 1NW

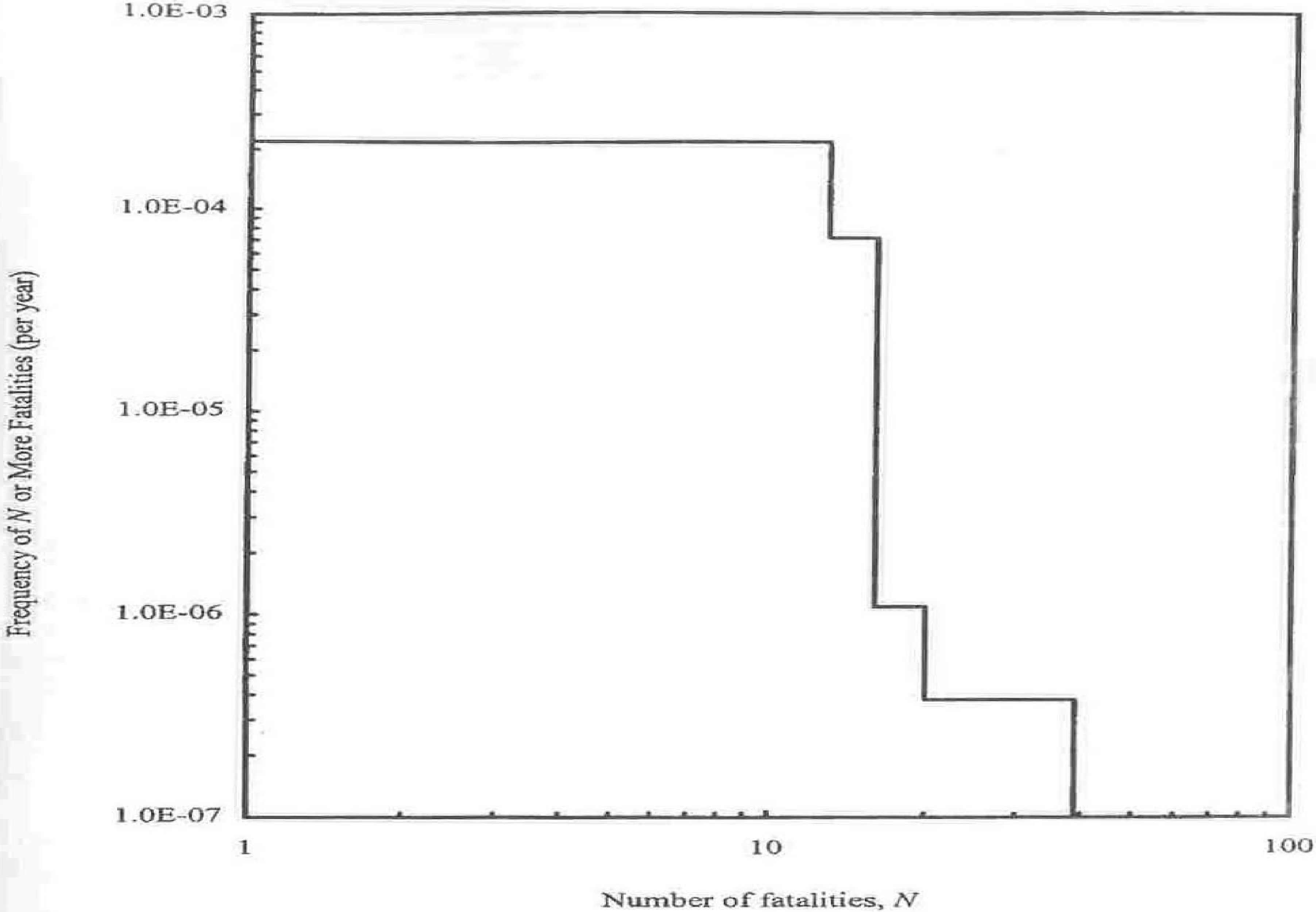


FIGURE 8.8. Societal risk F-N curve for chlorine rail tank car loading example.

Other Societal Risk Measures

- Maximum individual risk
  - The person incurring the maximum individual risk is located at the center of the west edge of the populated area = 2.4 X 10^{-5} yr^{-1}
- Average rate of death

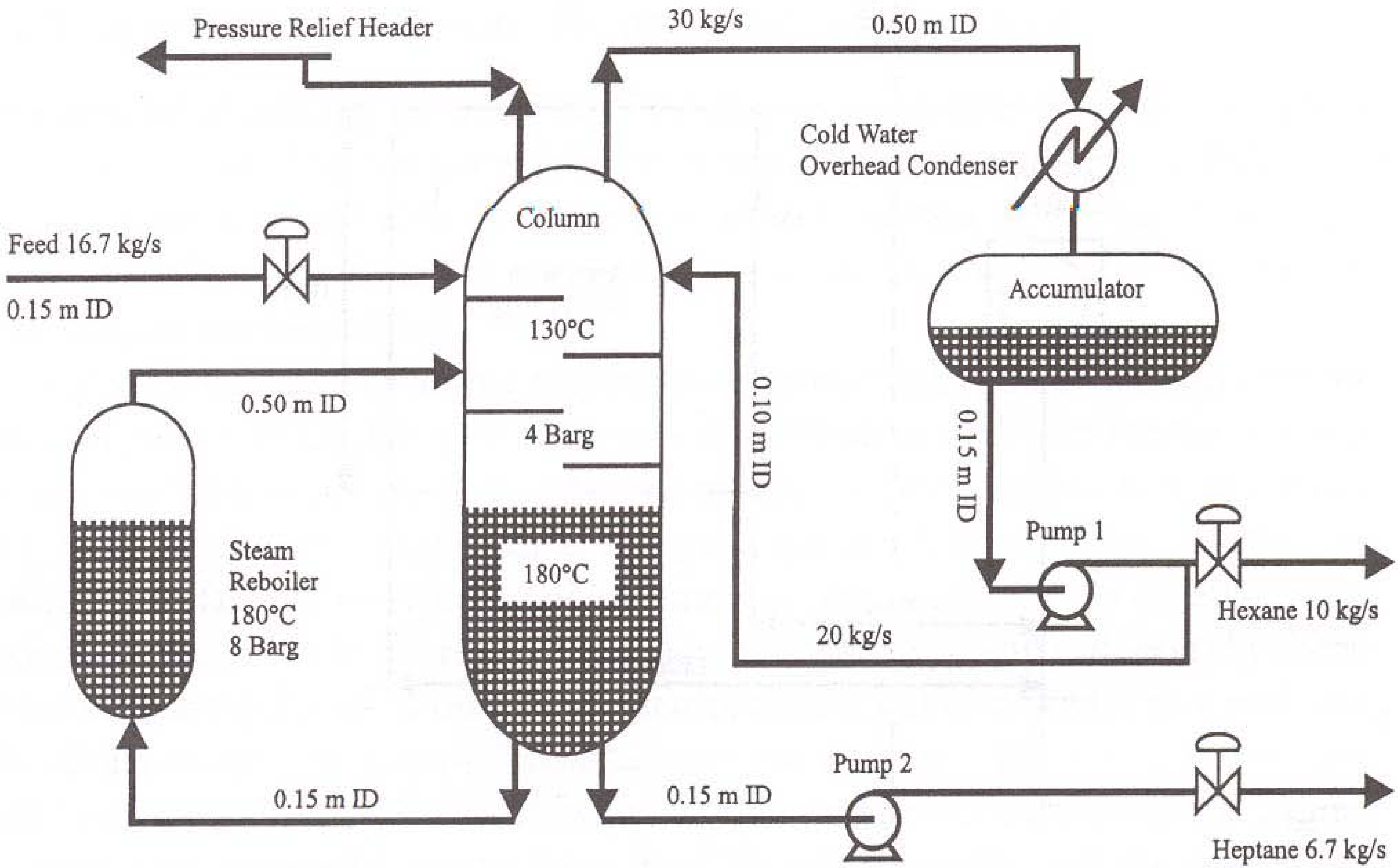
$$ROD = \sum_{i=1}^{n} f_i N_i$$

- f_i is the frequency of incident outcome case i (yr^{-1})
- N_i is the number of fatality result from incident outcome case i
- n is the number of incident outcome case

- ROD = $(7.3 \times 10^{-5})(13) + (7.3 \times 10^{-5})(16) + (7.3 \times 10^{-5})(13) + (3.8 \times 10^{-7})(20) + (3.8 \times 10^{-7})(39) + (3.8 \times 10^{-7})(20)$
- $= 3.1 \times 10^{-3}$ fatalities/year

Distillation Column

- Description
  - A C6 distillation column is used to separate hexane and heptane from a feed stream consisting of 58%(wt) hexane and 42%(wt) heptane
  - The column operating pressure is 4 barg and the temperature range is 130-160 C from the top to the bottom of the column
  - The column bottoms and reboiler inventory is 6000 kg(13,228 lb) and there are about 10,000 kg(22,046 lb) of liquid on the trays
  - The condenser is assumed to have no liquid holdup and the accumulator drum inventory is 12,000 kg(26,455 lb)
  - The material in the bottom of the column is approximately 90% heptane and 10% hexane



Piping Diameter	Total Length
0.10 m	10 m
0.15 m	15 m
0.50 m	25 m

TABLE 8.14. Physical Properties[a]

Physical Properties	Hexane	Heptane
Boiling point (°C)	69	99
Molecular weight	86	100
Upper flammable limit (vol %)	7.5	7.0
Lower flammable limit (vol %)	1.2	1.0
Heat of combustion (J/kg)	4.5×10^7	4.5×10^7
Ratio of specific heats, *k*	1.063	1.054
Liquid density at boiling point (kg/m^3)	615	614
Heat of vaporization at boiling point (J/kg)	3.4×10^5	3.2×10^5
Liquid heat capacity (J/kg-°K)	2.4×10^3	2.8×10^3

[a]From *DIPPR Handbook* (AIChE, 1987)

Description(cont.)

- This is an old plant, and, to the east, 80 m away, is an on site office and warehouse complex containing 200 people, distributed uniformly on 1 ha(100 X 100 m) of land
- Only one average weather condition is considered
  - A wind speed of 1.5 m/s and F stability

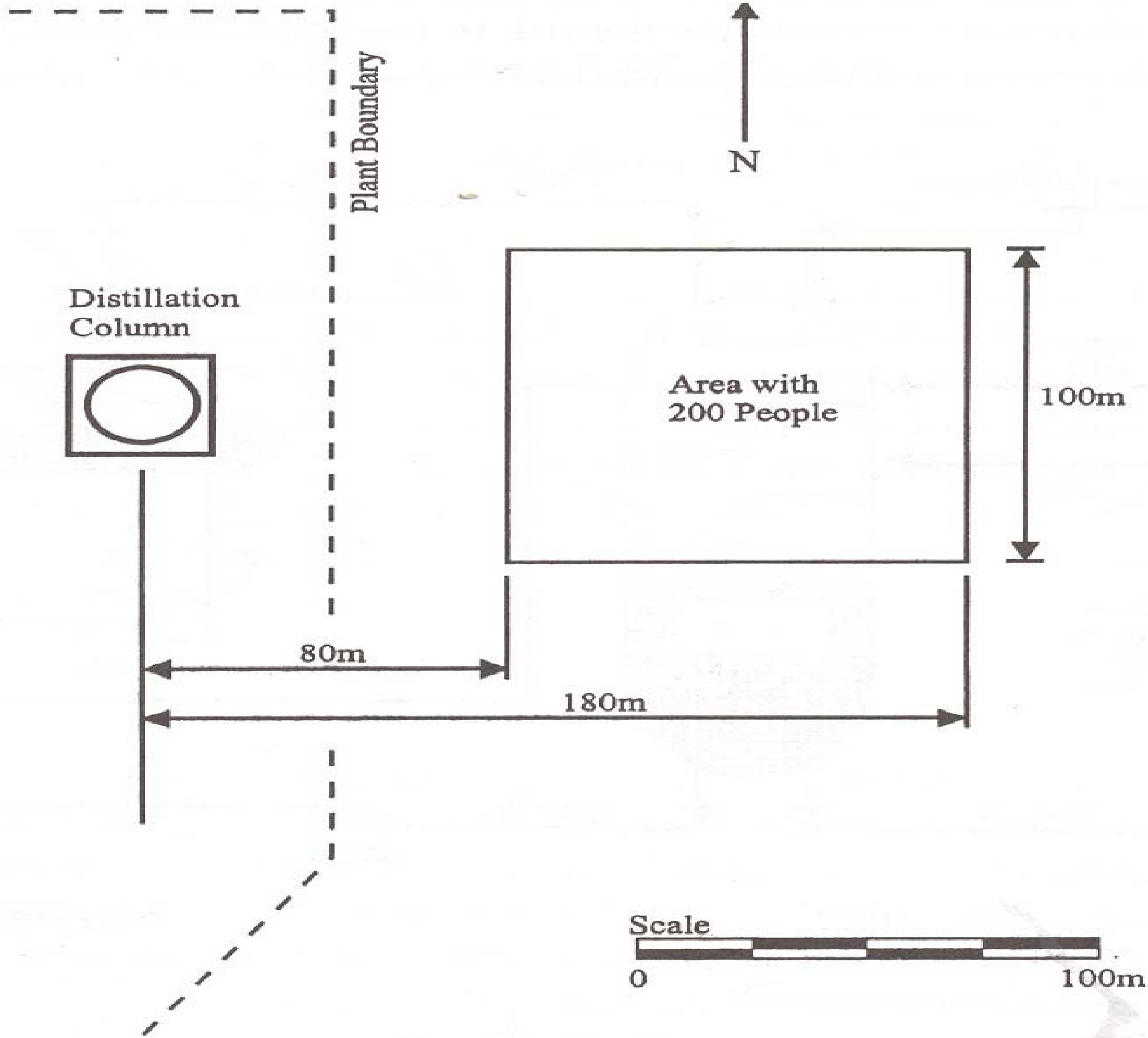


FIGURE 8.11. The plant layout and surroundings.

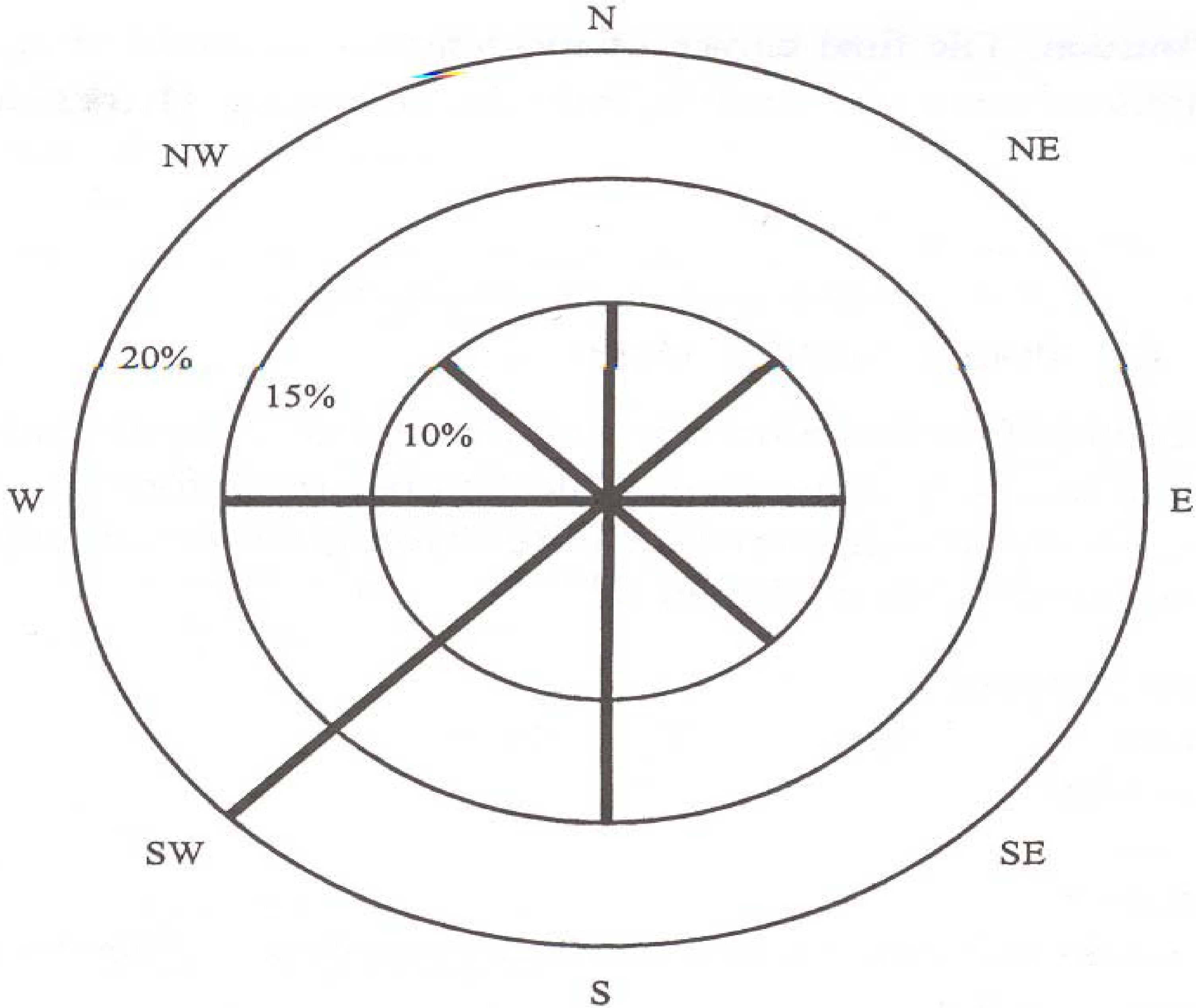


FIGURE 8.12. The wind rose for Case Study 8.2.

Identification, Enumeration and Selection of Incidents

- The possible incident list
  - Complete rupture
    - Column
    - Accumulator
    - Reboiler
    - Condenser
  - Liquid leaks(full bore rupture and hole equivalent to 20% of diameter)
    - Column feed line
    - Reboiler feed line
    - Heptane pump suction line
    - Heptane pump discharge line
    - Condenser discharge line
    - Reflux pump suction line
    - Reflux pump discharge line
    - Shell leak(of column, accumulator, reboiler or condenser) of hole size equivalent to 20% of pipe diameter only
  - Vapor Leak(full bore rupture and hole equivalent to 20% of diameter)
    - Column overhead line
    - Reboiler discharge line
    - Shell leakage(of the column, accumulator, reboiler or condenser) of hole size equivalent to 20% of pipe diameter only

- This set can be reduced to the representative set of incidents through the following assumptions and judgment
  - There are no automatic isolation valve within this system
  - All liquid lines have diameter of either 0.10 or 0.15 m
  - Both vapor lines are 0.5 m in diameter
- The above assumption produce the following representative set of incidents
  - A. a catastrophic failure of the column, reboiler, condenser, accumulator or any full bore liquid or vapor line rupture
  - B. liquid release through a hole of diameter equal to 20% of a 0.15 m diameter line
  - C. a vapor release through a hole of diameter equal to 20% of a 0.5 m diameter line

Incident Consequence Estimation

- Flash, discharge and dispersion calculations(Incident A,B and C)
  - Incident A : Catastrophic failure

$$F_V = C_P \frac{(T - T_b)}{h_{fg}}$$

    - C_P = average liquid heat capacity over the range T to T_b (2400J/kg K for hexane, 2800J/kg K for heptane)
    - T = initial temperature(130 C for hexane, 160 C for heptane)
    - T_b = final temperature or atmospheric boiling point(69 C for hexane, 99 C for heptane)
    - h_{fg} = heat of vaporization(3.4 X 10^5 J/kg for hexane, 3.2 X 10^5 J/kg for heptane)
    - F_V = fraction of liquid flashed to vapor
  - Calculated flash fraction are 0.43 for hexane and 0.53 for heptane

TABLE 8.15. Data Used for Instantaneous Heavy Gas Dispersion Calculations

Quantity	Instantaneous release
Mass released	28,000 kg
Release rate	—
Temperature	69°C
Dilution factor	10
Cloud radius	Equal to height
Atmospheric stability	Stable (F)
Wind speed	1.5 m/s
Surface roughness parameter	0.1 m
Ambient temperature	20°C
Ambient humidity	80%

TABLE 8.16. Results of Dispersion Calculations for the Instantaneous Release (Incident A)

Time (s)	Distance downwind (m)	Cloud radius (m)	Cloud height (m)	Center-line concentration (vol %)	Cloud temperature (°K)
0	0	32	32	7.8[a]	309
20	30	91	14	2.2	297
40	60	125	11	1.5	296
57	85	148	9.5	1.2	295

[a]The initial concentration is calculated for a 10 times dilution of hot hexane into ambient air. On mixing, the air will work, the hexane will cool, and the total volume of the cloud will increase. This results in an initial concentration of 7.8% (vol).

- Incident B and C : liquid and vapor release from hole in piping
  - The discharge rate for the liquid release(Incident B) can be estimated using Eq. (2.1.15), assuming a hole diameter of 0.03 m
    - The resulting discharge rate is 9.6kg/s
  - The discharge rate for the gaseous release(Incident C) can be estimated using Eq. (2.1.17), assuming a hole diameter of 0.10 m
    - The resulting discharge rate is 12.4kg/s
  - Average flow rate of representative average release of vapor(B and C) is 11 kg/s

TABLE 8.17. Data Used for Continuous Heavy Gas Dispersion Calculations

Quantity	Continuous release
Mass released	—
Release rate	11 kg/s
Temperature	69°C
Dilution factor	10
Cloud radius	Equal to height
Atmospheric stability	Stable (F)
Wind speed	1.5 m/s
Surface roughness parameter	0.1 m
Ambient temperature	20°C
Ambient humidity	80%

TABLE 8.18. Results of Dispersion Calculations for the Continuous Release (Incidents B and C)

Time (s)	Distance downwind (m)	Cloud radius (m)	Cloud height (m)	Center-line concentration (vol %)	Cloud temperature (°K)
0	0	3.7	3.7	7.8[a]	309
20	30	24	1.8	2.4	297
40	60	38	1.6	1.7	296
60	90	50	1.5	1.4	295
71	106	56	1.5	1.2	294

[a]The initial concentration is calculated for a 10 times dilution of hot hexane into ambient air. On mixing, the air will work, the hexane will cool, and the total volume of the cloud will increase. This results in an initial concentration of 7.8% (vol)

- Event trees
  - For incident A,B and C, a number of different incident outcomes are possible depending on (1) if, and when, ignition occurs and (2) the consequences of ignition
  - In order to define the incident outcomes for these release, two event trees have been constructed
    - Consider immediate or delayed ignition

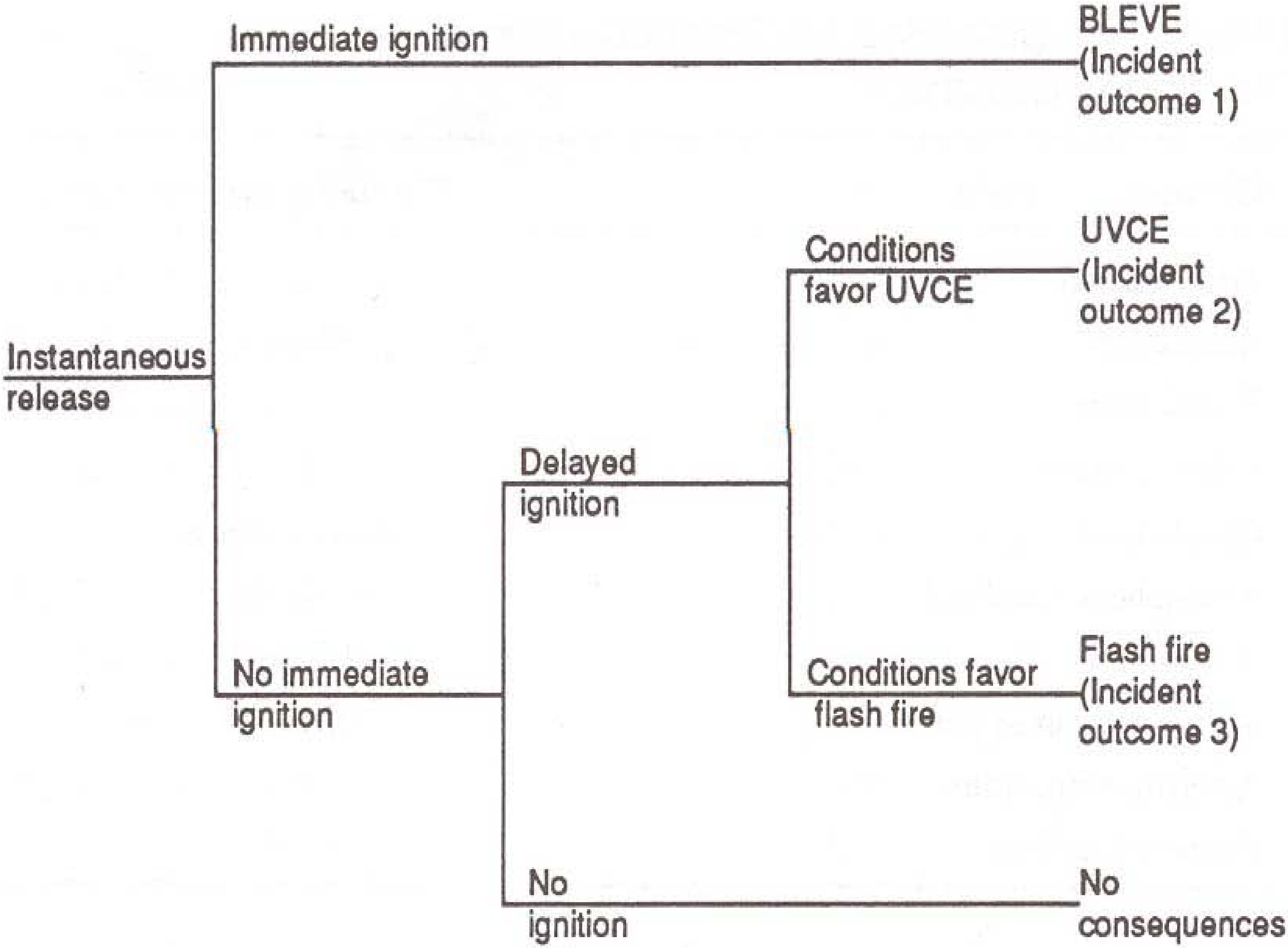


FIGURE 8.13. Event tree for Incident A.

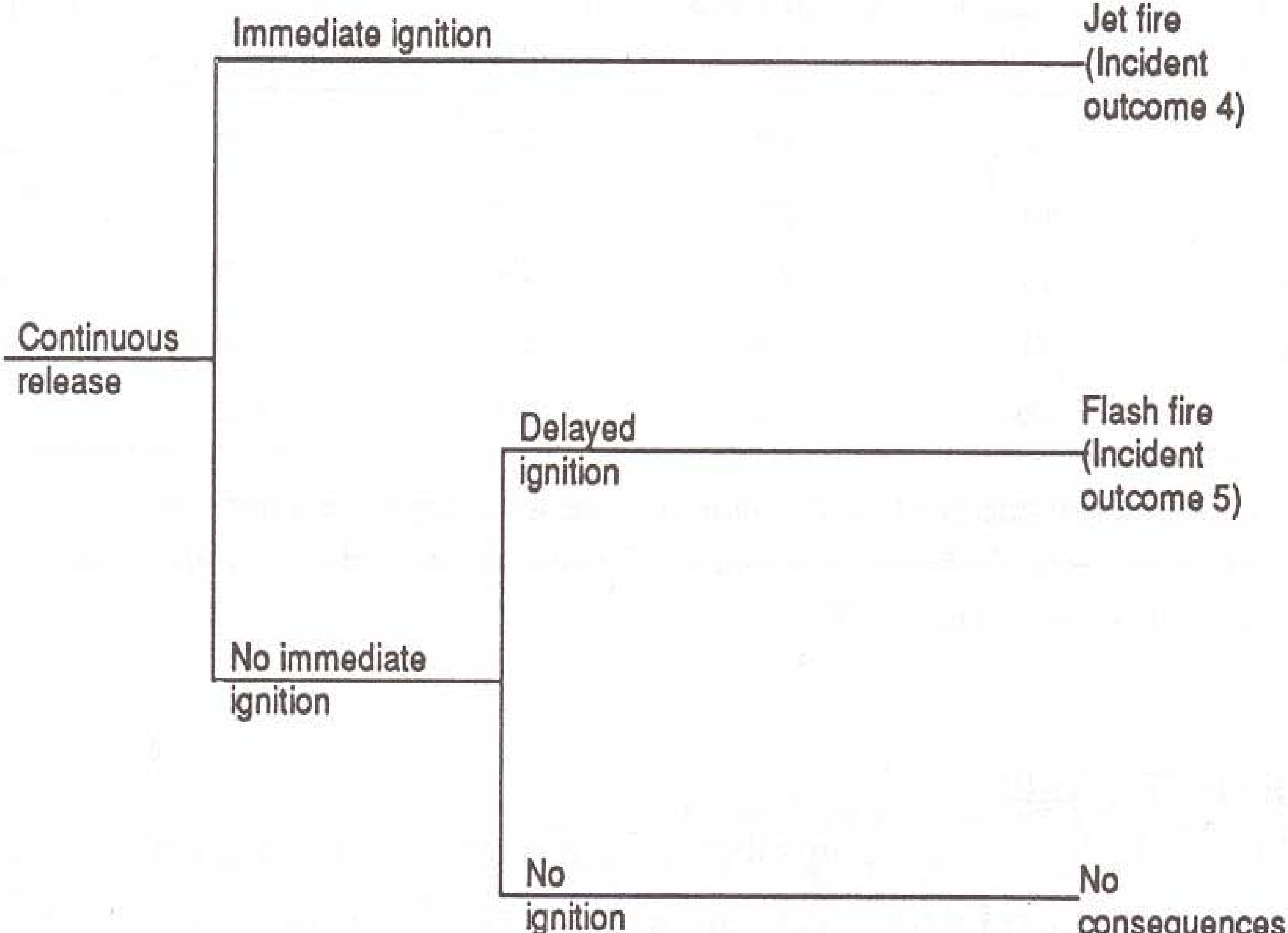


FIGURE 8.14. Event tree for Incidents B and C.

- From the event tree, the following incident outcomes are identified for the risk analysis
  - BLEVE due to immediate ignition of and instantaneous release
  - VCE due to delayed ignition of an instantaneous release
  - Flash fire due to delayed ignition of an instantaneous release
  - Jet fire from immediate ignition of a continuous release
  - Flash fire due to delayed ignition of a continuous release

Consequences of Incident Outcomes

- Incident outcome No. 1 : BLEVE due to immediate ignition of an instantaneous release
  - Quantity of hexane : 28,000 kg
  - Parameters are calculated using a software package
    - Peak BLEVE diameter : 181 m
    - BLEVE duration : 12 s
    - Center height of BLEVE : 136 m
  - For a duration of 12 seconds, the incident radiation required for fatality of an average individual id approximately 75 kW/m^2 (from figure 2.95)

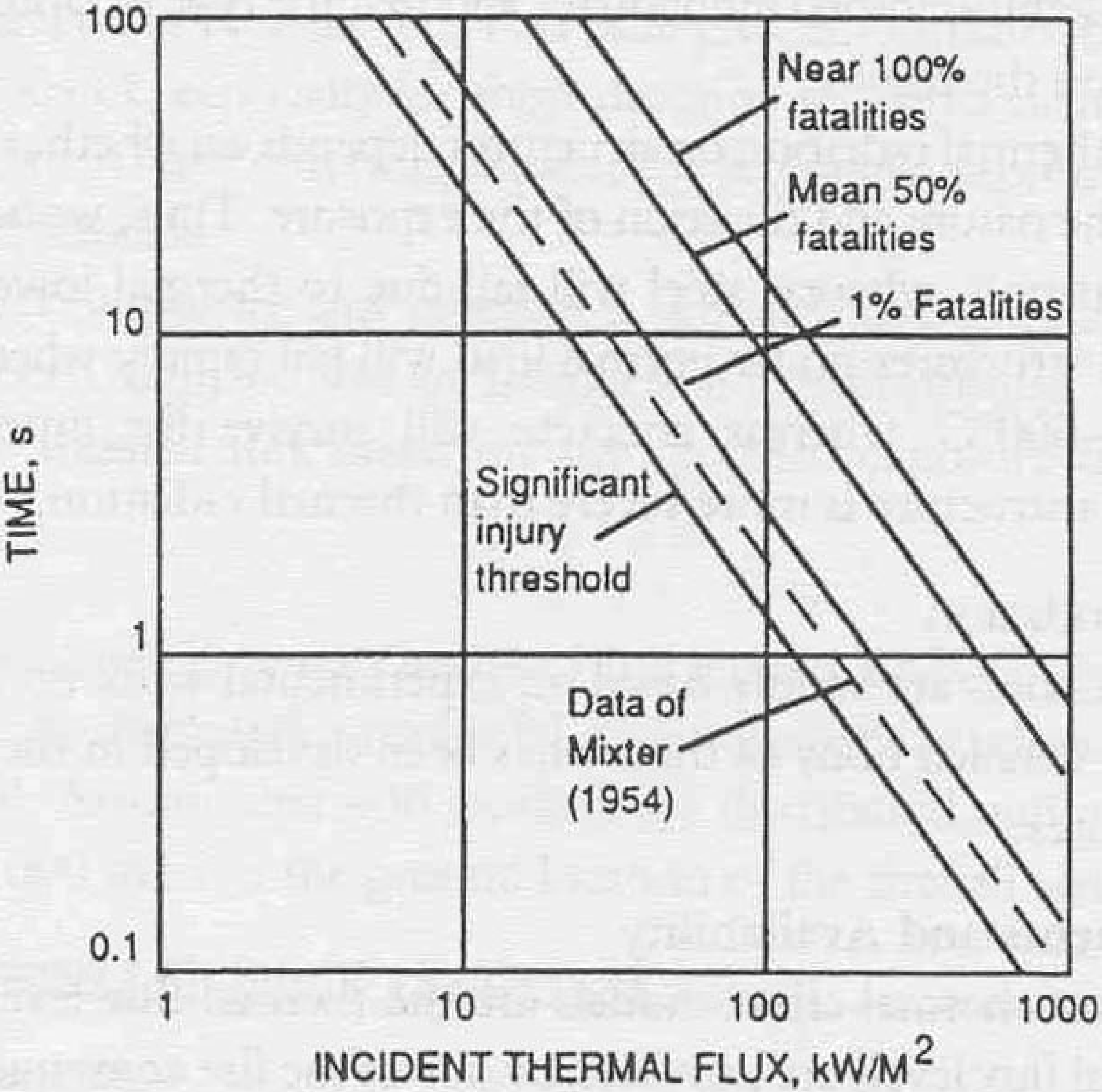


FIGURE 2.95. *Serious injury/fatality levels for thermal radiation (Mudan, 1984).*

- Incident radiation from a BLEVE

$$E_r = \tau_a E F_{21}$$

  - E_r is the emissive radiative flux received by a receptor
  - τ_a = transmissivity
  - E = surface emitted radiative flux(kW/m^2)
  - F_{21} is the view factor(dimensionless)
- Transimissivity

$$\tau_a = 2.02(P_W X_s)^{-0.09}$$

  - τ_a is the atmospheric transmissivity (fraction of the energy transmitted 0 to 1)
  - P_W is the water partial pressure(Pascal, N/m^2)
  - X_S is the path length distance from the frame surface to the target(m)

- Path length x

$$x = \sqrt{(H_{BLEVE}^{2} - r^{2}} - \frac{D_{MAX}}{2} = \sqrt{(136^{2} + r^{2}} - 90.5$$

  - r is the horizontal distance from the column to the receiver

- Assuming $P_W = 2810\ N/m^2$

$$\tau = 0.99[(136^{2} + r^{2})^{0.5} - 90.5]^{-0.09}$$

- View factor

$$F_{21} = \frac{D_{MAX}^{2}}{4r^{2}} = 8190r^{-2}$$

- Radiative emissive flux

$$E = \frac{RMH_C}{\pi D_{MAX}^2 t_{BLEVE}}$$

  - E is the radiative emissive flux(energy.area time)
  - R is the radiative fraction of heat of combustion(unitless)
  - M is the initial mass of fuel in the fireball(mass)
  - H_c is the net heat of combustion per unit mass(energy/kg)
  - D_{MAX} is the maximum diameter of the fireball(length)
  - t_{BLEVE} is the duration of the fireball(time)
 - For R =0.25 and the heat of combustion for hexane is 4.5 X 10^{-7} J/kg, E = 255 kW/m^2

$$E_r = \left(0.99\left[\left(\sqrt{136^2 + r^2}\right) - 90.5\right]^{-0.09}\right)(255)\left(8190r^{-2}\right)$$

- For a radiation level E_r of 75 kW/m^2, r=135 m

- Incident outcome No. 2 : unconfined vapor cloud explosion due to delayed ignition of instantaneous release
  - Use TNT equivalent model

$$W = \frac{\eta M E_c}{E_{TNT}}$$

    - W is the equivalent mass of TNT(kg)
    - η is an empirical explosion efficiency(assumed to be 0.1)
    - M is the mass of hydrocarbon(28,000 kg)
    - E_c is the heat combustion of hydrocarbon(4.5×10^7 kJ/kg for hexane)
    - E_{TNT} is the heat of combustion of TNT(4.6×10^6 J/kg)
  - So, the equivalent mass of TNT is 27,391 kg (60,387 lb)

- An overpressure of 3 psi is used to calculated the extent of fatal effect
- From a figure to figure 2.48, the scaled range(Z_G) for an overpressure of 3 psi is 15 ft/lb$^{1/3}$
- Actual distance

$$R_G = Z_G W^{1/3} = 15 \times 60{,}378^{1/3} = 588\,ft(179m)$$

- Incident outcome No. 3 : flash fire due to delayed ignition of an instantaneous release
  - For flash fire, approximate estimate for the extent of the fatal effect zone is the area over which the cloud is above the LFL
  - Circular zone of 148 m radius centered 85 m downwind
- Incident outcome No. 4 : jet fire from immediately ignition of a continuous release
  - There is no direction threat to the office/warehouse complex and this incident outcome is not considered further

- Incident outcome No. 5 : flash fire due to delayed ignition of a continuous release
  - The area over which the cloud formed by the continuous release is above the LFL can be derived from table 8.18
  - This gives a pie-shaped hazard zone 162 m long downwind(106 m distance + 56 m radius)
- The net result of these consequence effect calculation is that four other incident outcomes(Nos. 1, 2, 3 and 5) could impact the office/warehouse complex

Incident Frequency Estimation

- Frequencies of the representative set of incident
  - Use historical failure rate data

TABLE 8.19 Example Failure Frequency (for Illustration Purposes)

Item	Size of failure	Failure rate
Piping		
Small ≤ 50 mm dia.	Full bore rupture	8.8×10^{-7} (m yr^{-1})
	20% of pipe dia. rupture	8.8×10^{-7} (m yr^{-1})
Medium > 50 mm dia.	Full bore rupture	2.6×10^{-7} (m yr^{-1})
≤ 150 mm dia.	20% of pipe dia. rupture	5.3×10^{-6} (m yr^{-1})
Large > 150 mm dia.	Full bore rupture	8.8×10^{-8} (m yr^{-1})
	20% of pipe dia. rupture	2.6×10^{-6} (m yr^{-1})
Fractionating system (excluding piping)	Serious leakage	1.0×10^{-5} (m yr^{-1})
	Catastrophic rupture	6.5×10^{-6} (m yr^{-1})

Incident A : Instantaneous release

- This incident includes the following system
  - Catastrophic rupture of any component in the fractionating system
  - Catastrophic(full bore) rupture of any pipework
- There is approximately 25 m of 0.5 m diameter piping and 25 m of 0.15 m equivalent diameter piping included in this incident
  - Catastrophic rupture of fractionating system
    - 6.5×10^{-6} yr^{-1}
  - Full bore of 25 m of medium pipe
    - $25 \times 2.6 \times 10^{-7} = 6.5 \times 10^{-6}$ yr^{-1}
  - Full bore of 25 m large pipe
    - $25 \times 8.8 \times 10^{-8} = 2.2 \times 10^{-6}$ yr^{-1}
  - Total = 1.5×10^{-5} yr^{-1}

Incident B and C : continuous release

- Includes holes of 20% of the diameter for all piping and serious leakage from vessel
- There is approximately 25 m of large 0.5 m diameter piping and 25 m of medium 0.15 m diameter piping
  - Leaks from 25 m of medium pipe
    - $25 \times 5.3 \times 10^{-6} = 1.3 \times 10^{-4}\ yr^{-1}$
  - Leaks from 25 m of large pipe
    - $25 \times 2.6 \times 10^{-6} = 6.5 \times 10^{-5}\ yr^{-1}$
  - Serious leakage from fractionating system
    - $1.0 \times 10^{-5}\ yr^{-1}$
  - Tatal
    - $2.1 \times 10^{-4}\ yr^{-1}$

Probabilities of Incident Outcomes

- The probability of each outcome
  - Determined by assigning probabilities to all of the branches of the event trees
  - The branch probabilities for these event tree have been derived using engineering judgment

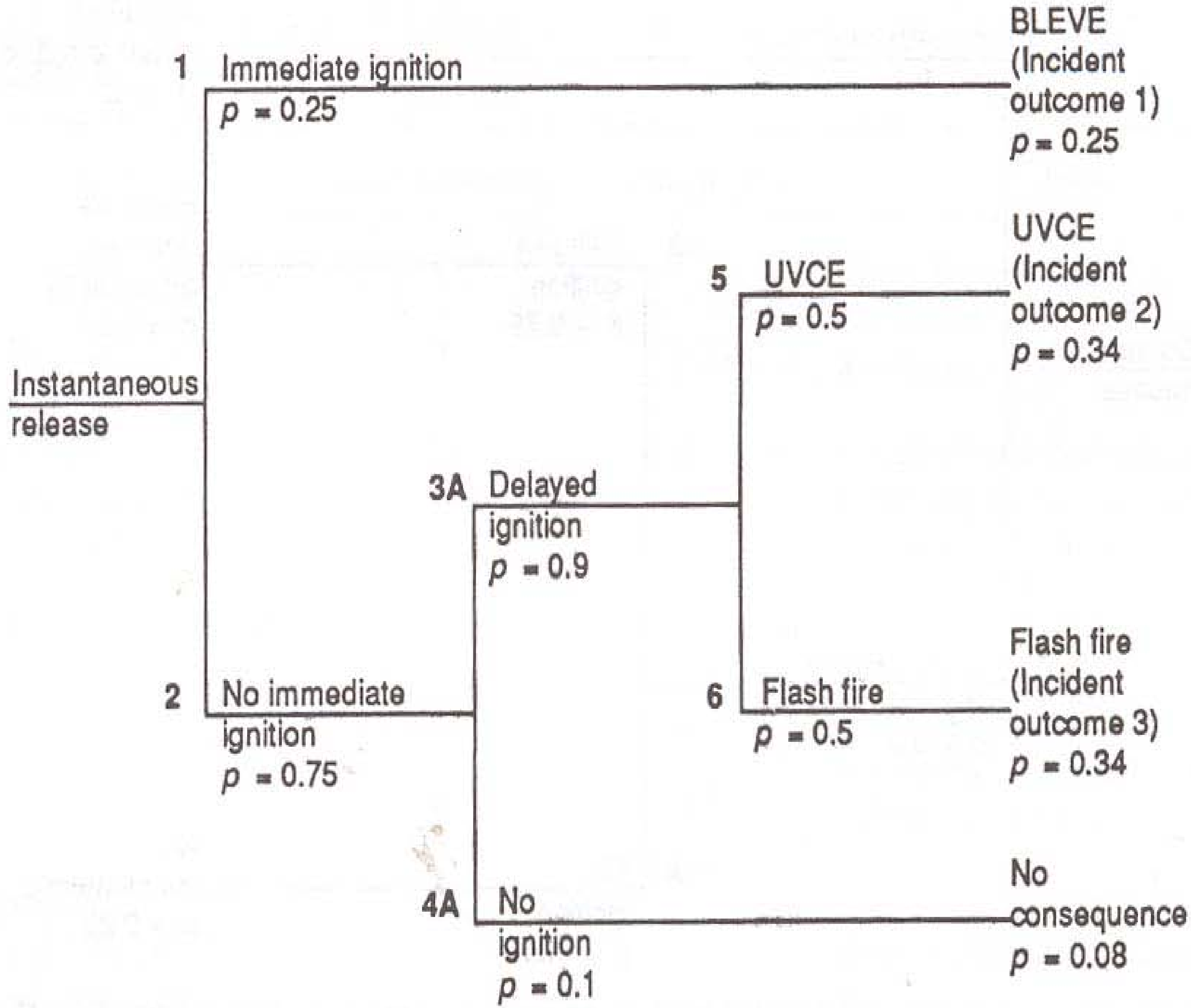


FIGURE 8.15. Event tree for Incident A, instantaneous release; wind from SW, W. and NW directions (directions affecting residential area).

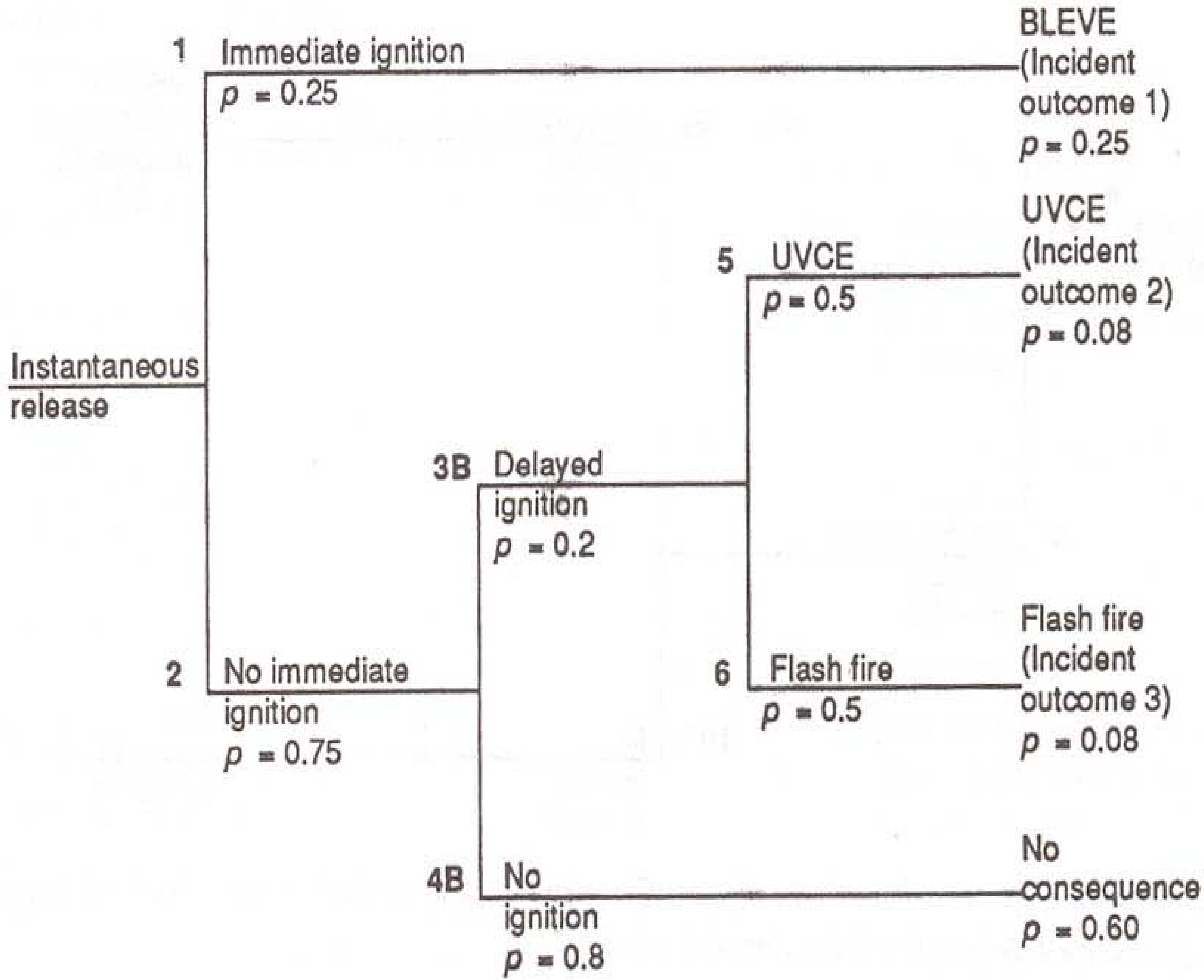


FIGURE 8.16. Event tree for Incident A, instantaneous release; wind from all other directions (directions away from residential area).

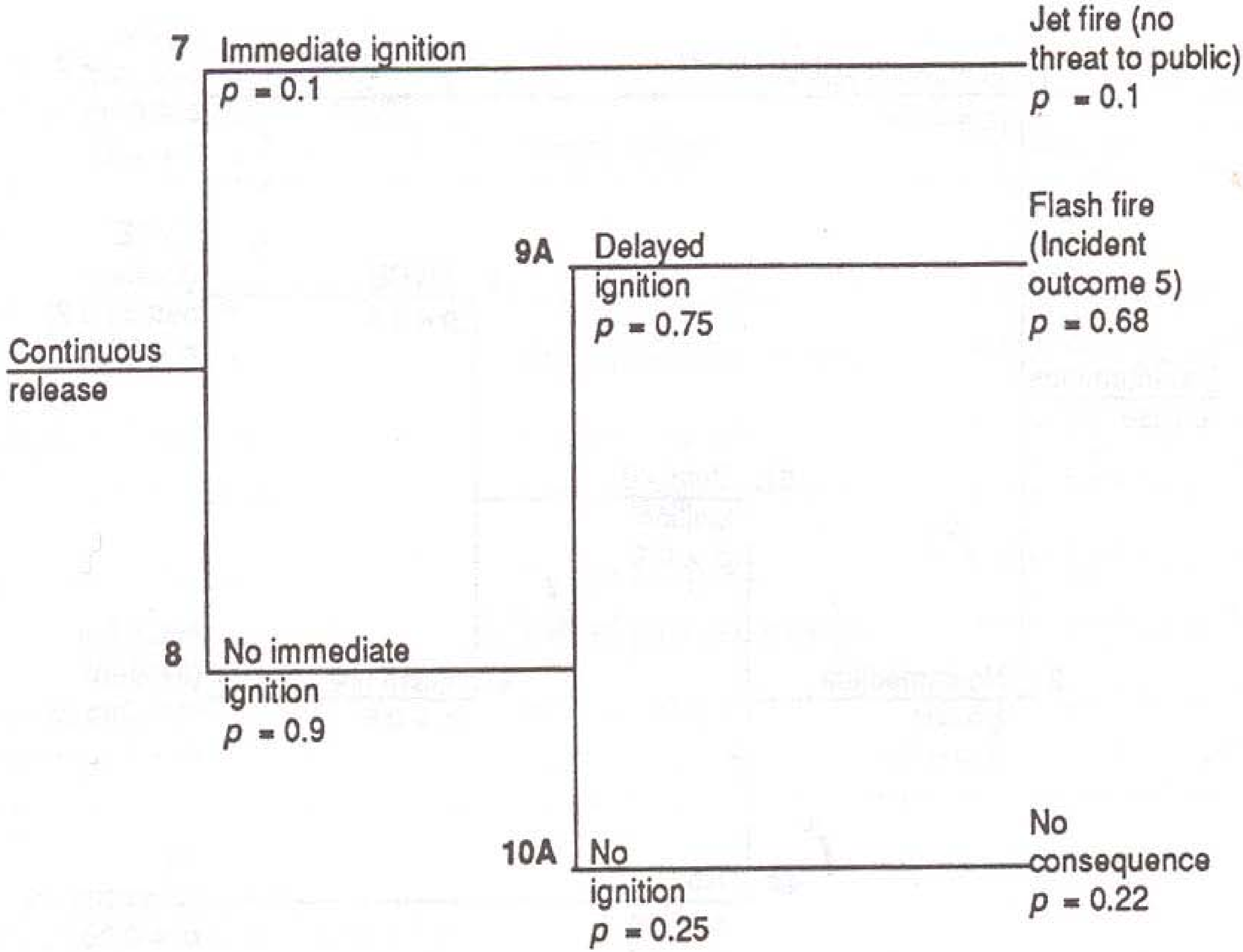


FIGURE 8.17. Event tree for Incidents B and C, continuous release; wind from SW, W. and NW directions (directions affecting residential area).

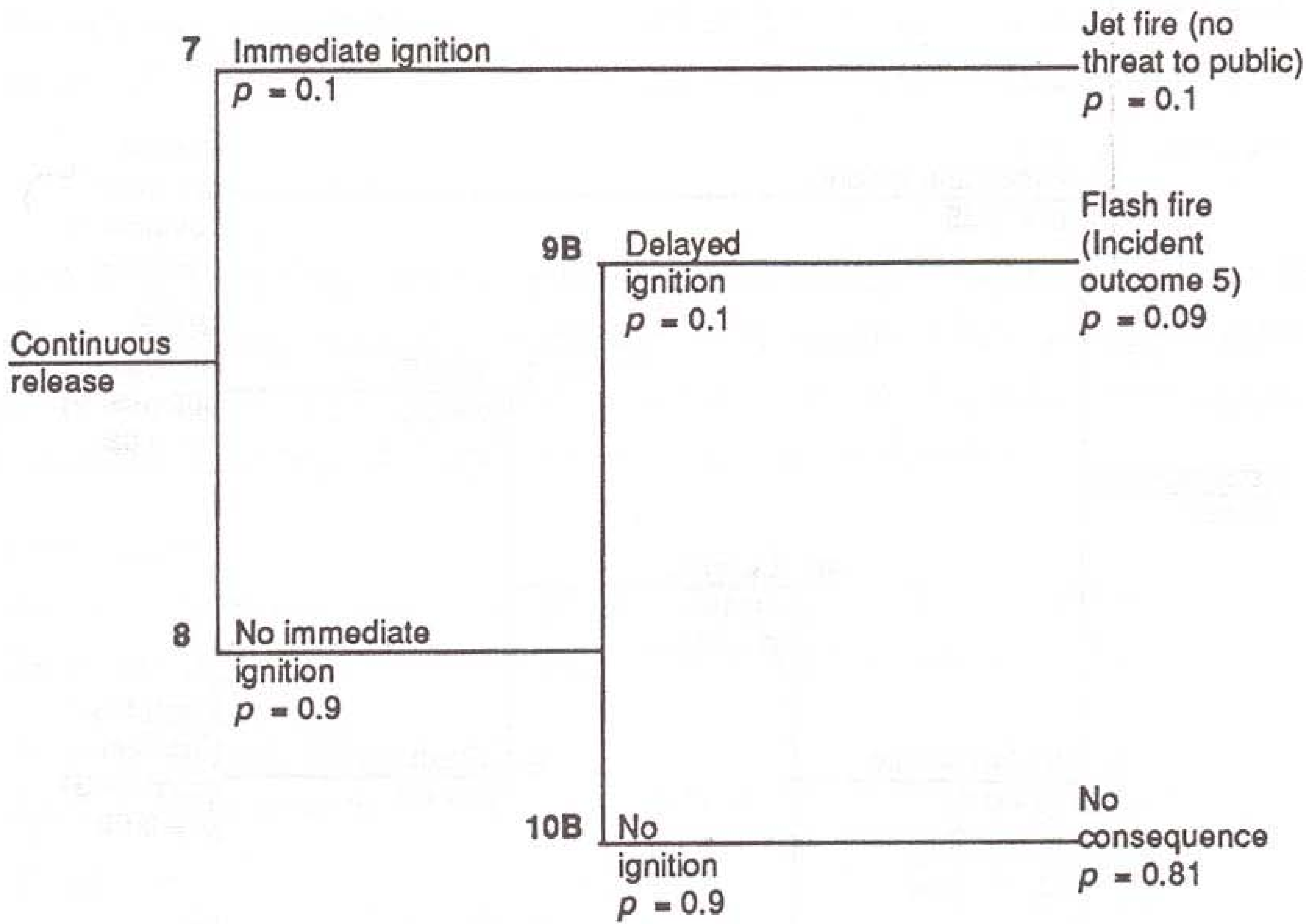


FIGURE 8.18. Event tree for Incidents B and C, continuous release; wind from all other directions (directions away from residential area).

TABLE 8.21. Event Tree Branch Probabilities—Instantaneous Release from Figures 8.15 and 8.16

Branch	Branch number	Probability	Basis
Immediate ignition (BLEVE)	1	0.25	Cause for failure may be fire and the release will initially extend to a wide area
No immediate ignition	2	0.75	
Delayed ignition [From Figure 8.15 (wind from SW, W & NW)]	3A	0.9	Ignition likely due to large size of cloud and the presence of population resulting in larger number of ignition sources
No ignition	4A	0.1	
UVCE	5	0.5	High likelihood of UVCE because the release is a very large quantity of flashing liquid
Flash Fire	6	0.5	
Delayed ignition [From Figure 8.16 (wind from all other directions)			Lower likelihood of ignition due to smaller number of ignition sources
No ignition			

TABLE 8.22. Event Tree Probabilities—Continuous Release from Figures 8.17 and 8.18

Branch	Branch number	Probability	Basis
Immediate ignition	7	0.1	Low likelihood of immediate ignition due to lack of local ignition sources and low rate of release
No immediate ignition	8	0.9	
Delayed ignition [From figure 8.17 (wind from SW, W & NW)]	9A	0.75	High likelihood of delayed ignition due to presence of population
No ignition	10A	0.25	
Delayed ignition [From figure 8.18 (wind from all other directions)]	9B	0.1	Low likelihood of delayed ignition due to smaller number of ignition sources
No ignition	10B	0.9	

- Preparation of incident outcome case frequencies
  - Event tree analysis developed the instantaneous and continuous release incidents to four specific incident outcomes that can impact the office/warehouse complex

TABLE 8.20. Incident Outcomes Impacting the Residential Area

Incident outcome number	Incident outcome
1	BLEVE due to immediate ignition of an instantaneous release
2	UVCE due to delayed ignition of instantaneous release
3	Flash Fire due to delayed ignition of an instantaneous release
5	Flash Fire due to delayed ignition of continuos release

TABLE 8.23. Frequencies of Incident Outcome Cases

Incident	Incident outcome	Incident frequency (yr^{-1})	Incident outcome probability[a]	Incident outcome frequency	From		Directional probability[b]	Incident outcome case frequency (yr^{-1})
A	1 BLEVE	1.5×10^{-5}	0.25	3.8×10^{-6}	—	—	—	3.8×10^{-6}
A	2 VCE	1.5×10^{-5}	0.34	5.1×10^{-6}	SW	NE	0.20	1.0×10^{-6}
			0.34	5.1×10^{-6}	W	E	0.15	7.7×10^{-7}
			0.34	5.1×10^{-6}	NW	SE	0.10	5.1×10^{-7}
			0.08	1.2×10^{-6}	N	S	0.10	1.2×10^{-7}
			0.08	1.2×10^{-6}	NE	SW	0.10	1.2×10^{-7}
			0.08	1.2×10^{-6}	E	W	0.10	1.2×10^{-7}
			0.08	1.2×10^{-6}	SE	NW	0.10	1.2×10^{-7}
			0.08	1.2×10^{-6}	S	N	0.15	1.8×10^{-7}
A	3 Flash Fire	1.5×10^{-5}	0.34	5.1×10^{-6}	SW	NE	0.20	1.0×10^{-6}
			0.34	5.1×10^{-6}	W	E	0.15	7.7×10^{-7}
			0.34	5.1×10^{-6}	NW	SE	0.10	5.1×10^{-7}
			0.08	1.2×10^{-6}	N	S	0.10	1.2×10^{-7}
			0.08	1.2×10^{-6}	NE	SW	0.10	1.2×10^{-7}
			0.08	1.2×10^{-6}	E	W	0.10	1.2×10^{-7}
			0.08	1.2×10^{-6}	SE	NW	0.10	1.2×10^{-7}
			0.08	1.2×10^{-6}	S	N	0.15	1.8×10^{-7}
B & C	5 Flash Fire	2.1×10^{-4}	0.68	1.4×10^{-4}	SW	NE	0.20	2.9×10^{-5}
			0.68	1.4×10^{-4}	W	E	0.15	2.1×10^{-5}
			0.68	1.4×10^{-4}	NW	SE	0.10	1.4×10^{-5}
			0.09	1.9×10^{-5}	N	S	0.10	1.9×10^{-6}
			0.09	1.9×10^{-5}	NE	SW	0.10	1.9×10^{-6}
			0.09	1.9×10^{-5}	E	W	0.10	1.9×10^{-6}
			0.09	1.9×10^{-5}	SE	NW	0.10	1.9×10^{-6}
			0.09	1.9×10^{-5}	S	N	0.15	2.9×10^{-6}

Risk Estimation

- Individual risk
  - The individual risk in the area around the column is estimated from above incident outcome case frequencies and consequence effect zone
  - Incident outcome
    - BLEVE
      - A circle of radius 135 m centered on the column
    - VCE
      - A circle of radius 179 m centered 85 m from the column
    - Flash fire(instantaneous)
      - A circle of radius 148 m centered 85 m from the column
    - Flash fire(continuous)
      - A pie shaped section(64 angle) that extends a total of 162 m from the column
      - The radius is 56 m centered on a point 106 m from the column

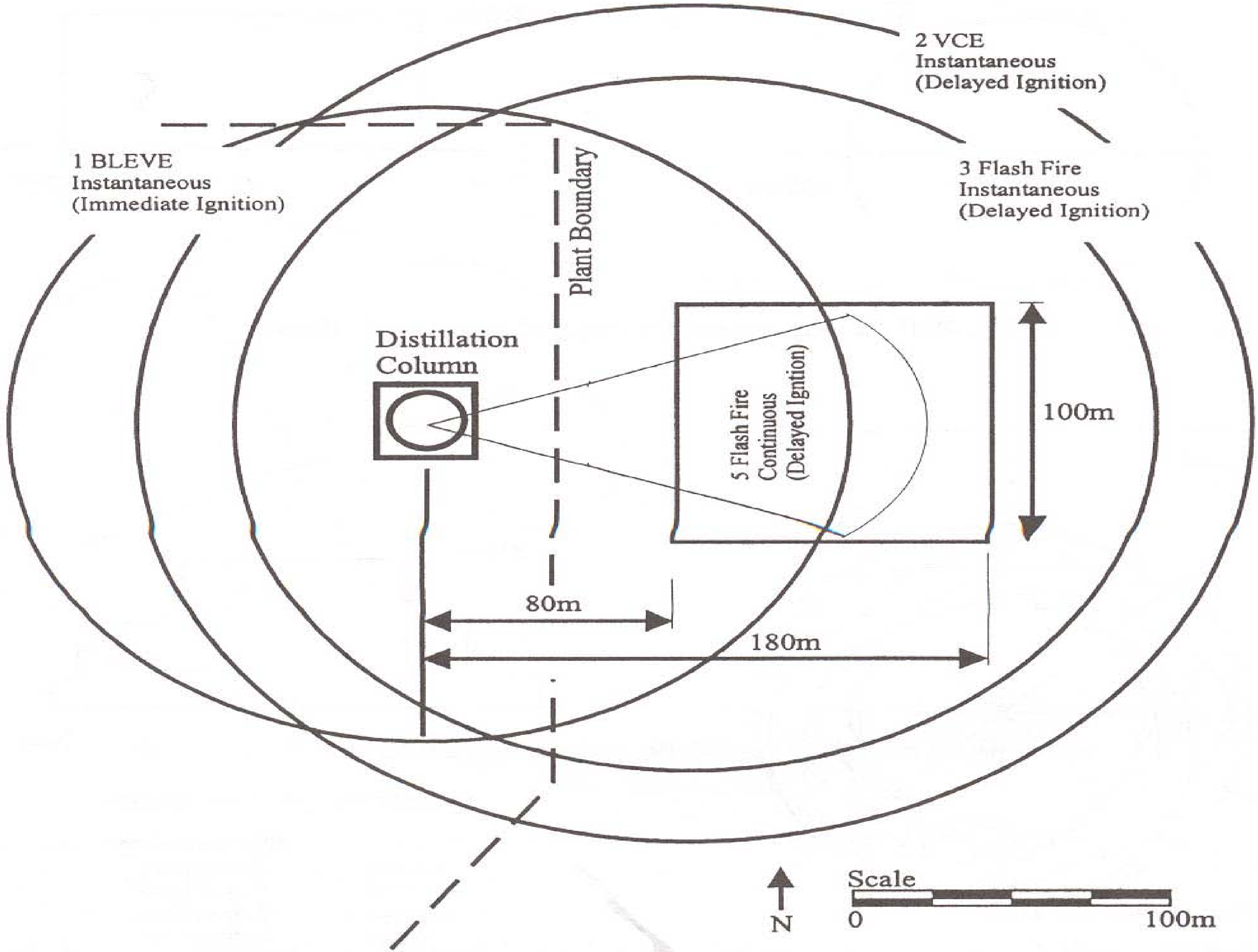


FIGURE 8.19. The plant layout and surroundings.

- The four consequences effects described above can be divided into 3 common types
  - Circular shaped, centered on column(incident outcome 1)
  - Circular shaped, centered 85 m from column(incident outcome 2 and 3)
  - Pie shaped, originating at column(incident outcome 5)

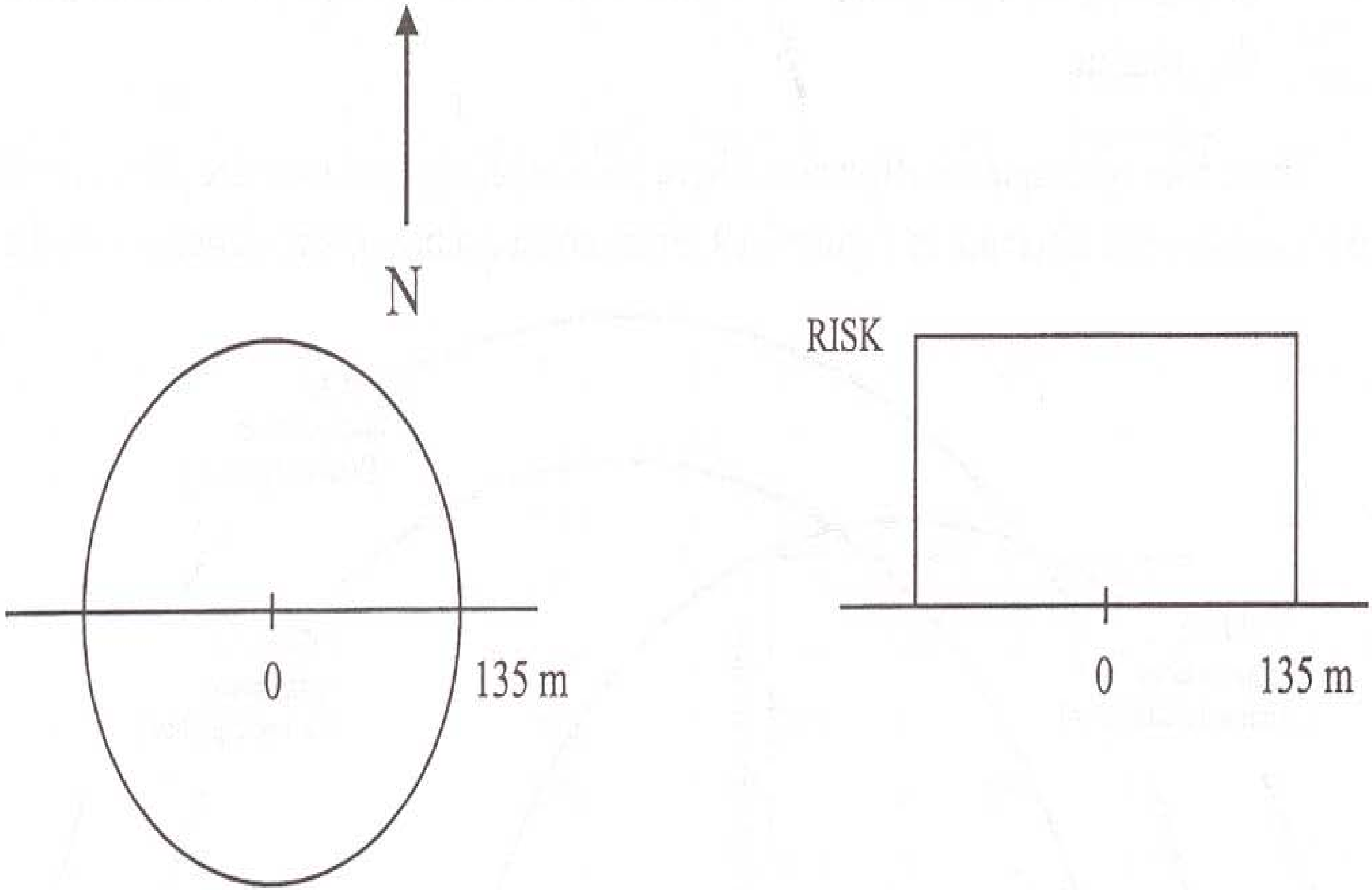
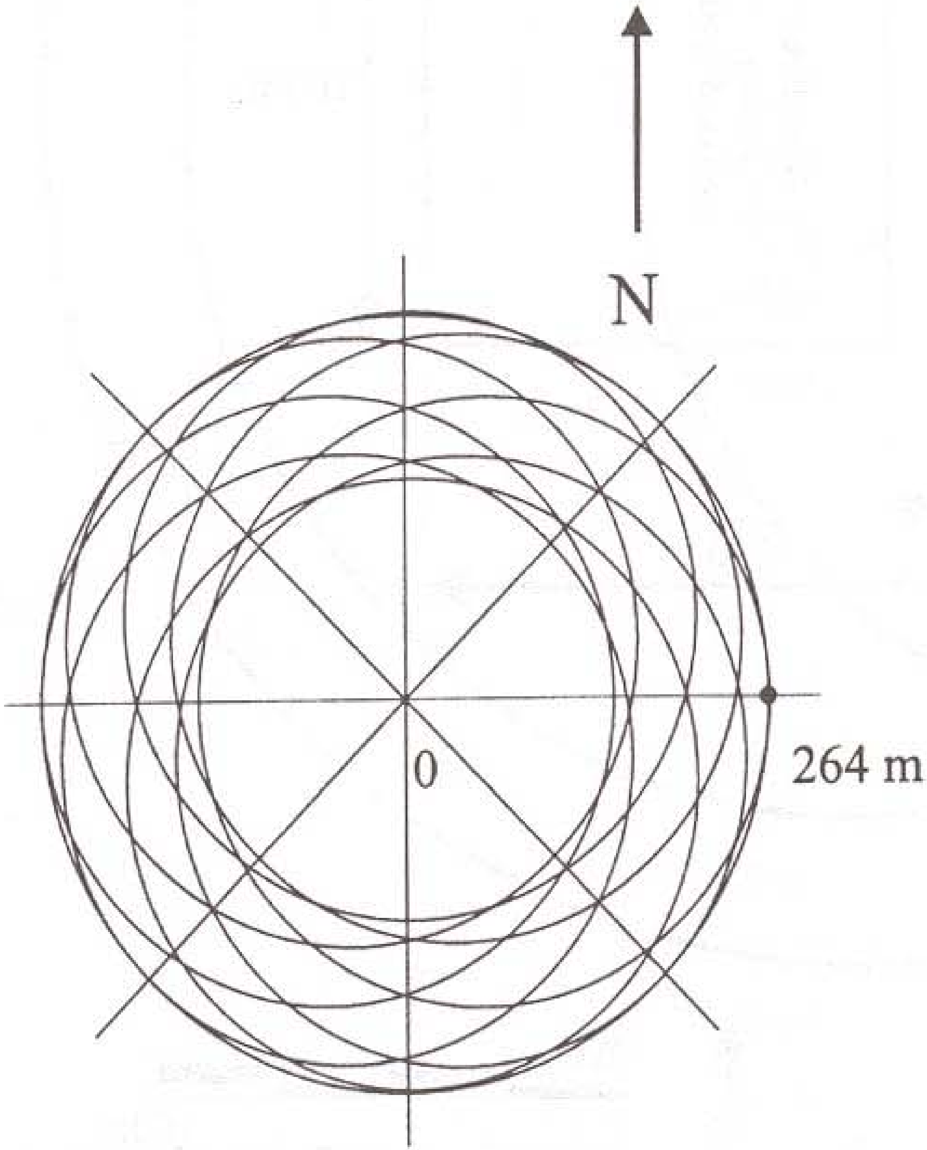
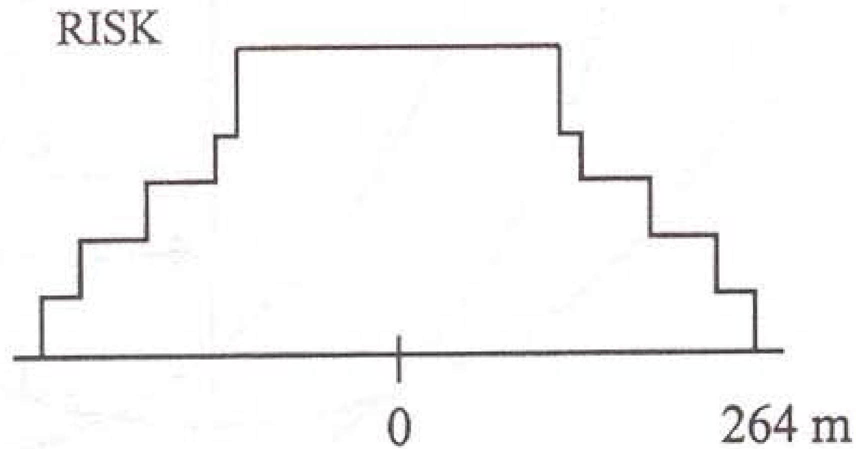


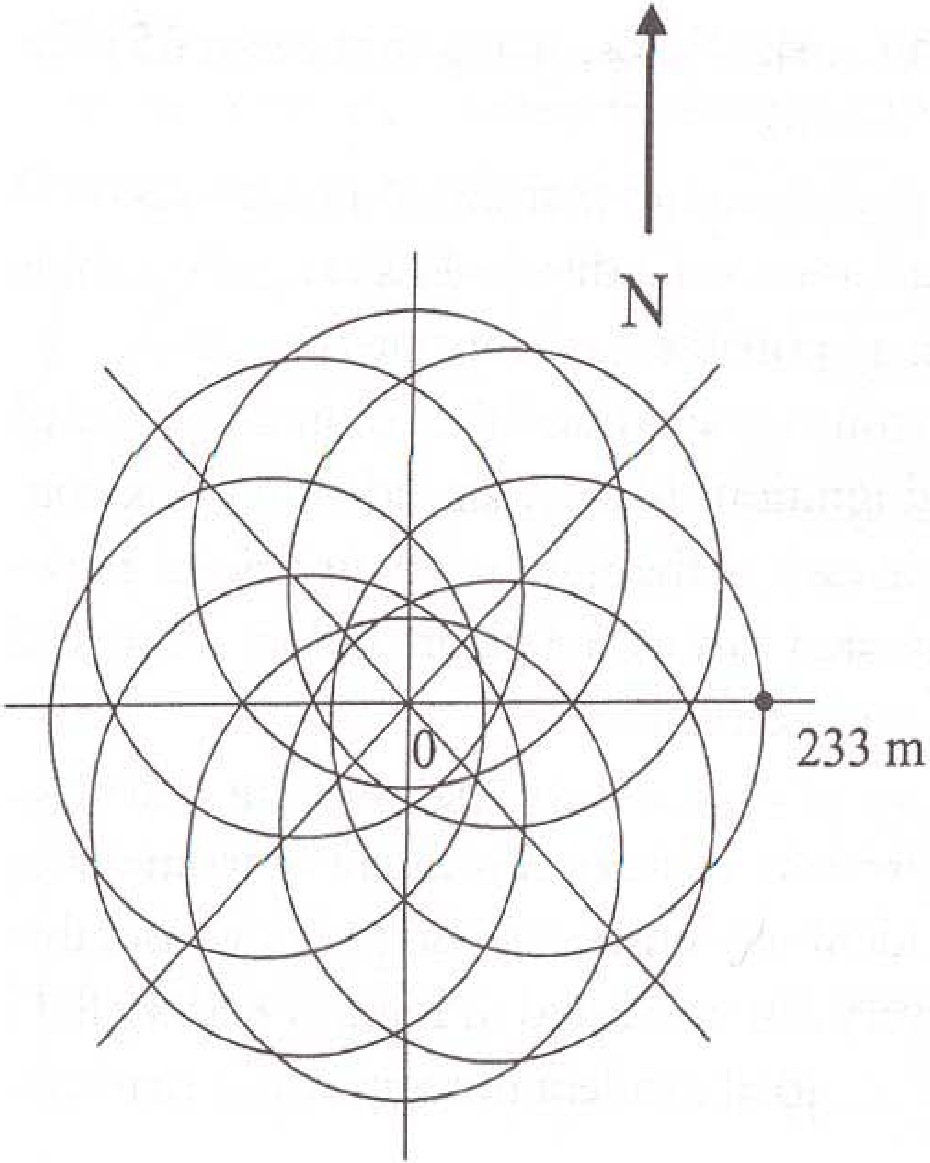
FIGURE 8.20. Risk profile for Incident outcome 1: BLEVE.

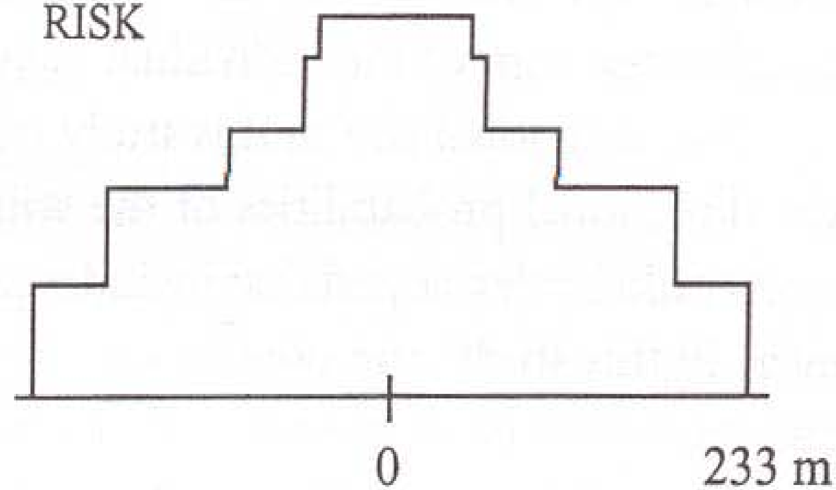




Distance (m)	*Risk contribution*
0-94	All 8 directions
94-108	7 directions
157-228	5 directions
228-264	3 directions
> 264	0 directions

FIGURE 8.21. Risk profile for Incident outcome 2: VCE.





Distance (m)	*Risk contribution*
0-63	All 8 directions
63-75	7 directions
75-120	5 directions
120-194	3 directions
194-233	1 directions
> 233	0 directions

FIGURE 8.22. Risk profile for incident outcome 2: flash fire (instantaneous).

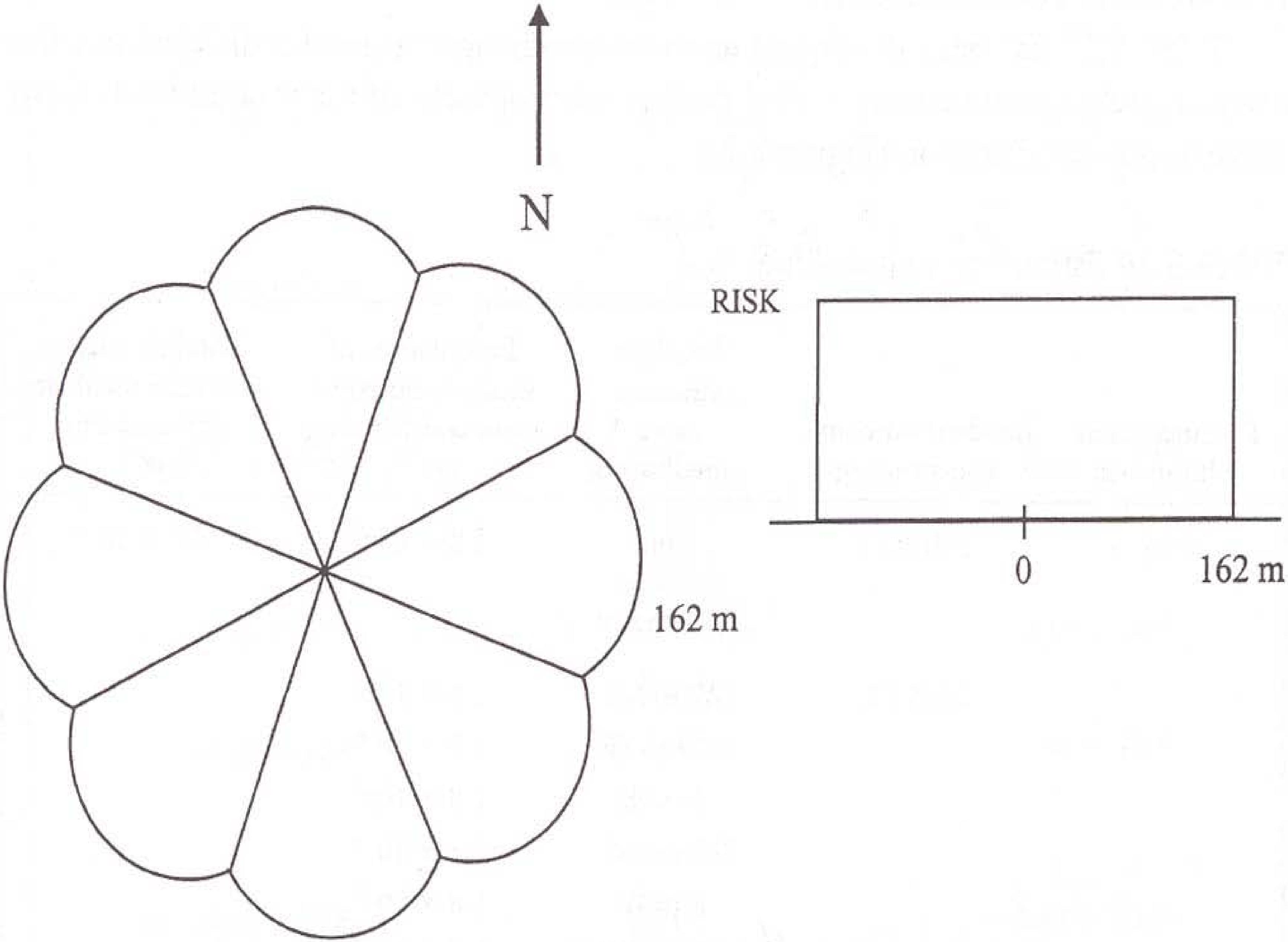


FIGURE 8.23. Risk profile for incident outcome 5: flash fire (continuous).

TABLE 8.24 Estimation of Individual Risk

Distance from column (m)	Incident outcomes contributing	Incident outcome cases contributing	Frequencies of incident outcome cases contributing (yr^{-1})	Total frequency for each incident outcome case (yr^{-1})
0-63	1 BLEVE	Wind direction independent	3.8×10^{-6}	5.7×10^{-6}
	2 UVCE	SW to NE	1.6×10^{-6}	
		NW to SE	1.2×10^{-6}	
		N to S	1.8×10^{-7}	
		NE to SW	1.8×10^{-7}	
		E to W	1.8×10^{-7}	
		SE to NW	1.8×10^{-7}	
		S to N	2.8×10^{-7}	4.6×10^{-6}
	3 Flash Fire (Inst.)	Same as 2		4.6×10^{-6}
	5 Flash Fire (Cont)	SW to NE	5.0×10^{-5}	1.1×10^{-4}
		W to E	3.8×10^{-5}	
		NW to SE	2.5×10^{-5}	
			Total individual risk =	**$1.25 \times 10^{-4}\ yr^{-1}$**

TABLE 8.25. Total Individual Risk at Discrete Distances in the East Direction[a]

Distance segment (m)	Incident outcome case that no longer impact on the total individual risk	Total individual risk (yr^{-1})
At 0 up to 63	Flash Fire (Cont.) N to S NE to SW E to W SE to NW S to N	7.39×10^{-5}
At 63 up to 75	Flash Fire (Inst.) E to W	7.38×10^{-5}
At 75 up to 94	Flash Fire (Inst.) SE to NW NE to SW	7.36×10^{-5}
At 94 up to 108	UCVE E to W	7.34×10^{-5}
At 108 up to 120	UVCE NE to SW SE to NW	7.32×10^{-5}
At 120 up to 135	Flash Fire (Inst.) N to S S to N	7.29×10^{-5}
At 135 up to 157	Flash Fire (Cont.) SW to NE NW to SE	2.63×10^{-5}
At 157 up to 162	UVCE N to S S to N	2.60×10^{-5}
At 162 up to 194	Flash Fire (Cont.) W to E	4.59×10^{-6}
At 194 up to 228	Flash Fire (Inst.) SW to NE NW to SE	3.06×10^{-6}
At 228 up to 233	UVCE SW to NE NW to SE	1.53×10^{-6}
At 233 up to 264	Flash Fire (Inst.) W to E	7.65×10^{-6}
>264	UVCE W to E	0

[a]From the data in this table, a curve for the total individual risk curve in the east direction can be developed, which is shown in Figure 8.21.

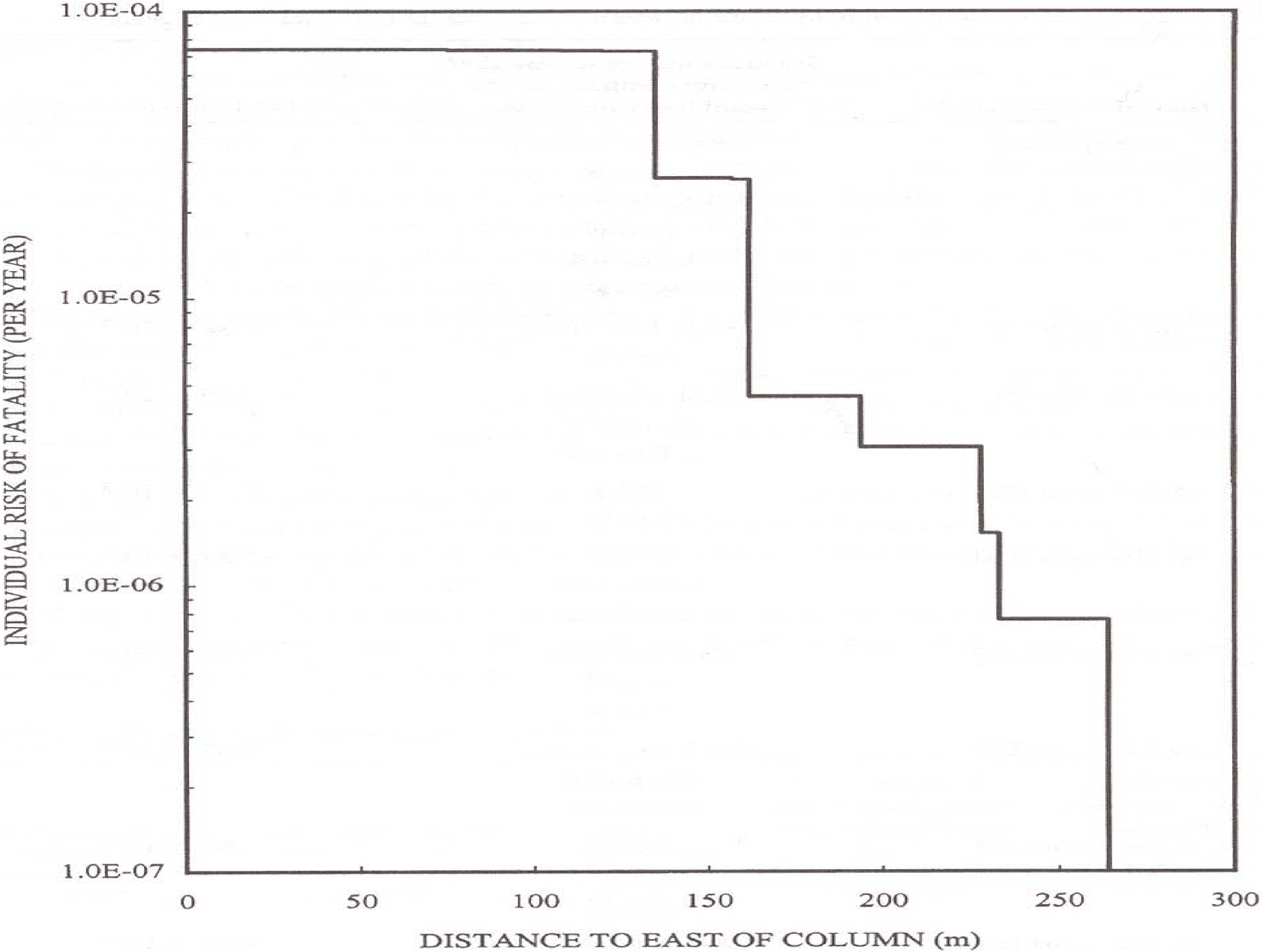


FIGURE 8.24. Individual risk versus distance in the east direction.

- Some observations on the results
  - The risk near the column has probably been underestimated, since small incidents that may contribute to the risk in this area have been excluded from the analysis(e.g., jet fire hazards)
  - The choice of only two places for ignition simplifies the real situation of ignition point at intermediate location due to office/warehouse complex, fired process equipment, roads etc
  - The use of only one weather condition(F stability, 1.5 m/s wind speed)
  - The risk from VCE is probably overestimated because of the high explosive yield chosen

Societal Risk

TABLE 8.26. Estimation of Number of Fatalities for Each Incident Outcome Case

Incident outcome case	Incident outcome case frequency (yr^{-1})	Estimated number of fatalities
1 BLEVE	3.8×10^{-6}	80
2 VCE		
SW to NE	1.0×10^{-6}	200
W to E	7.7×10^{-7}	150
NW to SE	5.1×10^{-7}	200
N to S	1.2×10^{-7}	130
NE to SW	1.2×10^{-7}	80
E to W	1.2×10^{-7}	80
SE to NW	1.2×10^{-7}	80
S to N	1.8×10^{-7}	130
3 Flash Fire (Inst.)		
SW to NE	1.0×10^{-6}	130
W to E	7.7×10^{-7}	150
NW to SE	5.1×10^{-7}	130
N to S	1.2×10^{-7}	40
NE to SW	1.2×10^{-7}	0
E to W	1.2×10^{-7}	0
SE to NW	1.2×10^{-7}	0
S to N	1.8×10^{-7}	40
5 Flash Fire (Cont.)		
SW to NE	2.9×10^{-5}	5
W to E	2.1×10^{-5}	40
NW to SE	1.4×10^{-5}	5