Measurement, Calculation and Presentation of Risk Estimates

2009_2nd semester

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Measurement, Calculation and Presentation of Risk Estimates

- Risk measure
  - Defines risks as a measure of economic loss, human injuries or environmental damage in terms of both the likelihood and magnitude of the loss, injury or damage
  - Three commonly ways of combining incident frequency and consequence data to produce risk estimates
    - Risk indices
    - Individual risk measures
    - Societal risk measures

TABLE 4.1. Presentation of Measures of Risk

Risk measure	Presentation format
	Indices
Equivalent social cost index	A single number index value representation
Fatal accident rate	A point estimate of fatalities/10^8 exposure hours
Individual hazard index	An estimate of peak individual risk or FAR
Average rate of death	A number representing the estimated average number of fatalities per unit time
Mortality index	A single value representation of consequence
	Individual risk
Individual risk contour	Contour lines connecting points of equal risk superimposed over a local map
Individual risk profile or risk transect	A graph of individual risk as a function of distance from the plant in a specified direction
Maximum individual risk	A single numerical value of individual risk corresponding to the person at highest risk
Average individual risk (exposed population)	A single numerical value estimating the average risk to a person in the exposed population
Average individual risk (total population)	A single numerical value estimating the average risk to a person in a predetermined population, whether or not all members of that population are exposed to the hazard
	Societal risk
Societal risk curve (F-N curve)	A graph of the cumulative probability or frequency of events causing *N* or more fatalities, injuries or exposures versus *N*, the number of fatalities, injuries, or exposures
Average societal risk	Another term for average rate of death
Aggregate Risk	A term for societal risk to personnel in a building or facility introduced in API 750 (API, 1995)

- Risk indices
  - Single number or tabulations of numbers which are correlated to the magnitude of risk
  - Represent simplifications of more complex risk measures and have unit which have real physical meaning(fatal accident rate, individual hazard index, average rate of) death
  - Limitation
    - There may not be absolute criteria for accepting or rejecting the risk
    - Indices lack resolution and do not communicate the same information as individual or societal risk measure

Types of Risk indices-1

- FAR(fatal accident rate)
  - Estimated number of fatalities per 10^8 exposure hours
- IHI(individual hazard index)
  - Actual time that a person is exposed to the hazard of concern
- Average rate of death
  - Average number of fatalities that might be expected per unit time from all possible incident
- Mortality index or number
  - Characterized the potential hazards of toxic material storage

Types of Risk indices-2

- Dow fire and explosion index
  - Estimate relative risk from fire and explosion
  - Estimate the magnitude of potential plant damage from a fire or explosion
- Dow chemical exposure index
  - Estimates risk associated with a single toxic chemical release

- Individual risk
  - Risk to a person in the vicinity of a hazard
  - Include the nature of the injury to the individual, likelihood of the injury occurring and the time period over which the injury might occur
  - Can be estimated for the most exposed individual, for group of individual at particular places or for an average individual in an effect zone

- Definition of some individual risk measures
  - Individual risk contours
    - The geographical distribution of individual risk
  - Maximum individual risk
    - The individual risk to the person exposed to the highest risk in an exposed population
  - Average individual risk
    - The individual risk averaged over the population that is exposed to risk from the facility
    - Calculated for the duration of the activity or may be averaged over the working day

- Societal risk
  - A measure of risk to a group of people
  - Expressed in terms of the frequency distribution of multiple casualty events(the F-N curve)
  - Societal risk estimation requires a definition of the population at risk around the facility

Risk Presentation

- Risk presentation
  - Provide a simple quantitative risk description useful for decision making
  - Reduce this large volume of information to a manageable form
  - End result may be a single number index, a table, a graph and/or a risk map

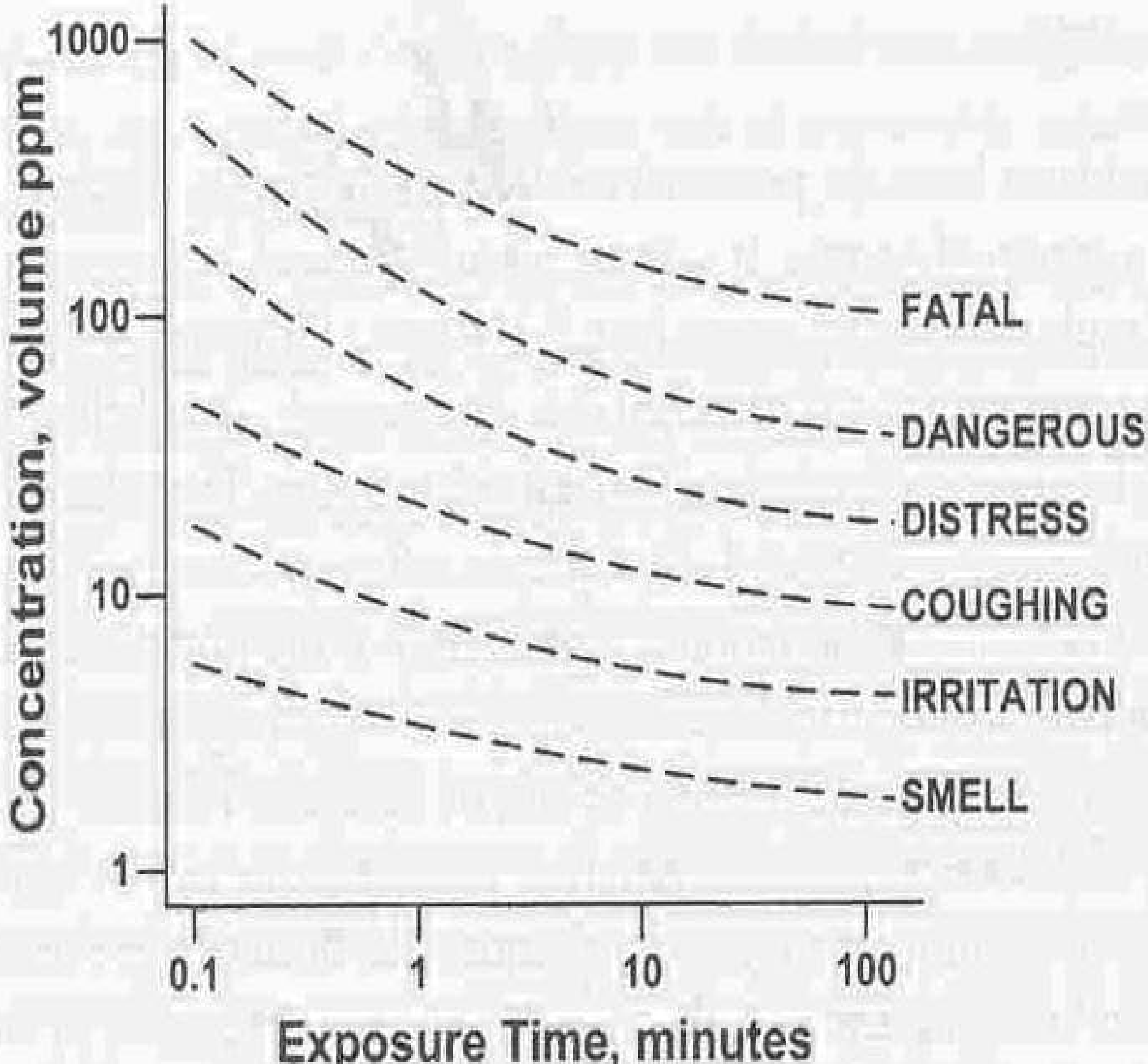


FIGURE 4.1. Typical relationship between injury levels and concentration/exposure for a toxic gas.

- Risk indices
  - Risk indices are single-number measurement, they are normally presented in tables
    - Foe example, Kletz(1977) has tabulated the FAR for various industries in the U.K.

TABLE 4.2. Fatal Accident Rates in Various Industries and Activities[a]

Activity	Fatal accident rate (fatalities/10^8 exposed hr)
British industry (overall)	4
Clothing and footwear manufacture	0–15
Vehicle manufacture	1–3
Timber, furniture, and so on	3
Metal manufacture, ship building	8
Agriculture	10
Coal mining	12
Railway shunters	45
Construction erectors	67
Staying at home (men 16–65)	1
Traveling by train	5
Traveling by car	57

[a] From Kletz (1977).

- Individual risk
  - Common form are risk contour plots(figure 4.2) and individual risk profiles also known as risk transect(figure 4.3)
  - Risk contour shows individual risk estimates at specific point on a map
  - Risk profile is a plot of individual risk as a function of distance from the risk source

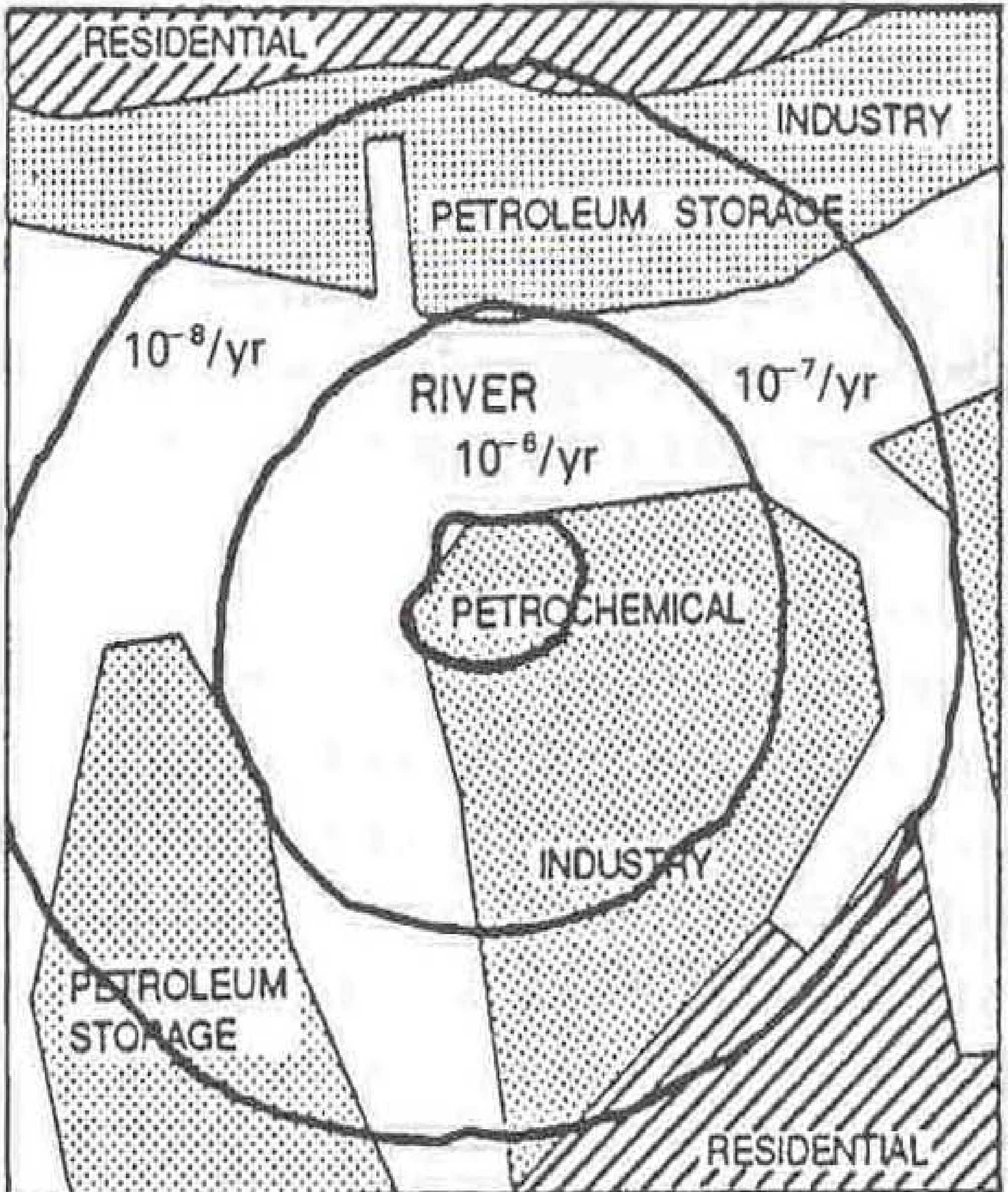


FIGURE 4.2. Example of an individual risk contour plot. Note: The contours connect points of equal individual risk of fatality, per year.

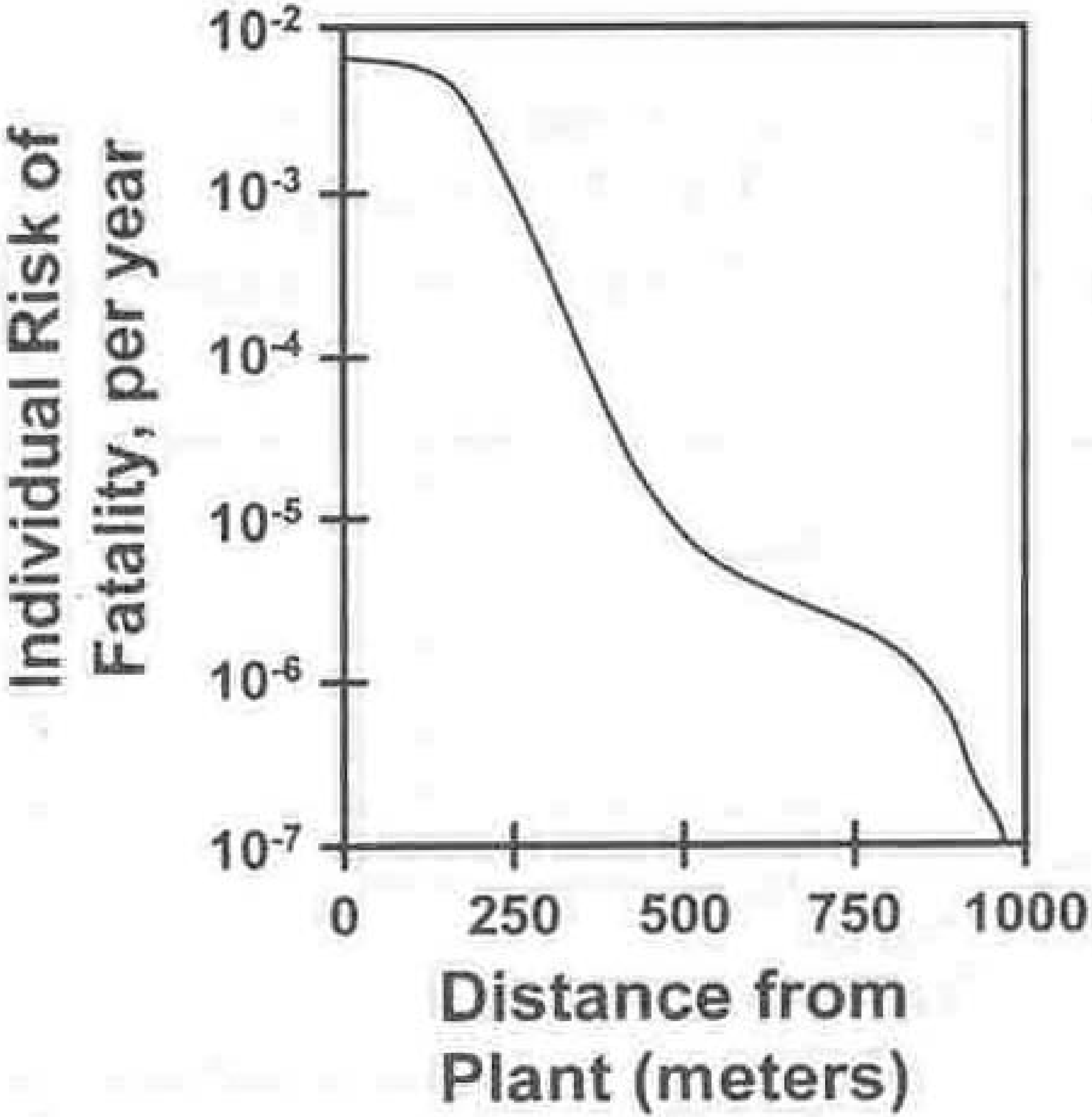


FIGURE 4.3. Example of an individual risk profile, or risk transect.

- Societal risk
  - Addresses the number of people who might be affected by hazardous incidents
  - Common form of societal risk is known as an F-N curve (frequency-number)
  - F-N curve
    - A plot of cumulative frequency versus consequences
  - Figure 4.4
    - Sample F-N curve for a single liquefied flammable gas facility

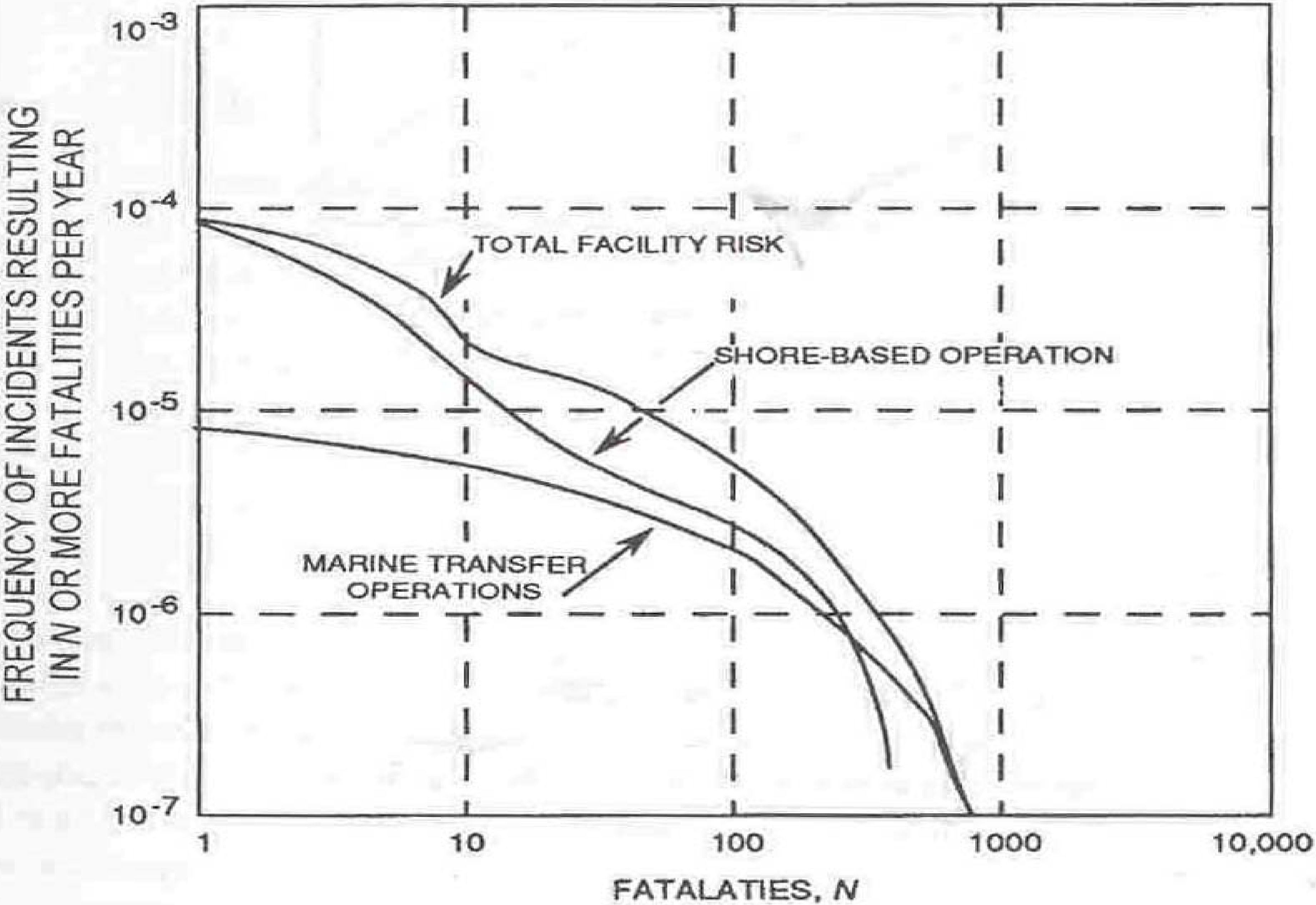


FIGURE 4.4. Example of a societal risk F-N curve.

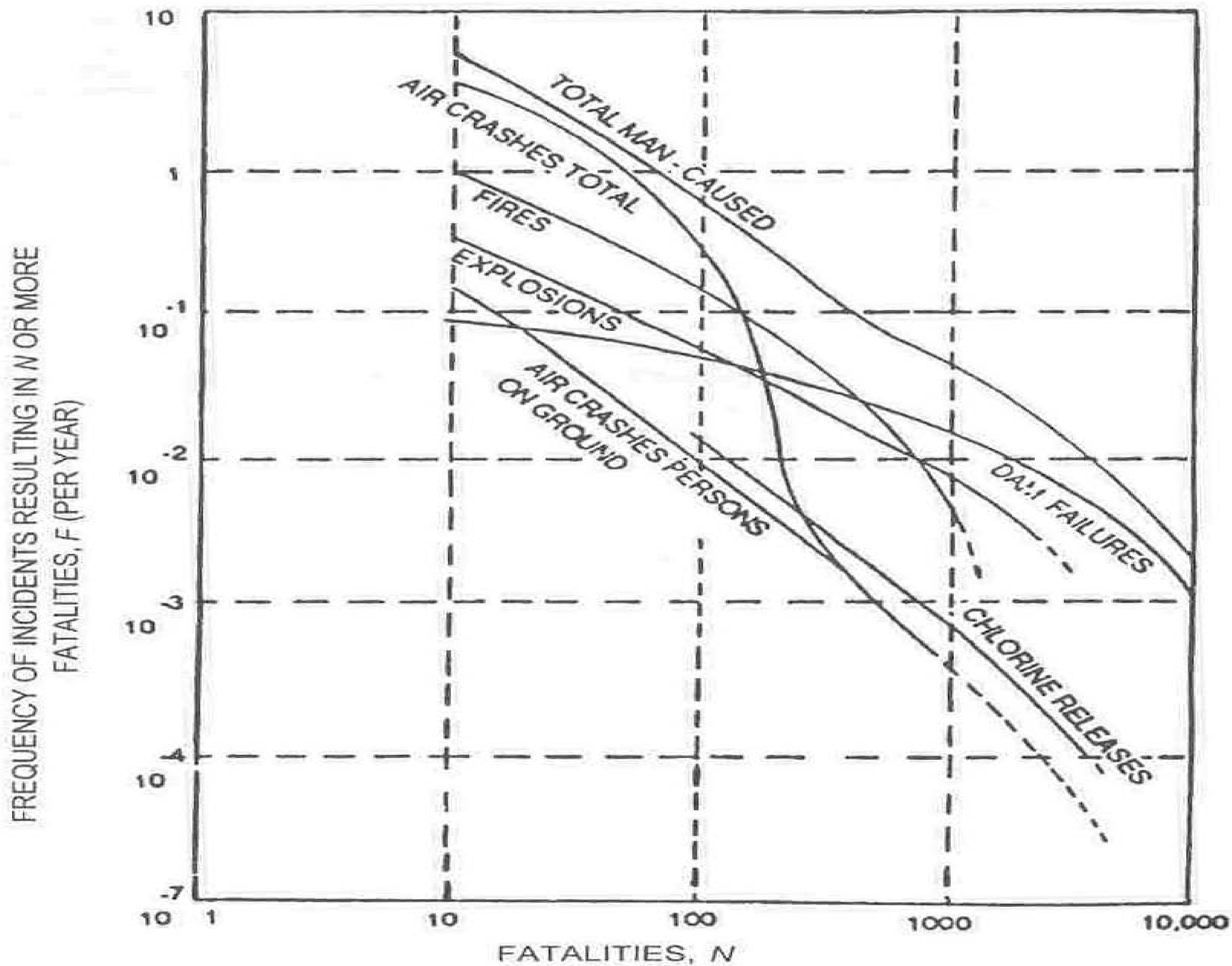


FIGURE 4.5. Some examples of U.S. societal risk estimates. From Rasmussen (1975).

Selection of Risk Measures

- Factors to be considered in the risk measures
  - Study objective
    - Major component of a scope of work document
  - Required depth of study
    - Table 4.3 risk measures possible from depth of study
  - End uses
  - Population at risk
    - Individual risk
    - Societal risk

Selection of Presentation Format

- Considering factors in deciding which presentation forms
  - User requirements
  - User knowledge
  - Effectiveness of communicating results
  - Potential unrevealed uses and audiences
  - Need for comparative presentations

Risk Calculation

- Individual risk
  - Total individual risk at each point is equal to the sum of the individual risks

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i} \qquad (1)$$

- $IR_{x,y}$ is total individual risk of fatality at geographical location x,y(chances of fatality per year, or yr^{-1})
- $IR_{x,y,i}$ is the individual risk of fatality at geographical location x,y from incident outcome case I (chance of fatality per year, or yr^{-1})
- n is the total number of incident outcome cases considered in the analysis

- Individual risk are obtained from

$$IR_{x,y,i} = f_i p_{f,i} \qquad (2)$$

  - f_i is the frequency of incident outcome case i, from frequency analysis(yr^{-1})
  - $p_{f,i}$ is the probability that incident outcome case i will result in a fatality at location x,y, from the consequence and effect models

$$f_i = F_I \, p_{O,i} \, p_{OC,i} \qquad (3)$$

- F_I is the frequency of incident i, which has incident case i as one of its incident outcome cases(yr^{-1})
- $p_{O,i}$ is the probability that the incident outcome, having i as one of its incident outcome case, occurs, given that incident I has ocurred
- $p_{OC,i}$ is the probability that incident outcome case i occurs given the occurrence of the precursor incident I and the incident outcome corresponding to the outcome case i

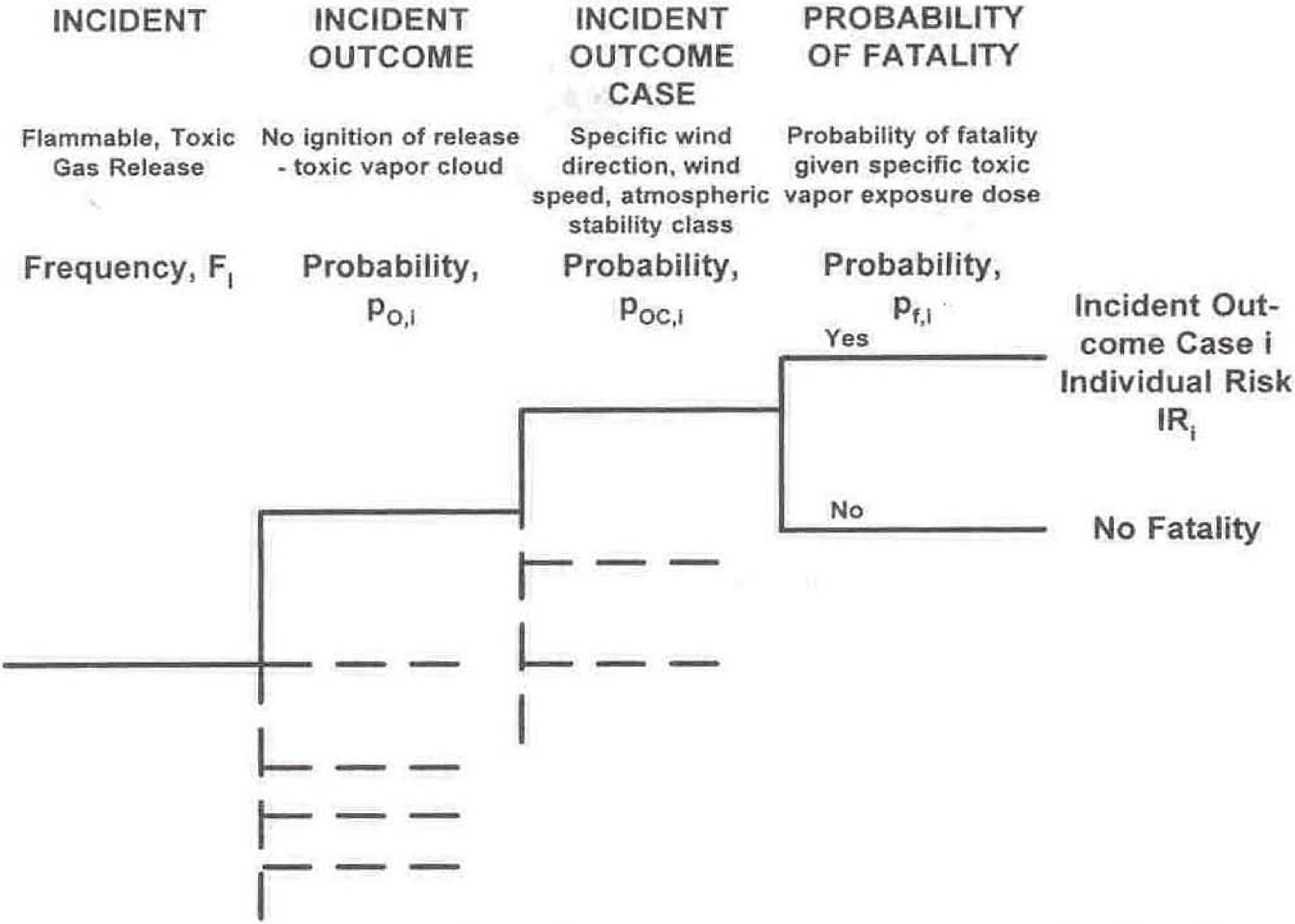


FIGURE 4.6. A sample event tree illustrating individual risk calculations [Eqs. (4.4.2) and (4.4.3)] for one incident outcome case resulting from a flammable, toxic gas release.

Individual Risk Contours

- General approach
  - Requires eqs.(1)(2) at every geographical location
  - Incorporates detailed treatment of ignition sources and a wide variety of weather conditions
  - Requires definition of frequency and effect zone for each incident outcome case
  - The result is a list of individual risk estimates at the geographic locations considered and then be plotted on a local map

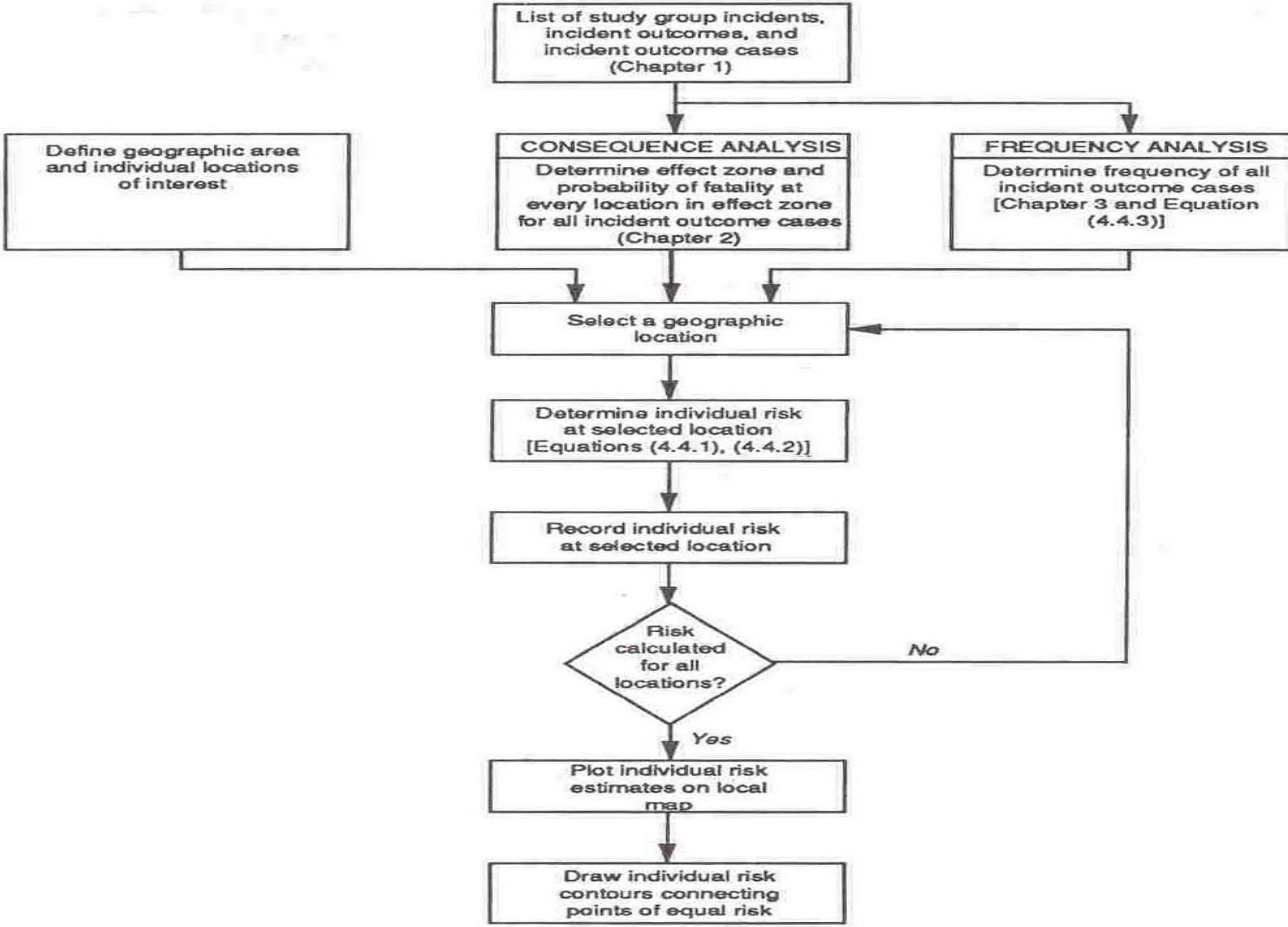


FIGURE 4.7. General procedure for calculation of individual risk contours.

- Simplified approaches
  - Based on following assumption
    - All hazards originate at point sources
    - The wind distribution is uniform
    - A single wind speed and atmospheric stability class can be used
    - No mitigation factors are considered
    - Ignition source are uniformly distributed
    - Consequence effect can be treated discretely
      - The level of effect within a particular effect zone is constant

- Simplified approach
  - Procedure
    - List all incident, incident outcome, incident outcome case
    - Calculate consequence and frequency for all incident outcome case
    - For incident outcome cases affected by wind direction , estimate the width of the effect zone in terms of the angle enclosed
    - Reduce incident outcome case frequency by direction factor

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

- $f_{i,d}$ 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)

- Procedure(continue)
  - Assign an individual risk value to the contour
    - Frequency of the incident outcome case i assed to the individual risk of the next further risk contour

$$IRC_i = f(orf_{i,d}) + IRC_{i-1}$$

      - 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})
  - The result of risk calculations can be displayed as an individual risk transect

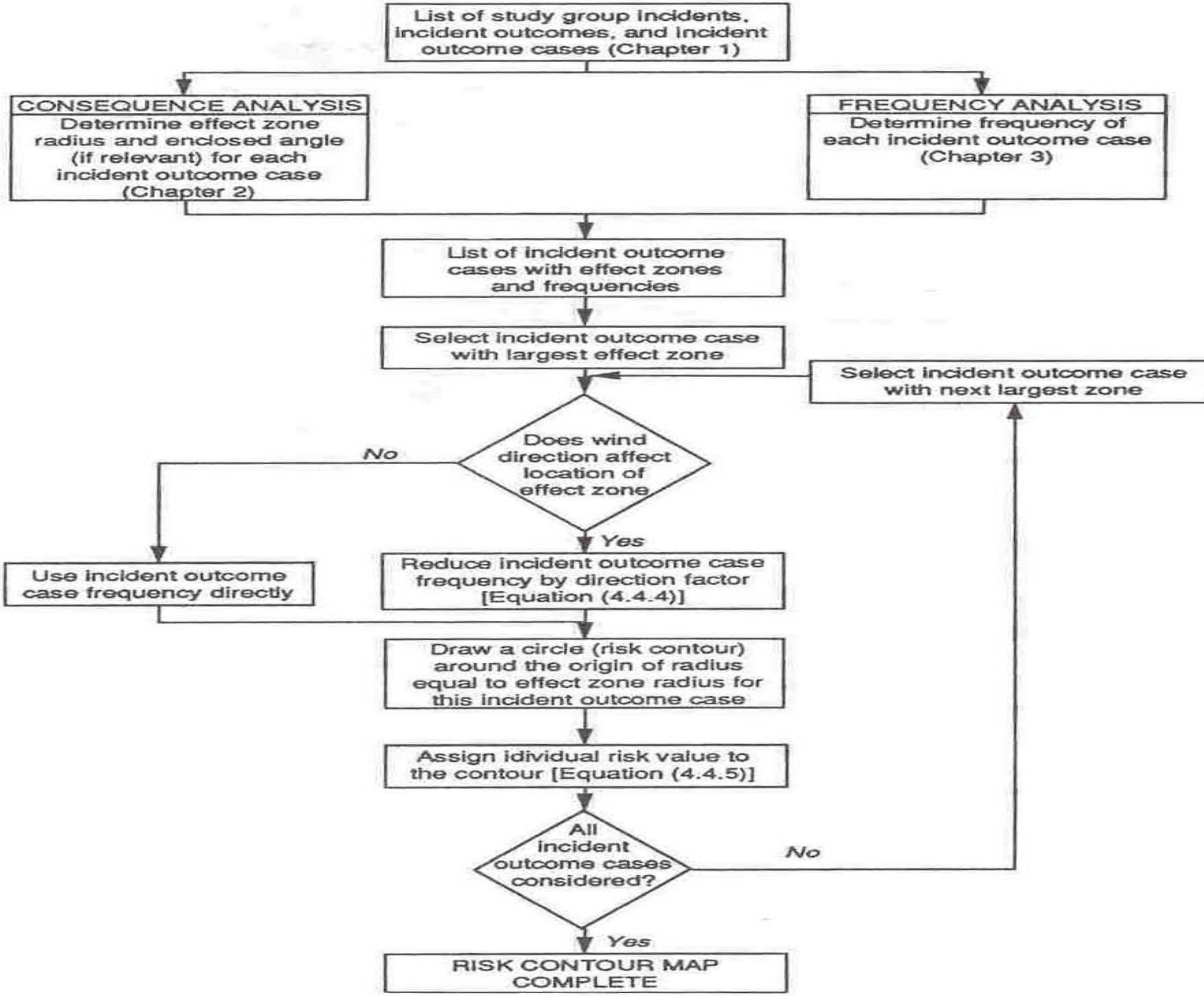


FIGURE 4.8. *A simplified procedure for individual risk contours.*

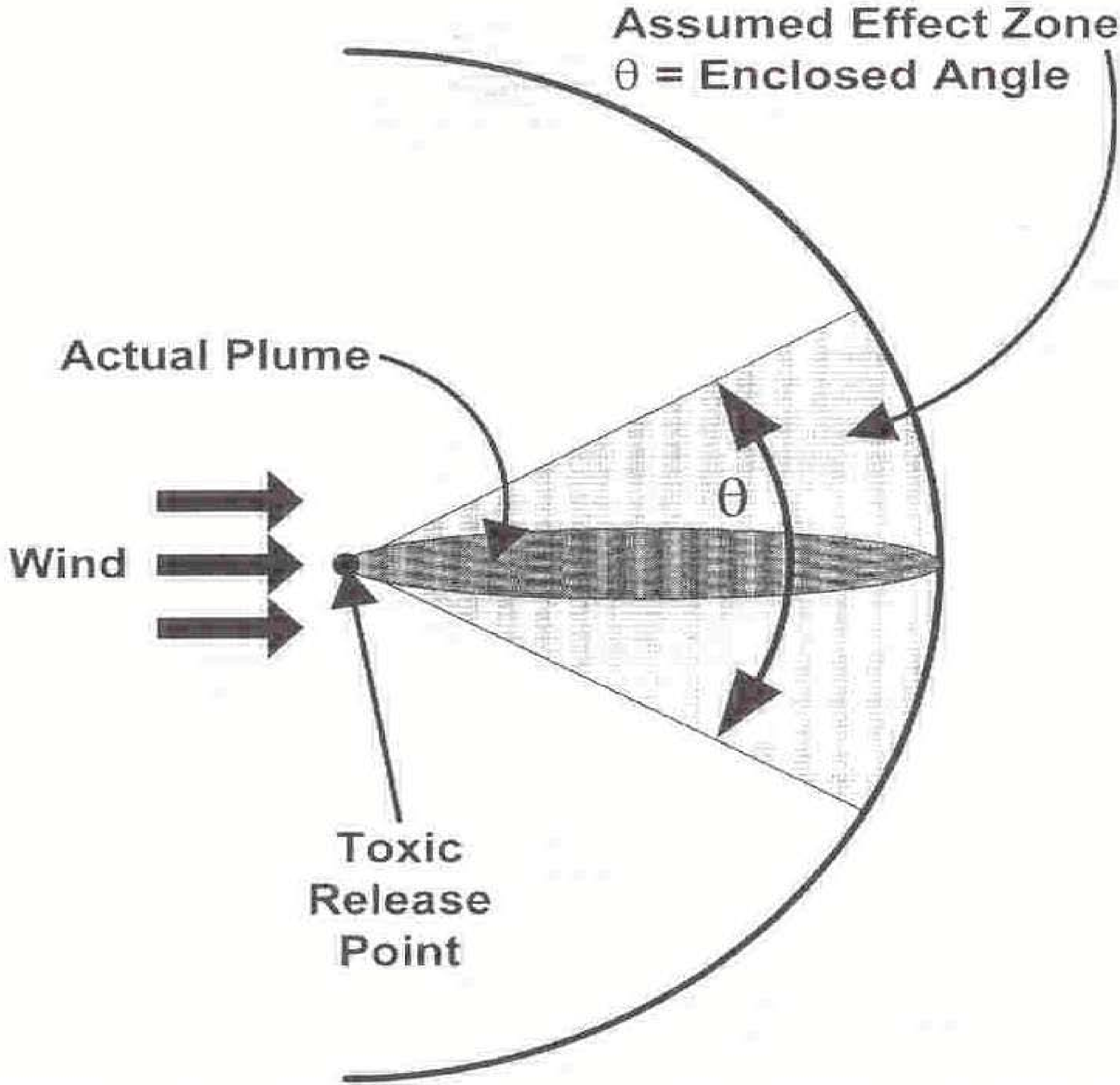
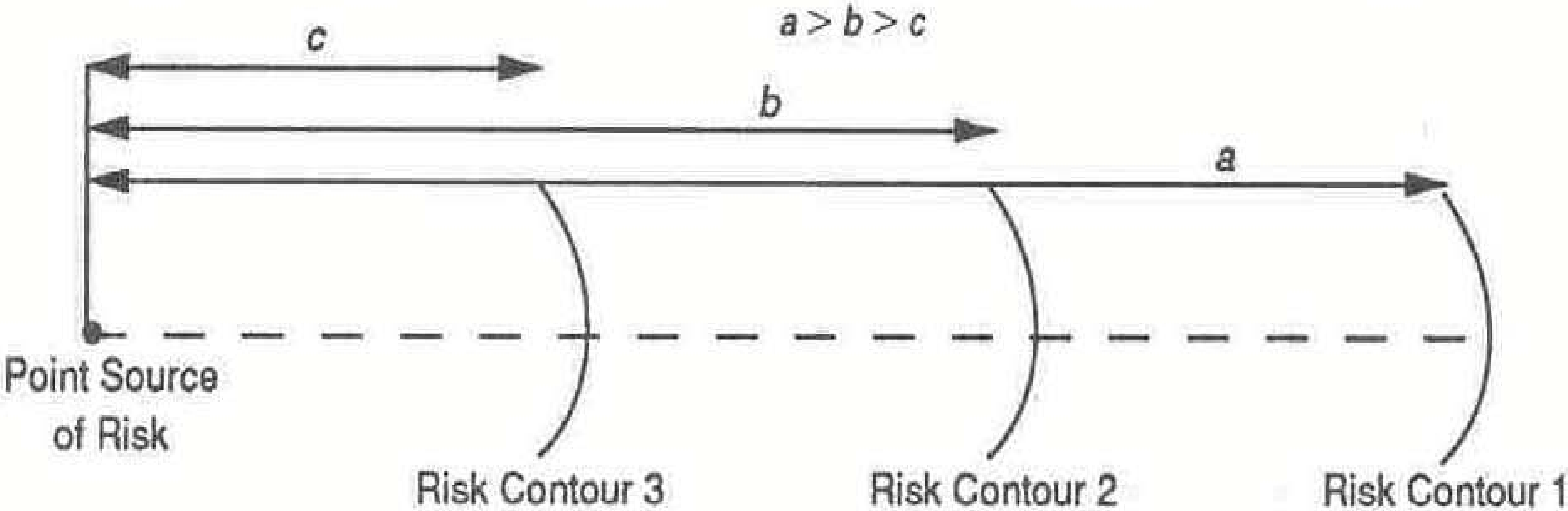


FIGURE 4.9. Effect zone for an incident outcome case dependent on wind direction for the simplified individual risk estimation procedure of Figure 4.8.

Incident outcome case number	Frequency f_i (year^{-1})	Impact zone affected by Wind?	θ_i (deg)	$f_{i,d}$ (year^{-1}) [Equation (4.4.4)]	Length of effect zone
1	x	No	N.A.	N.A.	a
2	y	Yes	45	$y/8$	b
3	z	No	N.A.	N.A.	c

$a > b > c$



Risk [Equation (4.4.5)]

Risk Contour 3	Risk Contour 2	Risk Contour 1
$IRC_3 = IRC_2 + f_3$	$IRC_2 = IRC_1 + f_{2,d}$	$IRC_1 = 0 + f_1$
$IRC_3 = (x + y/8) + z$	$IRC_2 = (x) + y/8$	$IRC_1 = x$

FIGURE 4.10. Illustration of the simplified individual risk calculation procedure of Figure 4.7. Incident outcome cases 1 and 3 are not affected by wind direction. Incident outcome case 2 is wind dependent.

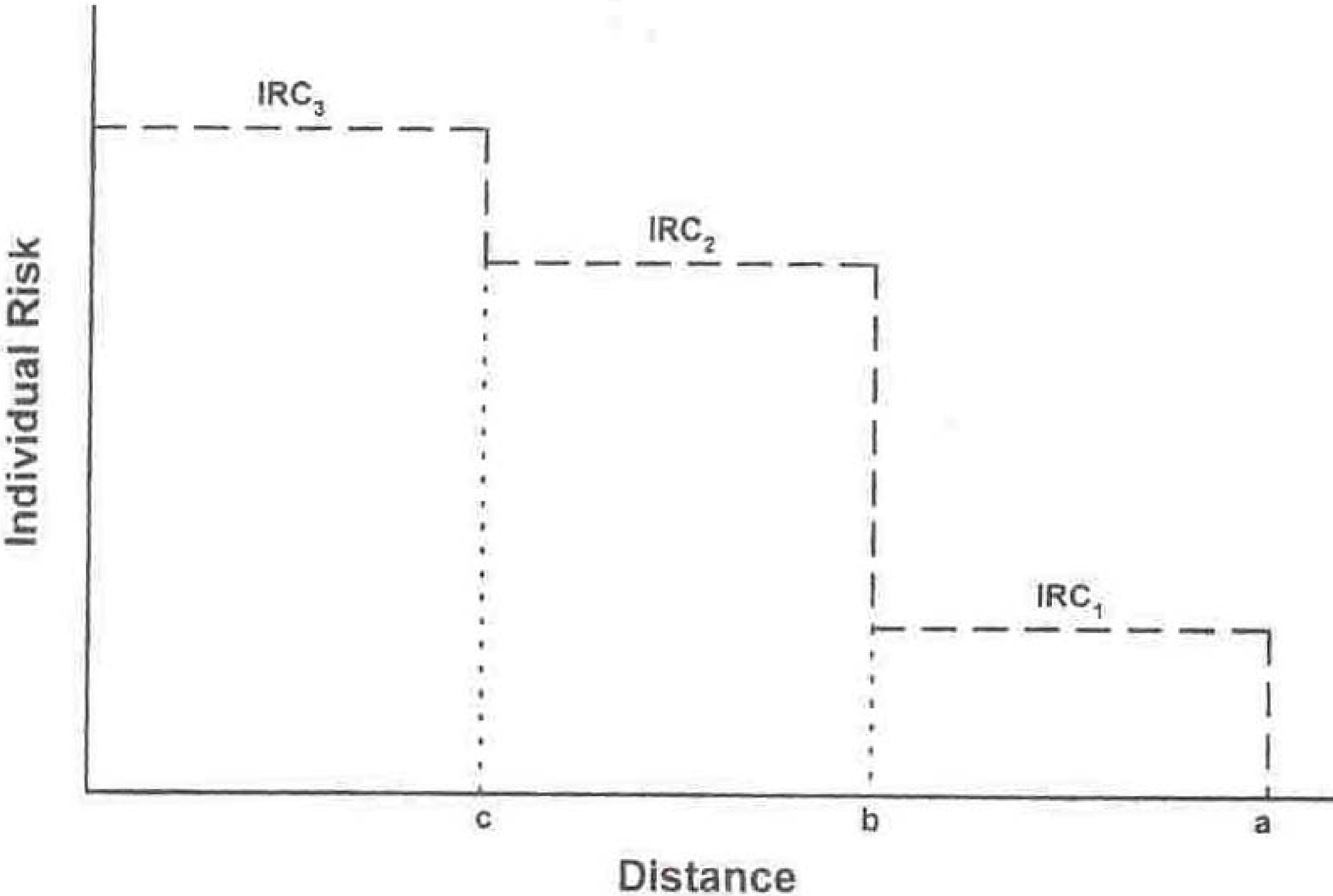


FIGURE 4.11. Risk transect for the example illustrated in Figure 4.10.

Other Individual Risk Measure

- Maximum individual risk
  - Determined by estimating the individual risk at all locations where people are actually present
- Average individual risk(exposed population)
  - Determined by averaging the individual risk of all persons exposed to risk from facility

$$IR_{AV} = \frac{\sum_{x,y} IR_{x,y} Px,y}{\sum_{x,y} P_{x,y}}$$

- IR_{AV} is the average individual risk in the exposed population(yr^{-1})
- $IR_{x,y}$ is the individual risk at location x,y(yr^{-1})
- $P_{x,y}$ is the number of people at location x,y

- Average individual risk(total population)
  - Determined by averaging the individual risk over a predetermined population without regard to whether or not entire population is subject to risk from the facility

$$IR_{AV} = \sum_{x,y} \frac{IR_{x,y} P_{x,y}}{P_T}$$

- P_T is the total predetermined population for averaging risk(number of people)

Societal Risk

- Societal risk
  - All of the information required for individual risk calculation is also required for societal risk
  - For a detailed analysis, the following may be needed
    - Information on population type(e.g., residential, office, factory, school, hospital) for evaluating mitigation factors
    - Information about time-of-day effect(e.g., for school)
    - Information about day-of-week effects(e.g., for industrial, educational or recreational facilities)
    - Information about percentage of time population is indoors for evaluating mitigating factors

- General procedure
  - The steps are the same as for individual risk calculation
  - Combine this information with population data to estimate the number of people affected by each incident outcome case
  - The number of people affected by each incident outcome case

$$N_i = \sum_{x,y} P_{x,y} p_{f,i}$$

    - N_i is the number of fatalities resulting from incident outcome case I
    - $P_{x,y}$ is the number of people at location x,y
    - $P_{f,i}$ is the probability that incident outcome case I will result in fatality at location x,y from consequence and effect model

General procedure(con.)

- Frequency of all incident outcome cases affecting N or more people

$$F_N = \sum_i F_i$$ **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

- The result is a data set giving F_N as a function of N, which is then plotted to give the F-N curve

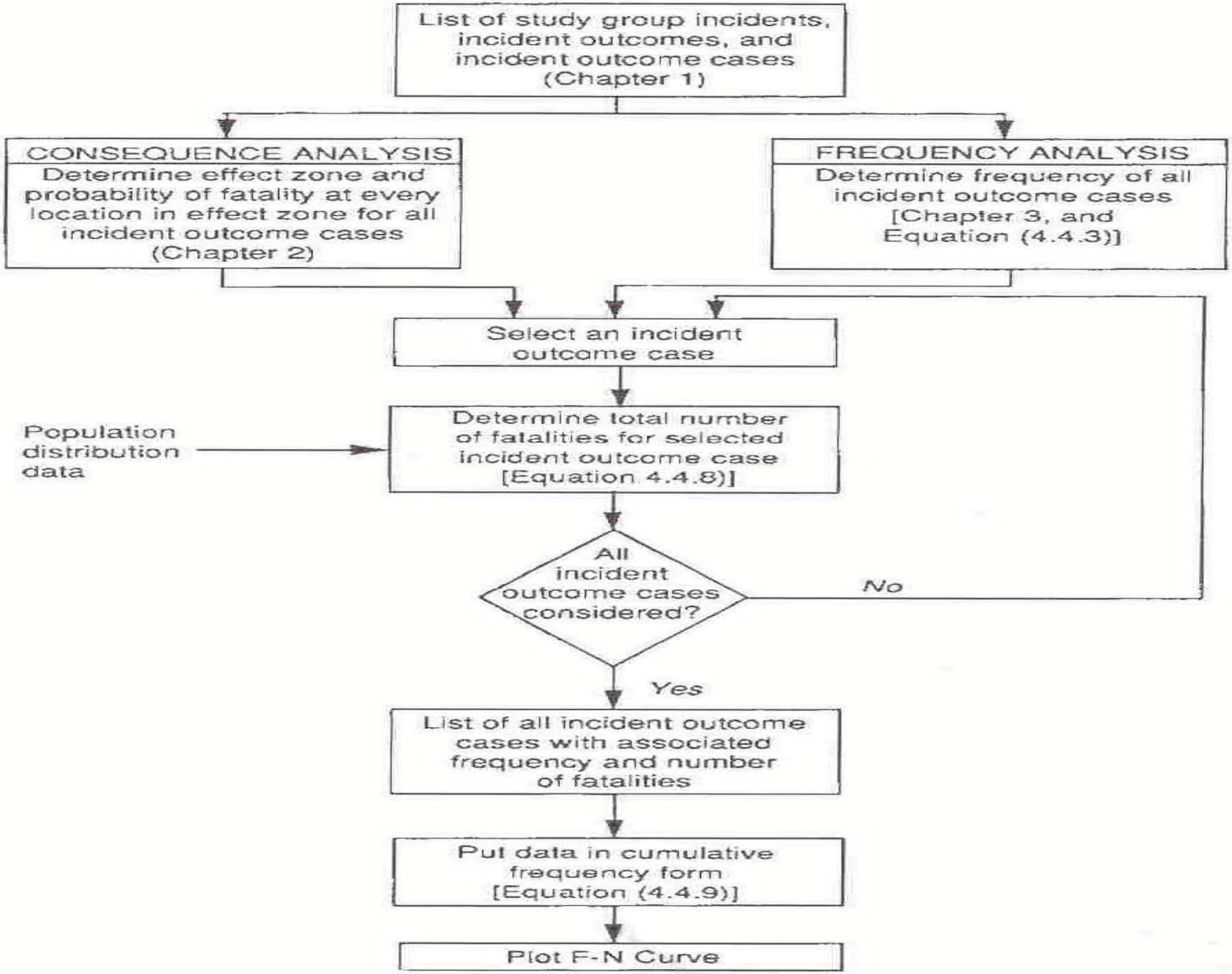


FIGURE 4.14. General procedure for calculation of societal risk F-N curves.

TABLE 4.4. Number of Fires in Which a Given Number of Fatalities Occurred in the United Kingdom 1968–1980[a,b]

Year	Total fires with fatalities	Number of fatalities per fire 1	2	3	4	5	6	7	8	9	10	11	12	14	15	18	21	22	24	28	30	37
1968	670	na	na	na	na	na	1	1	—	—	—	—	—	—	—	—	—	1	1	—	—	—
1969	716	na	na	na	na	na	3	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—
1970	707	na	na	na	na	na	2	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1971	666	567	na	na	na	na	2	1	—	1	—	—	—	1	1	—	1	—	—	—	—	—
1972	911	798	na	na	na	na	—	1	—	—	—	—	—	—	—	—	—	—	—	—	1	—
1973	856	750	na	na	na	na	2	1	—	—	1	—	—	—	—	1	—	—	—	—	—	—
1974	756	764	na	na	na	na	1	1	1	—	—	—	—	—	—	1	—	—	—	1	—	—
1975	na	708	na	na	na	na	2	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1976	759	682	36	28	11	1	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—
1977	609	544	38	14	4	5	1	2	—	—	—	1	—	—	—	—	—	—	—	—	—	—
1978	709	629	61	111	6	—	—	—	—	1	—	—	1	—	—	—	—	—	—	—	—	—
1979	963	873	69	10	8	—	1	1	—	—	1	—	—	—	—	—	—	—	—	—	—	—
1980	863	785	46	22	4	3	1	—	—	—	1	—	—	—	—	—	—	—	—	—	—	1
Totals		7101	250	85	33	9	16	10	2	2	3	2	1	1	1	2	1	1	1	1	1	1
Frequency, events per year		710	50	17	6.6	1.8	1.23	0.76	0.154	0.154	0.23	0.154	0.038[c]	0.076	0.076	0.051[c]	0.038[c]	0.038[c]	0.038[c]	0.025[c]	0.015[c]	0.025[c]
Frequency ≥n fatalities		788.6	78.6	28.6	11.66	5.06	3.46	2.39	1.63	1.48	1.23	1.00	0.846	0.760	0.690	0.615	0.46	0.38	0.301	0.231	0.154	0.076

[a]From Marshall (1987).

[b]Spaces marked na denote that statistics are not available. Columns for 1–5 deaths show frequencies derived from those years for which statistics are available. Statistics are incomplete for some years because of industrial action Mean values are based on the number of years for which statistics are available.

[c]Mean value based upon mean of a group of values of n.

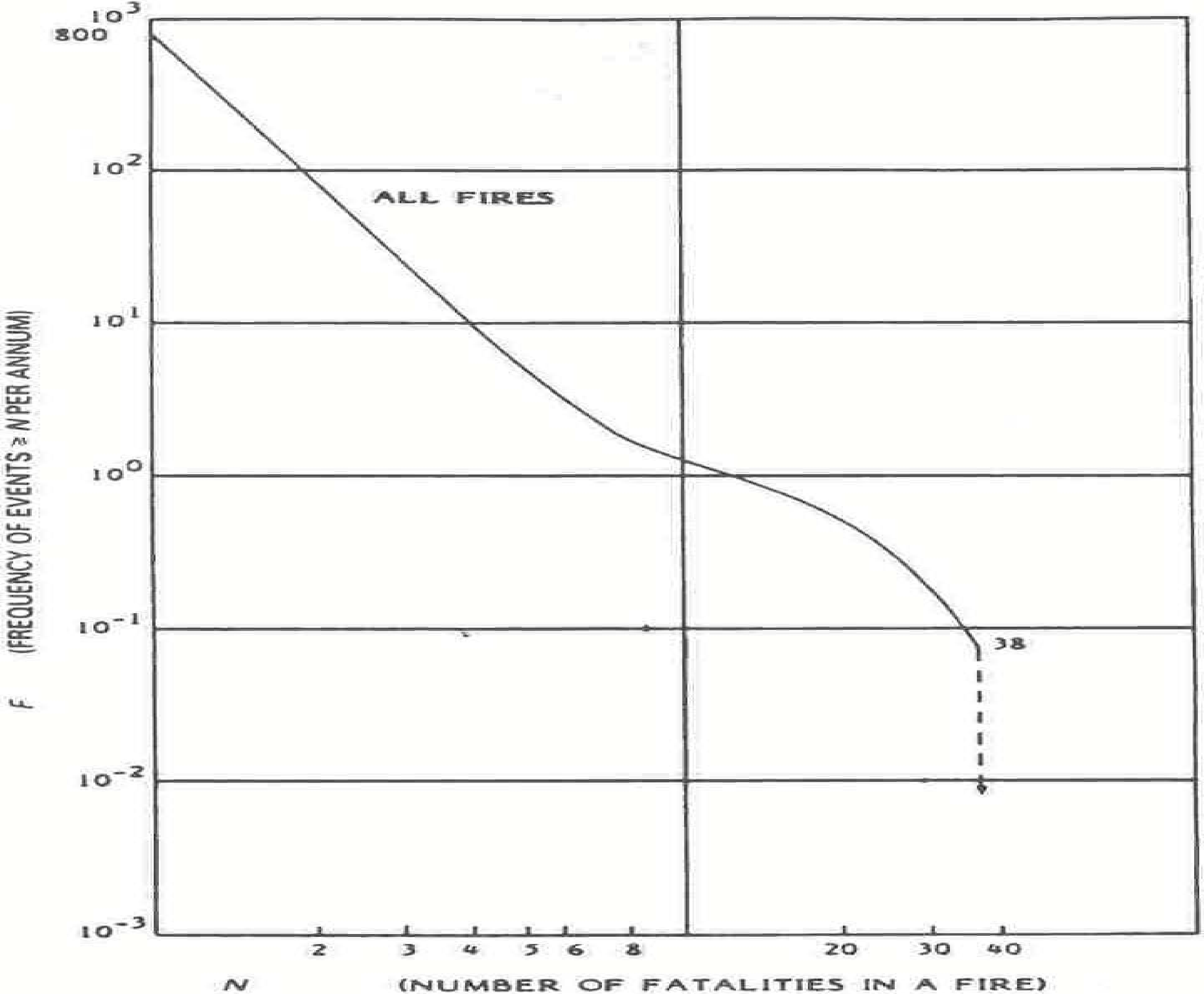


FIGURE 4.15. Plot of F-N fire statistics UK 1968–1980. From Marshall (1987).

Risk Indices

- Average rate of death(ROD)
  - A measure of societal risk and is not relevant to any specific individual at a particular place

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

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

- Equivalent social cost(ESO)
  - Weighted average rate of death that take into account society's perception that multiple-fatality incidents are more serious than a collection of incidents with fewer facility

$$ESO = \sum_{i=1}^{n} f_i (N_i)^p$$

    - p is the risk aversion power factor(p>1)
    - If p=1, equivalent social cost = average rate of death
  - For nuclear application
    - A value for p is 1.2(Okrent)
  - For chemical industry
    - A value of p is 2.0(Netherlands Government 1985)

Example Risk Calculation Problem

- Assumption
  - All hazards originate at a single point
  - Only two weather conditions occur
    - Atmospheric stability class and wind speed are always the same
    - Half of the time the wind blow from the northeast, and half of the time it blows from the southeast
  - There are people located around the site
  - Incident consequences are simple step functions
    - The probability of fatality from a hazardous incident at a particular location is either 0 or 1

Incident identification

- Potential incidents analysis using historical information, checklist or more of the hazard evaluation technique
  - An explosion resulting from detonation of an unstable chemical
  - A release of a flammable, toxic gas resulting from failure of a vessel
- Incident outcome
  - Incident I
    - Only one incident outcome and one incident outcome case
  - Incident II
    - Only two outcomes are assumed to occur
    - Of the gas release ignites there is a vapor cloud explosion
    - If the vapor cloud does not ignite, the result is a toxic cloud extending downwind from the release point

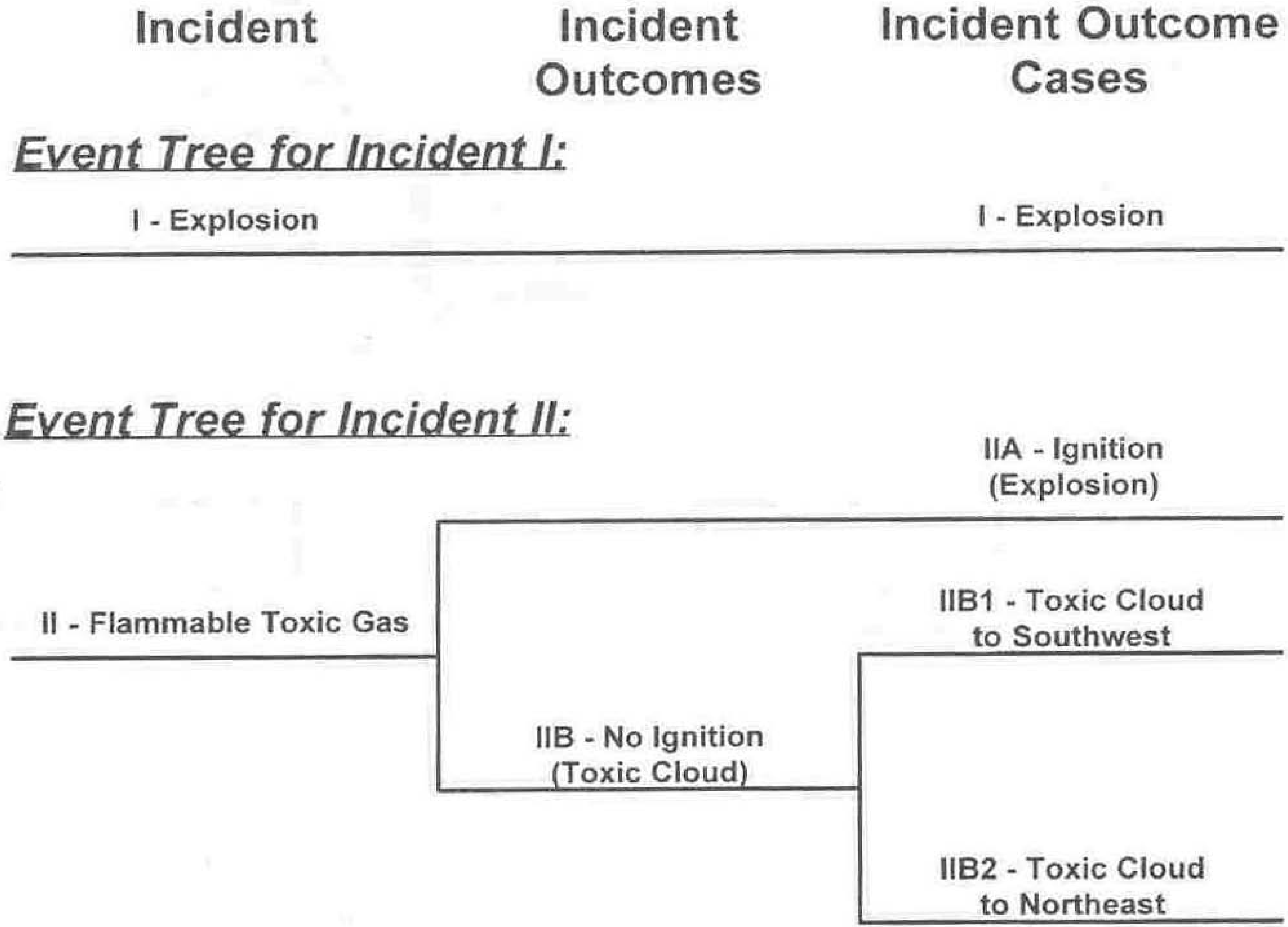


FIGURE 4.16. Event trees for the two incidents in the example risk calculation problem.

- Consequence and impact analysis
  - Determining the impact requires two steps
    - Estimates a physical concentration of material or energy at each location surrounding the facility
    - Estimate the impact that this physical concentration of material or energy has on people, the environment or property
      - Toxic material dose-response relationship

- Incident outcome case I(explosion)
  - The explosion is centered at the center point of the facility; all persons within 200m of the explosion center are killed(probability of fatality = 1.0); all persons beyond this distance are unaffected (probability of fatality = 0)
- Incident outcome case IIA(explosion)
  - The explosion is centered at the center point of the facility; all persons within 100m of the explosion center are killed(probability of fatality = 1.0); all persons beyond this distance are unaffected (probability of fatality = 0)
- Incident outcome cases IIB1, IIB2(toxic gas clouds)
  - All persons in a pie shaped segment of radius 400m downwind and 22.5 degree width are killed(probability of fatality = 1.0); all persons outside this area are unaffected(probability of fatality = 0)

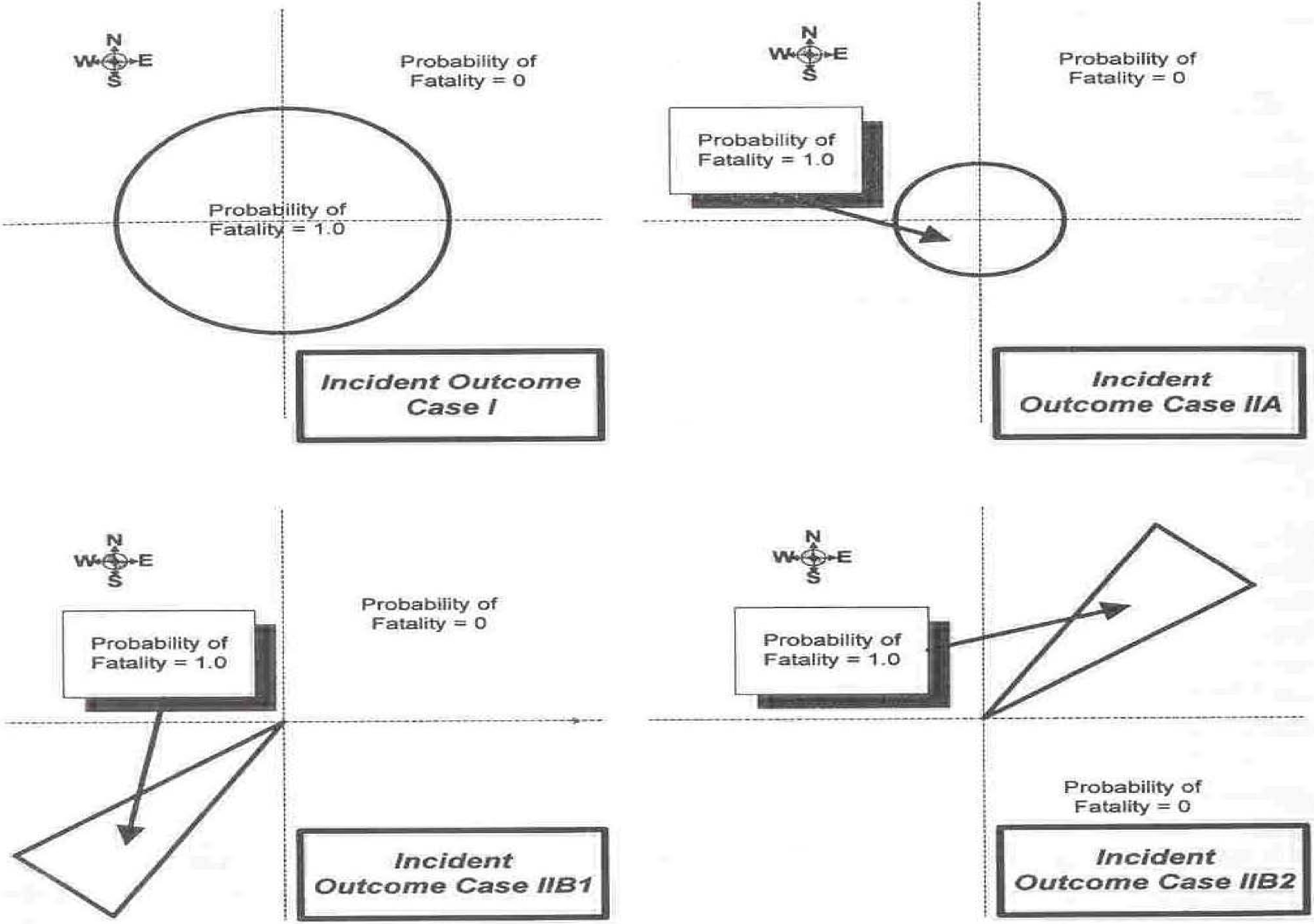


FIGURE 4.17. Impact zones for example problem incident outcome cases.

- Frequency analysis
  - Frequency estimates using FTA, ETA and the historical incident data
  - Incident I
    - Frequency = 1 X 10^{-6} event per year
  - Incident II
    - Frequency = 3 X 10^{-5} event per year
  - Incident II
    - Ignition probability = 33%

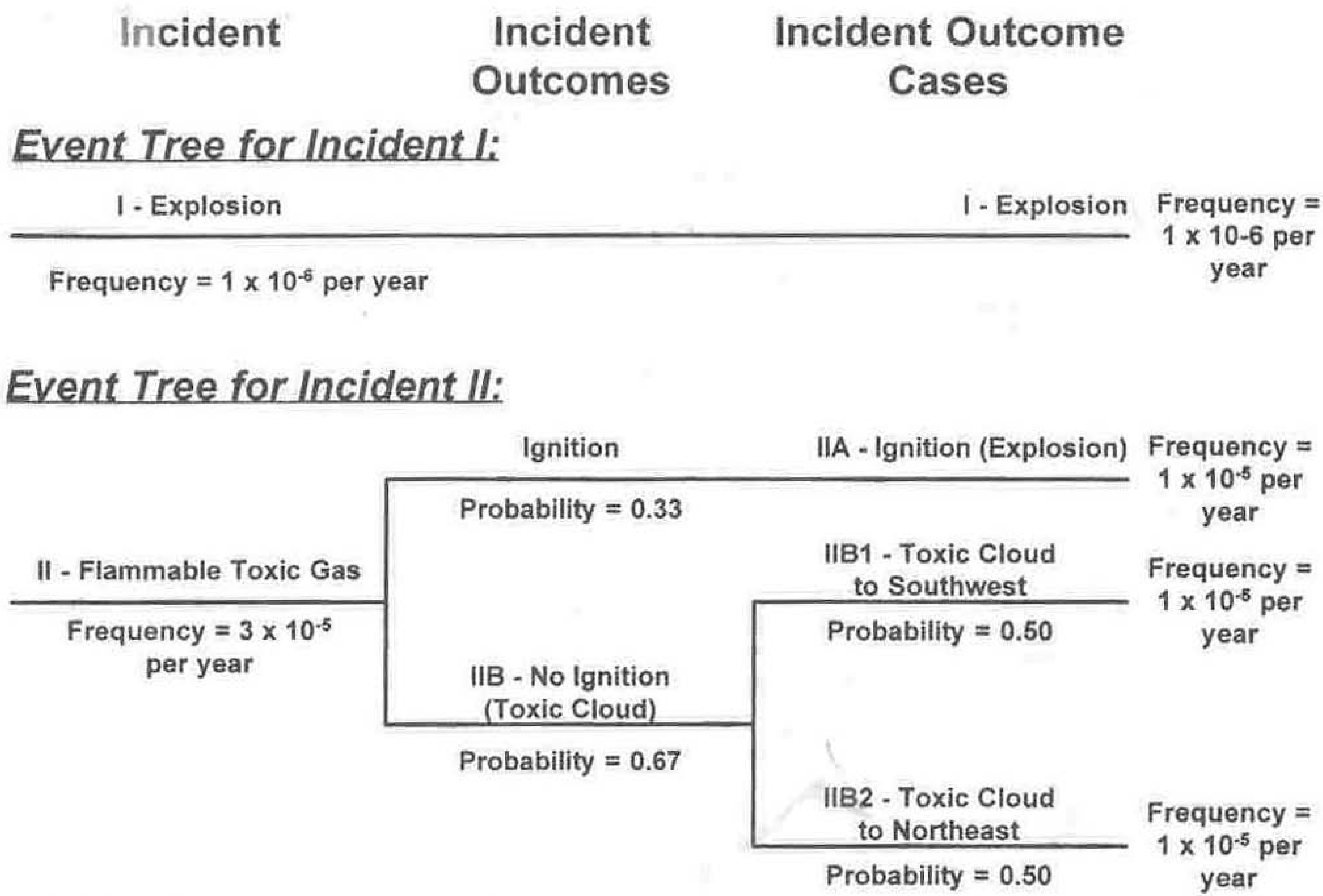


FIGURE 4.18. Frequency estimates for example problem incidents, incident outcomes, and incident outcome cases.

Individual risk estimation

- Individual risk contour

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i}$$

$$IR_{x,y,i} = f_i \, p_{f,i}$$

  - Probability of fatality =1, so the individual risk from that incident outcome case is equal to the frequency of that incident outcome case

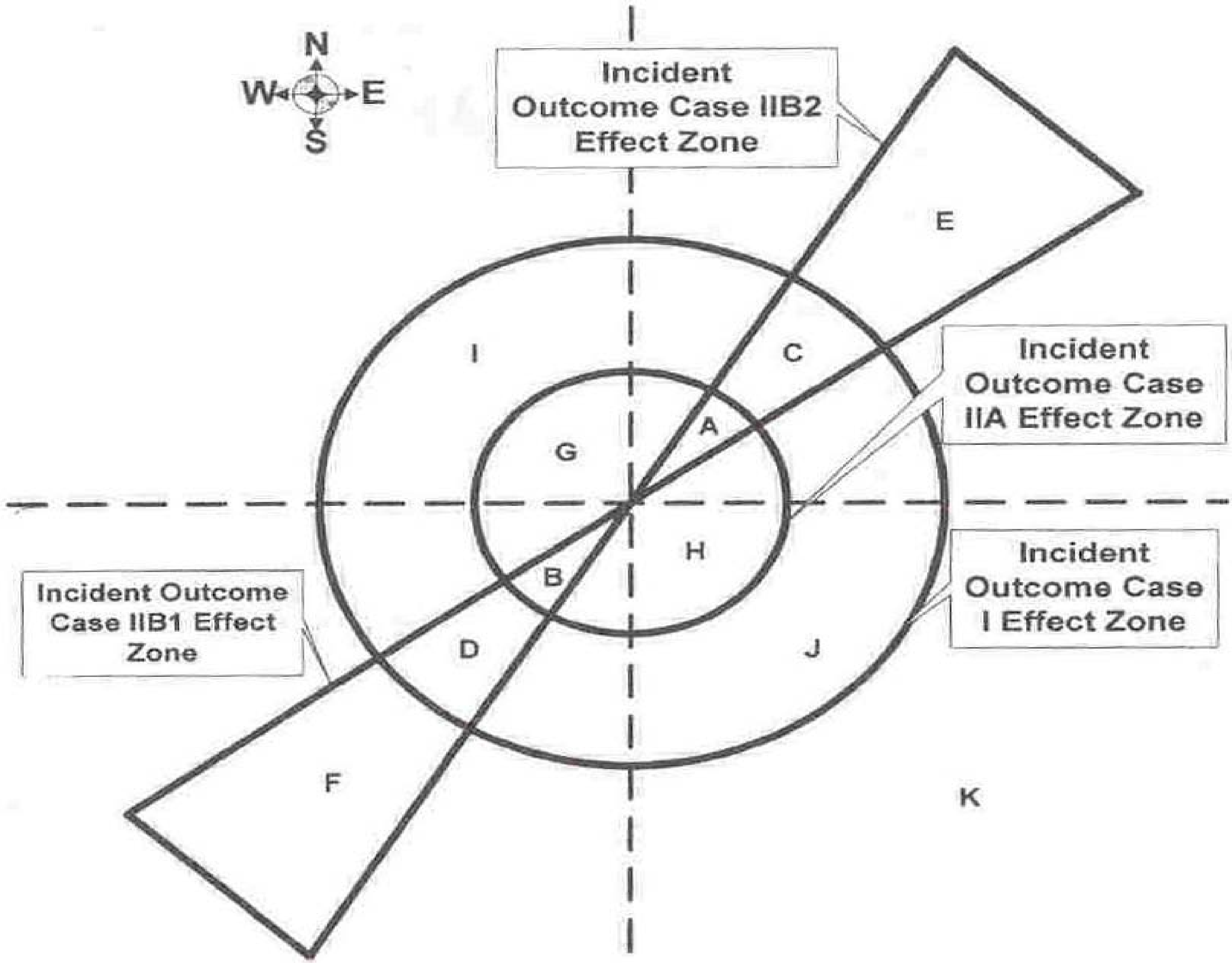


FIGURE 4.19. Example problem individual risk contour map.

TABLE 4.5. Individual Risk Calculations for Area "C" in Figure 4.19

Incident outcome case	f_i (per year)	$P_{f,i}$	IR_i (per year)
I	10^{-6}	1	10^{-6}
IIB2	10^{-5}	1	10^{-5}
	$IR = \sum IR_i = 1.1 \times 10^{-5}$		

TABLE 4.6. Individual Risk Results for the Example Problem

Region (see Figure 4.19)	Incidents impacting region	Total individual risk of fatality (per year)
A	I, IIA, IIB2	2.1×10^{-5}
B	I, IIA, IIB1	2.1×10^{-5}
C	I, IIB2	1.1×10^{-5}
D	I,IIB1	1.1×10^{-5}
E	IIB1	1.0×10^{-5}
F	IIB2	1.0×10^{-5}
G	I, IIA	1.1×10^{-5}
H	I, IIA	1.1×10^{-5}
I	I	1.0×10^{-6}
J	I	1.0×10^{-6}
K	None	0

- Individual risk profile
  - A graph showing the individual risk as a function of distance from the source of the risk in a particular direction

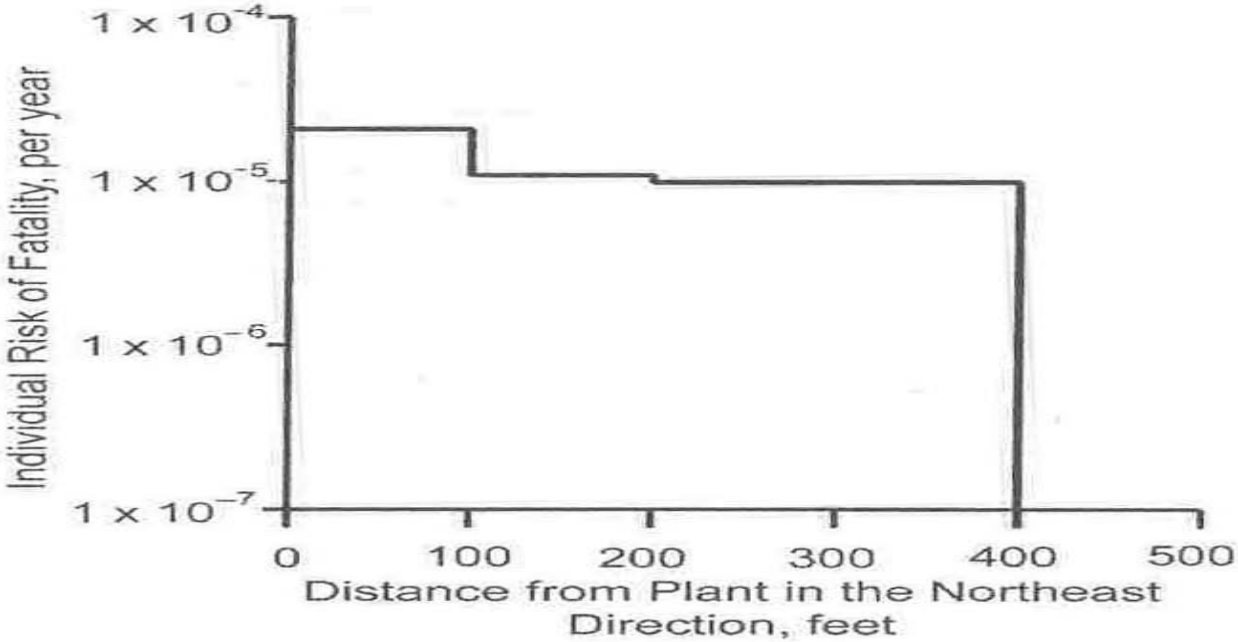


FIGURE 4.20. Individual risk transect in the northeast direction for the example problem.

Other individual risk measures

- Maximum individual risk
  - Highest value of individual risk at any geographical location
  - 2.1×10^{-5} per year
- Average individual risk
  - Estimates over a defined population
  - Applying Eq.(4.4.6) to the population in the example

$$IR_{AV} = \frac{(3)(10^{-5}) + (1)(10^{-6}) + (2)(1.1\times 10^{-5}) + (4)(10^{-5}) + (10)(10^{-6})}{3+1+2+4+10}$$

$$IR_{AV} = \frac{1.03\times 10^{-4}}{20}$$

  - $IR_{AV} = 5.2 \times 10^{-6}$ per year (for the exposed population)

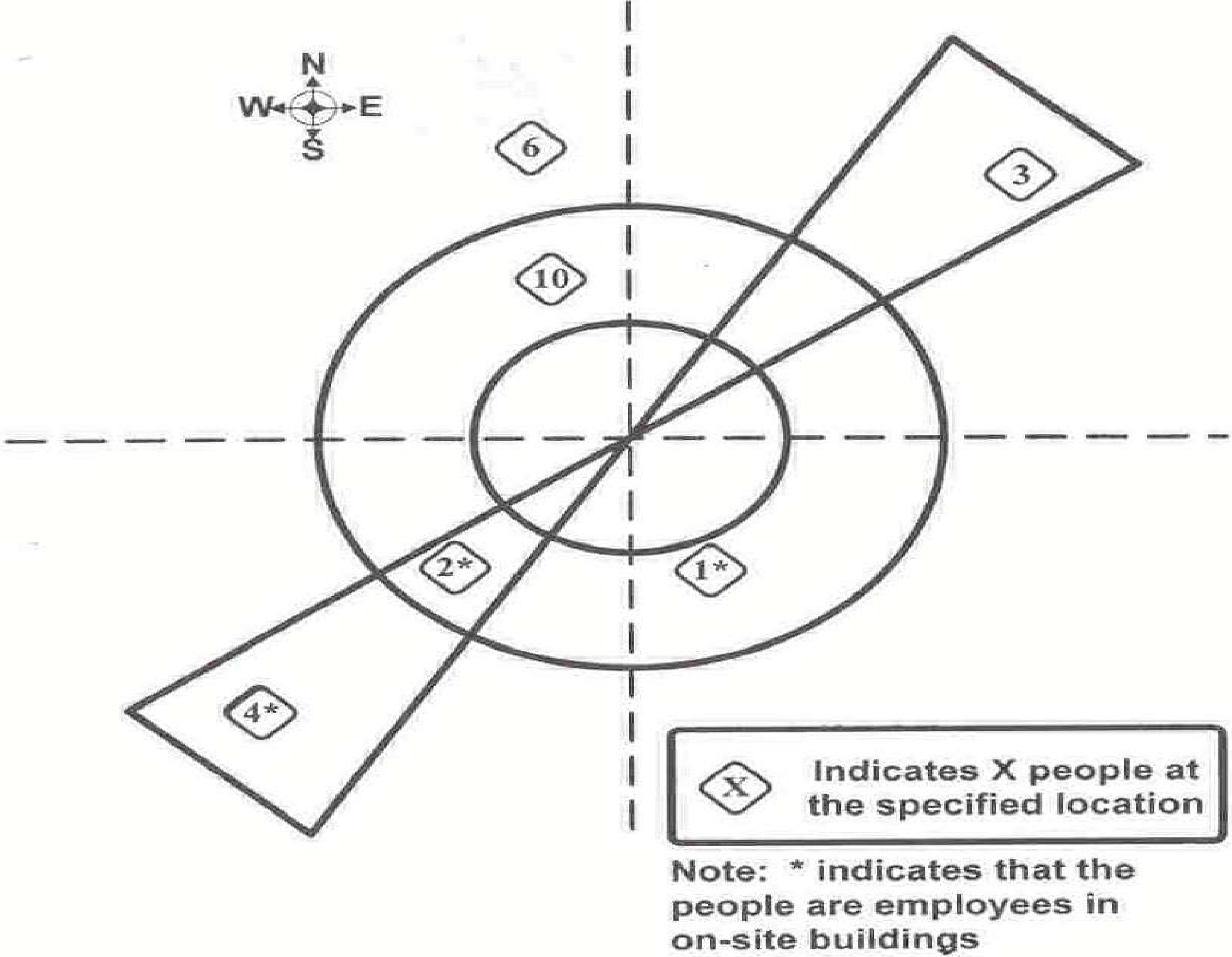


FIGURE 4.21. Example problem population distribution.

- Averaging individual risk for the total population

$$IR_{AV} = \frac{1.03 \times 10^{-4}}{26}$$

  - $IR_{AV} = 4.0 \times 10^{-6}$ per year (for the total population)
- Averaging individual risk to on-site employee
  - $IR_{AV} = [(2)(1.1 \times 10^{-5}) + (4)(10^{-5}) + (1)(10^{-6})] / (1+2+4)$

    Region D Region F Region J

    $IR_{AV} = (6.03 \times 10^{-5}) / 7$
  - $IR_{AV} = 9 \times 10^{-6}$ per year (for the plant employee population)
- Fatal Accident Rate(FAR)
  - A measure of employee risk in an exposed population
  - $FAR = IR_{AV} (1.14 \times 10^{4}) = (9 \times 10^{-6})(1.14 \times 10^{4})$
  - FAR = 0.1 fatality / 10^{8} man-hours of exposure

- Societal risk calculation
  - Measures estimate both the potential size and likelihood of incidents with multiple adverse outcomes
- F-N curve
  - 1st step is to calculate the number of fatalities resulting from each incident outcome case
  - Table 4.7 summarizes the estimated number of fatalities for the four incident outcome cases

TABLE 4.7. Estimated Number of Fatalities from Each Example Problem Incident Outcome Case

Incident outcome case	Frequency F_i (per year)	Estimated number of fatalities N
I	1.0×10^{-6}	13
IIA	1.0×10^{-5}	0
IIB1	1.0×10^{-5}	6
IIB2	1.0×10^{-5}	3

TABLE 4.8. Example Problem Cumulative Frequency Data for F-N Curve

Estimated number of fatalities N	Incident outcome cases included	Total frequency F_N (per year)
3+	I, IIB1, IIB2	2.1×10^{-5}
6+	I, IIB1	1.1×10^{-5}
13+	I	1.0×10^{-6}
>13+	None	0

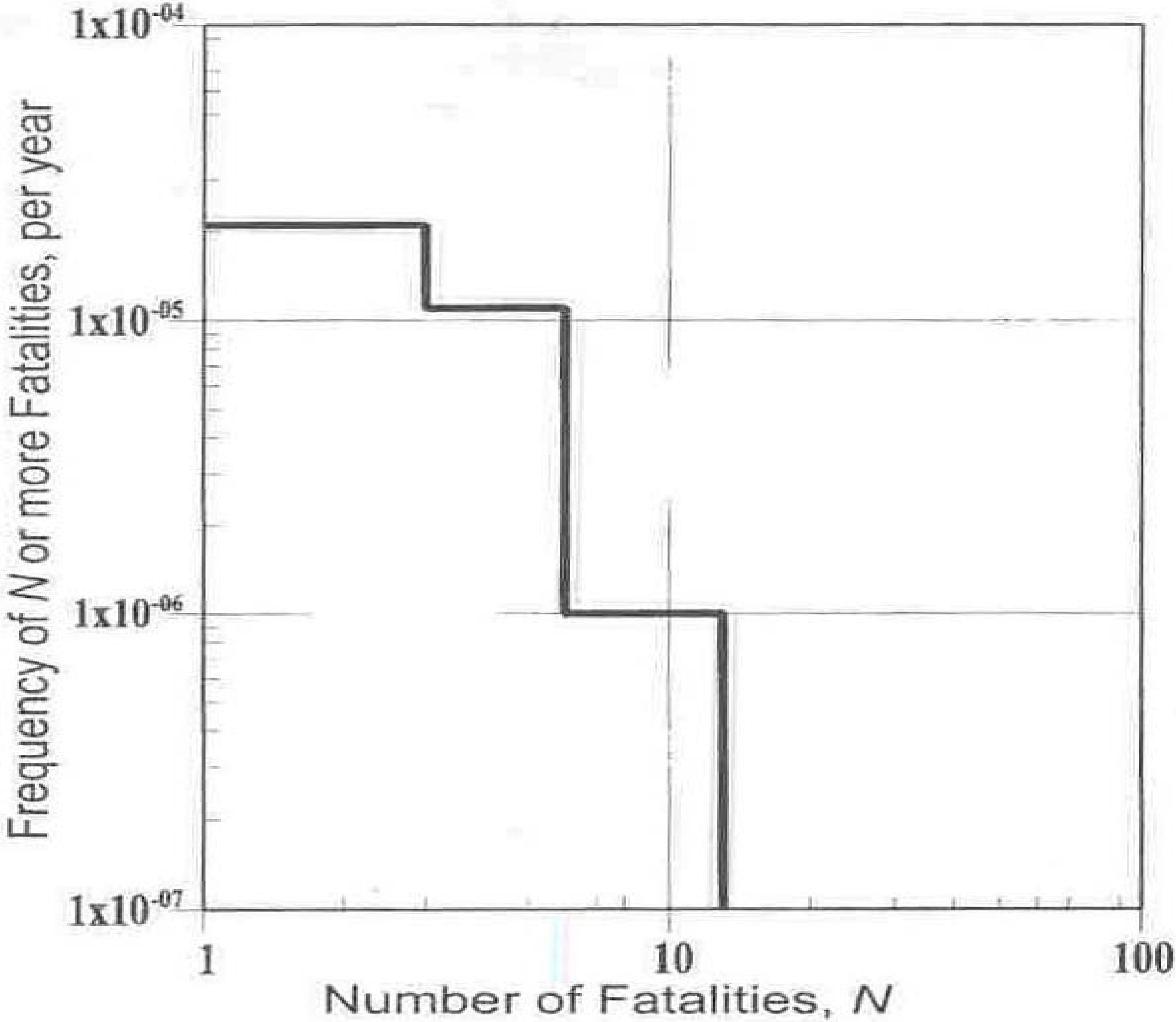


FIGURE 4.22. Societal risk F-N curve for the example problem.

Other societal risk measures

- Average rate of death(ROD)
  - Estimated average number of fatalities in the population from all potential incidents
  - ROD = $(1.0 \times 10^{-6}/yr)(13) + (1.0 \times 10^{-5}/yr)(0) + (1.0 \times 10^{-5}/yr)(6) + (1.0 \times 10^{-5}/yr)(3)$
  - ROD = 1×10^{-4} fatalities per year
- Aggregate risk
  - Societal risk applied to specific group of people with a facility
  - Aggregate risk index
    - $= (1.0 \times 10^{-6}/yr)(3) + (1.0 \times 10^{-5}/yr)(6)$
    - $= 6.3 \times 10^{-5}$ fatalities per year

TABLE 4.9. Estimated Number of Fatalities for the Employee Population in on-Site Buildings from Each Example Problem Incident Outcome Case

Incident outcome case	Frequency F_i (per year)	Estimated number of fatalities in the employee population in on-site buildings, N
I	1.0×10^{-6}	3
IIA	1.0×10^{-5}	0
IIB1	1.0×10^{-5}	6
IIB2	1.0×10^{-5}	0

TABLE 4.10. Example Problem Cumulative Frequency Data for Aggregate Risk Curve for Employee Population in on-Site Buildings

Number of fatalities in the employee population in on-site buildings, N	Incident outcome cases included	Total frequency F_N (per year)
3+	I, IIB1	1.1×10^{-5}
6+	IIB1	1.0×10^{-5}
>6+	None	0

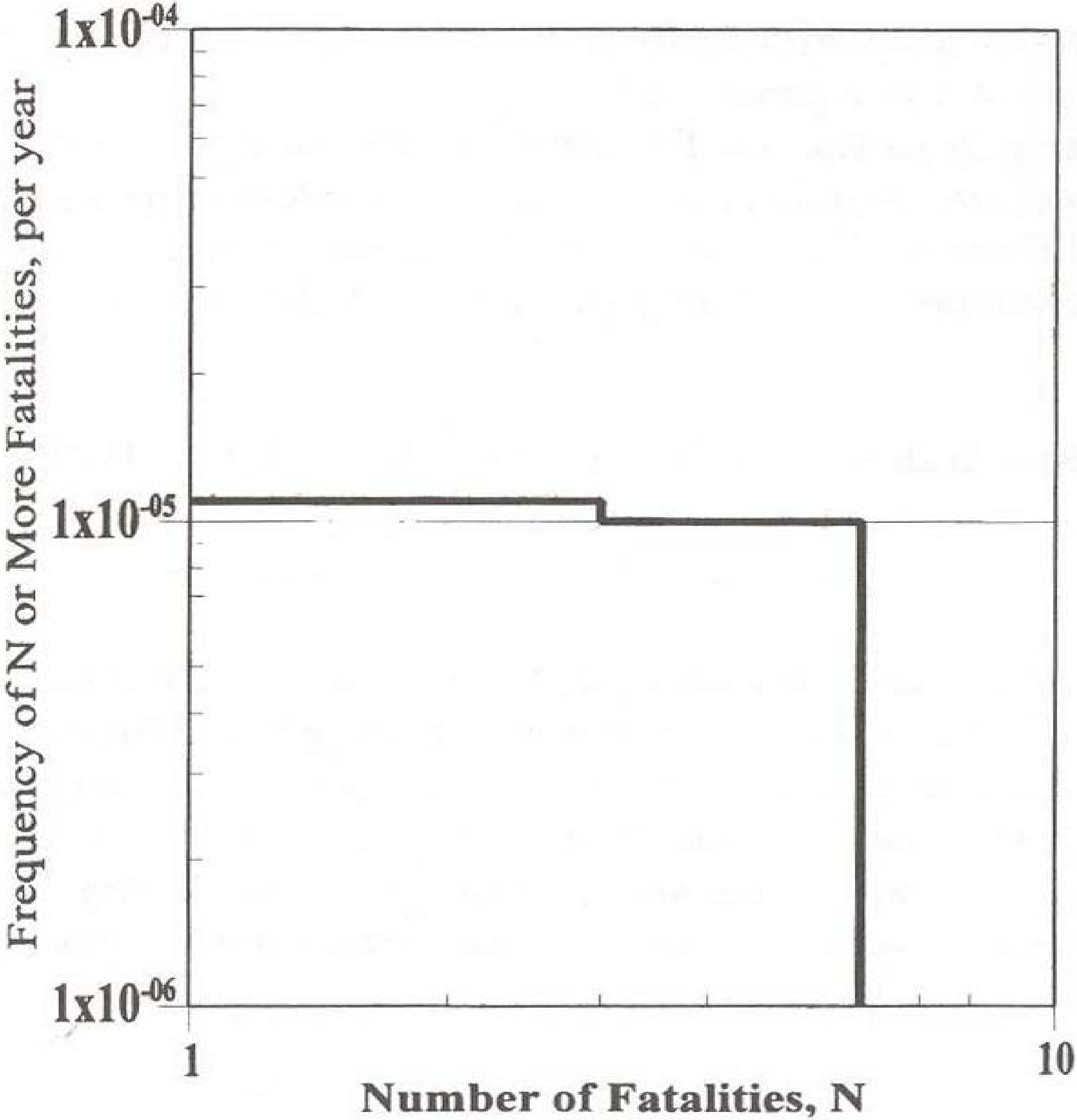


FIGURE 4.23. Aggregate risk curve for employee population in on-site buildings.

Other societal risk measures (cont.)

- Equivalent social cost index(ESC)
  - Societal risk measure which attempts to account for society's aversion to large incident
  - p=1.2 ESC = 1.8×10^{-4}
  - p=2.0 ESC = 2.3×10^{-3}

TABLE 4.11. Summary of Risk Results for the Example Problem

Risk measure	Result
Individual Risk	
Risk contours	See Figure 4.19 and Table 4.6
Risk transect	See Figure 4.20
Maximum	2.1×10^{-5} per year
Maximum for actual person	1.1×10^{-5} per year
Average, exposed population	5.2×10^{-6} per year
Average, total population	3.4×10^{-6} per year
Average, employee population	9×10^{-6} per year
Fatal accident rate	0.1 fatalities per 10^8 person-hours of exposure
Societal Risk	
F-N curve	See Figure 4.22
Aggregate risk curve	See Figure 4.23
Average rate of death	1.0×10^{-4} fatalities per year
Aggregate risk index	6.3×10^{-5} fatalities per year
Equivalent social cost index, total population ($p = 1.2$)	1.4×10^{-4}
Equivalent social cost index, total population ($p = 2$)	6.2×10^{-4}

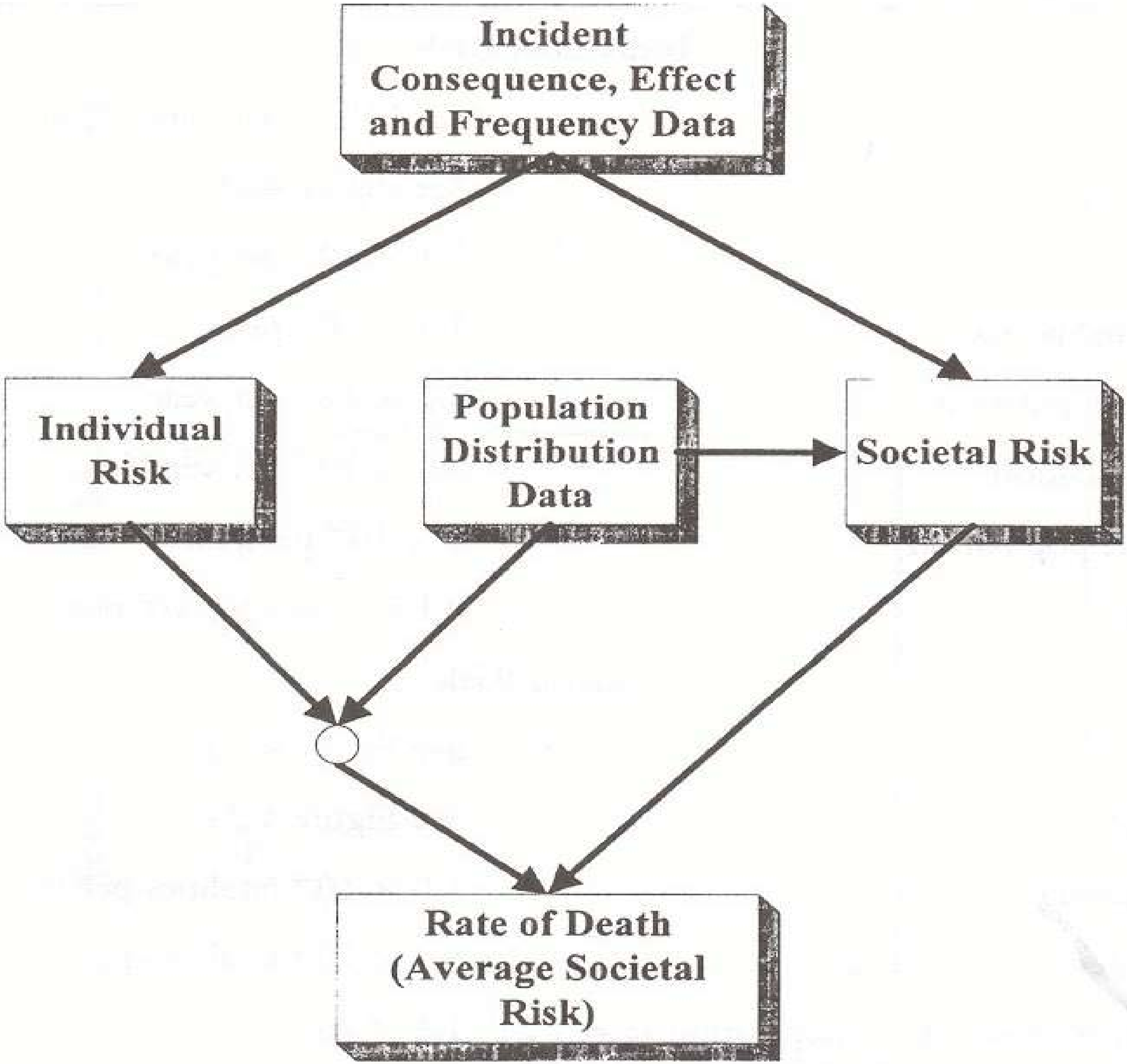


FIGURE 4.24. Relationship between individual and societal risk calculations.

Risk Uncertainty, Sensitivity and Importance

- Risk uncertainty
  - Literature on uncertainty analysis
    - PRA Procedure Guide(NUREG, 1983)
    - Cox and Baybutt (1981)
    - Parry and Winter (1980)
  - Baybutt(1986) offers three generic sources of uncertainty
    - Model uncertainty
      - Reflect the weaknesses, deficiencies and inadequacies intrinsic to any model
    - Data uncertainty
    - General quality uncertainties
      - Involve the “Completeness” and “Comprehensiveness”

TABLE 4.12. The Nature of Uncertainty by Generic Source[a]

Source of uncertainty	Considerations
Models	Is the model adequate? For example, do the binary event tree and fault tree models represent the process adequately? Is uncertainty introduced by mathematical or numerical approximations? If the model is valid over a certain range, is it being used outside that range?
Model input data	Data may be incomplete or biased. Have all relevant equipment failures been considered? Do the available data apply to the particular case? (e.g., generic vs site-specific data) Is the method of data analysis valid?
Quality	Has the analysis been taken to sufficient depth? Have all human error and all common-cause failures been considered? Have all important physical processes been treated? Have all important event sequences been considered?

[a]This table is a modified version of Table 12-1 in the *PRA Procedures Guide* (NUREG, 1983).

- 5 tasks to analysis and treatment of uncertainty in CPQRA
  - Evaluation and representation of uncertainty in input data
  - Propagation of input data uncertainties through CPQRA
  - Combination of the uncertainties in the out put from each of the steps in the CPQRA methodology
  - Display and interpretation of the uncertainties in the final risk estimate
  - Treatment of uncertainties in decision making

TABLE 4.13. Sources of Uncertainty in CPQRA

System description
Process description or drawings are incorrect or out of date
Procedures do not represent actual operation
Site area maps and population data may be incorrect or out of date
Weather data from nearest available site may be inappropriate
Hazard identification
Recognition of major hazards may be incomplete (inexperienced analyst)
Screening techniques employed for selection of hazards for further evaluation may omit important cases
Consequence techniques
Uncertainties in physical modeling
Inappropriate model selection
Incorrect or inadequate physical basis for model
Inadequate validation
Inaccurate model parameters
Uncertainties in physical model data
Input data (composition, temperature, pressure)
Source terms for dispersion and other models
Uncertainties in effects modeling
Animal data inappropriate for humans (especially toxicity)
Mitigating effects may be omitted
Frequency techniques
Uncertainties in modeling
Extrapolation of historical data to larger scale operations may overlook hazards introduced by scale up to larger equipment
Limitation of fault tree theory requires system simplification
Incompleteness in fault and event tree analysis
Uncertainties in data
Data may be inaccurate, incomplete, or inappropriate
Data from related activities might not be directly applicable
Data generated by expert judgment may be inaccurate
Risk estimation
Assumption of symmetry
Uniform wind rose is rare
Uniform ignition sources may be inaccurate
Assumptions to reduce the depth of treatment
A single condition of wind speed and stability may be too restrictive
A limited number of ignition cases will reduce accuracy

- Sensitivity
  - Identify potential major contributors to overall uncertainty from a large list of incident
  - Sensitivity(S_j) to a parameter j
    - $Sj = \Delta R_j / \Delta P_j$
      - ΔR_j is the change in risk measure as a result of change in a model parameter j
      - ΔP_j is the change in model parameter j
    - For example a 10% change in the failure rate of an interlock(ΔP_j) may change the risk by a factor of 2(ΔR_j)
      - $S_{interlock} = 2/0.1 = 20$

- Importance
  - Identification of the major risk contributors is one of the most important uses of CPQRA
  - Risk estimation can involve hundreds of manual calculation
  - The final results of risk calculation and presentation are individual risk measures, societal risk F-N plots or risk indics