Explosion and Fire

2009_2nd semester

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Definition-1

- Deflagration
  - A propagating chemical reaction of a substance in which the reaction or propagating front is limited by both molecular and turbulent transport and advanced into the reacted substance at less than the sonic velocity in the unreacted materials
- Detonation
  - A propagating chemical reaction of a substance in which the reaction or propagating front is limited only by the rate of reaction and advanced into the reacted substance at or greater than the sonic velocity in the unreacted materials
- Flammable limits
  - The minimum (lower flammable limit, LFL) and maximum (upper flammable limit, UFL) concentration of vapor in air that will propagate a flame

Definition-2

- Flashpoint Temperature
  - The temperature of a liquid at which the liquid is capable of producing enough flammable vapor to flash momentarily
- Explosion
  - A release of energy that cause a blast (by AIChE/CCPS, 1994)
    - “blast” is defined as a transient change in the gas density, pressure and velocity of the air surrounding an explosion point
  - A rapid expansion of gases resulting in a rapidly moving pressure or shock wave (by Crowl and Louvar, 1990)
  - The bursting or rupture of an enclosure or a container due to the development of internal pressure (NFPA, 1986)

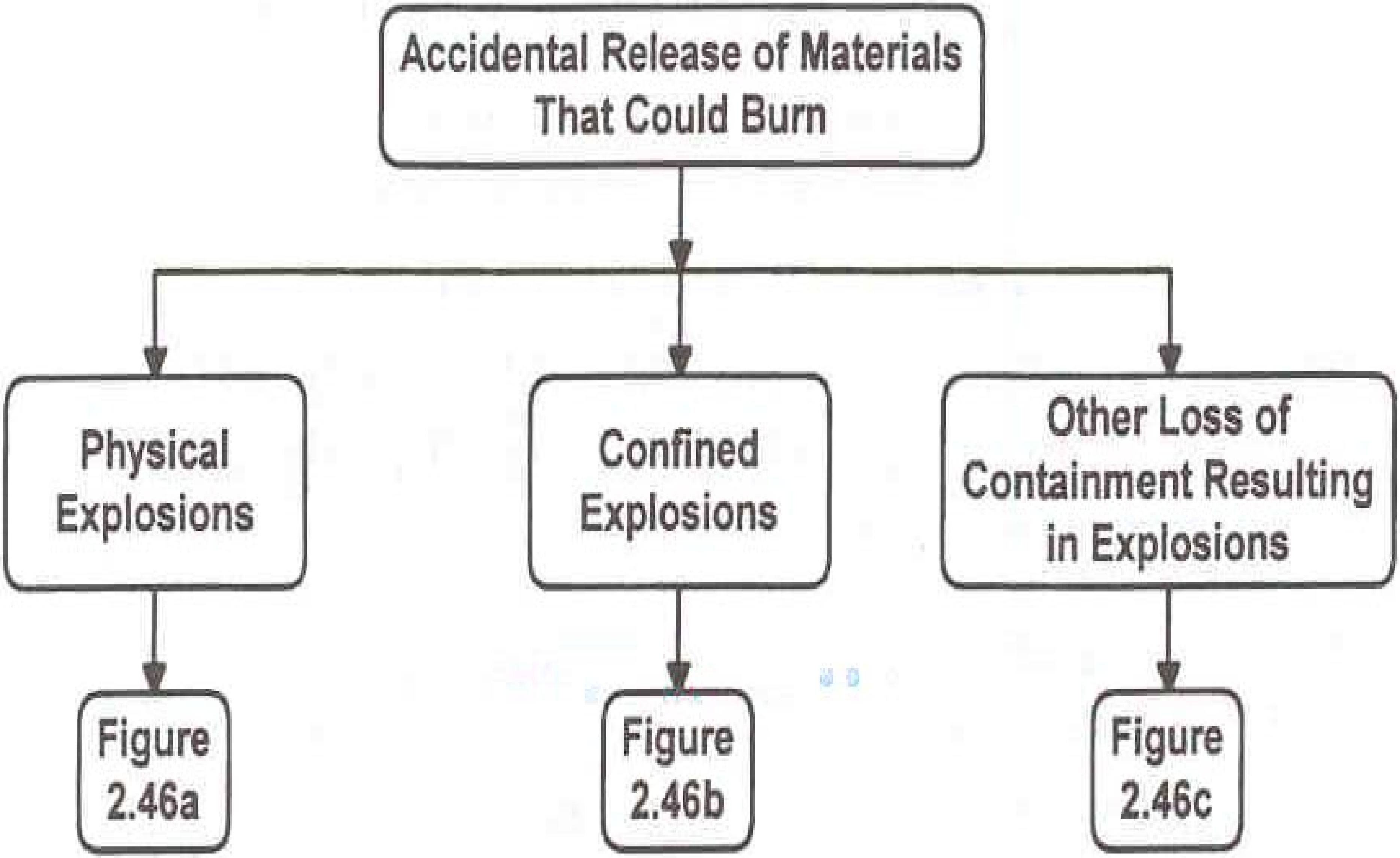

FIGURE 2.46. Logic diagram for explosion events.

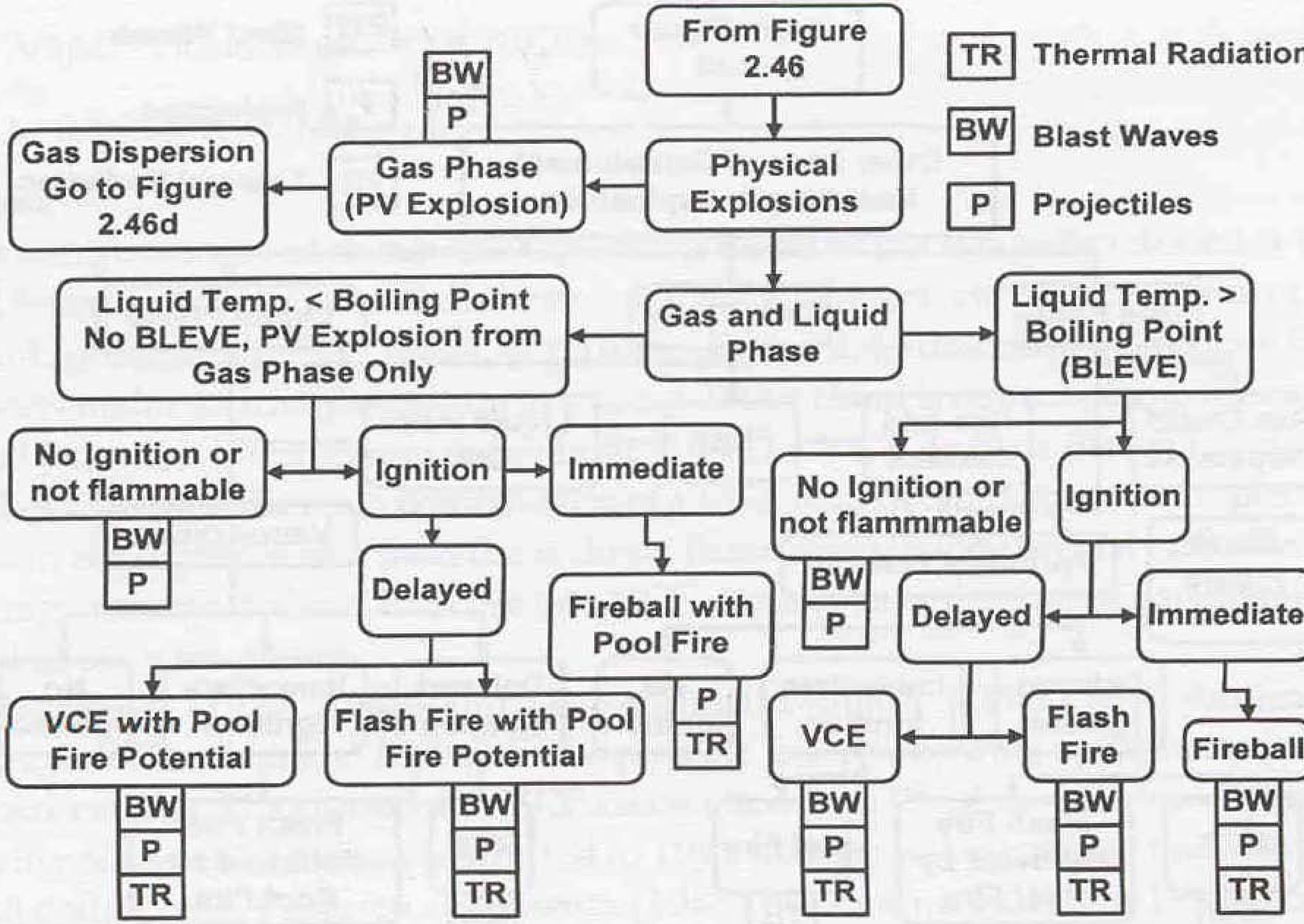

FIGURE 2.46a. Logic diagram for physical explosions.

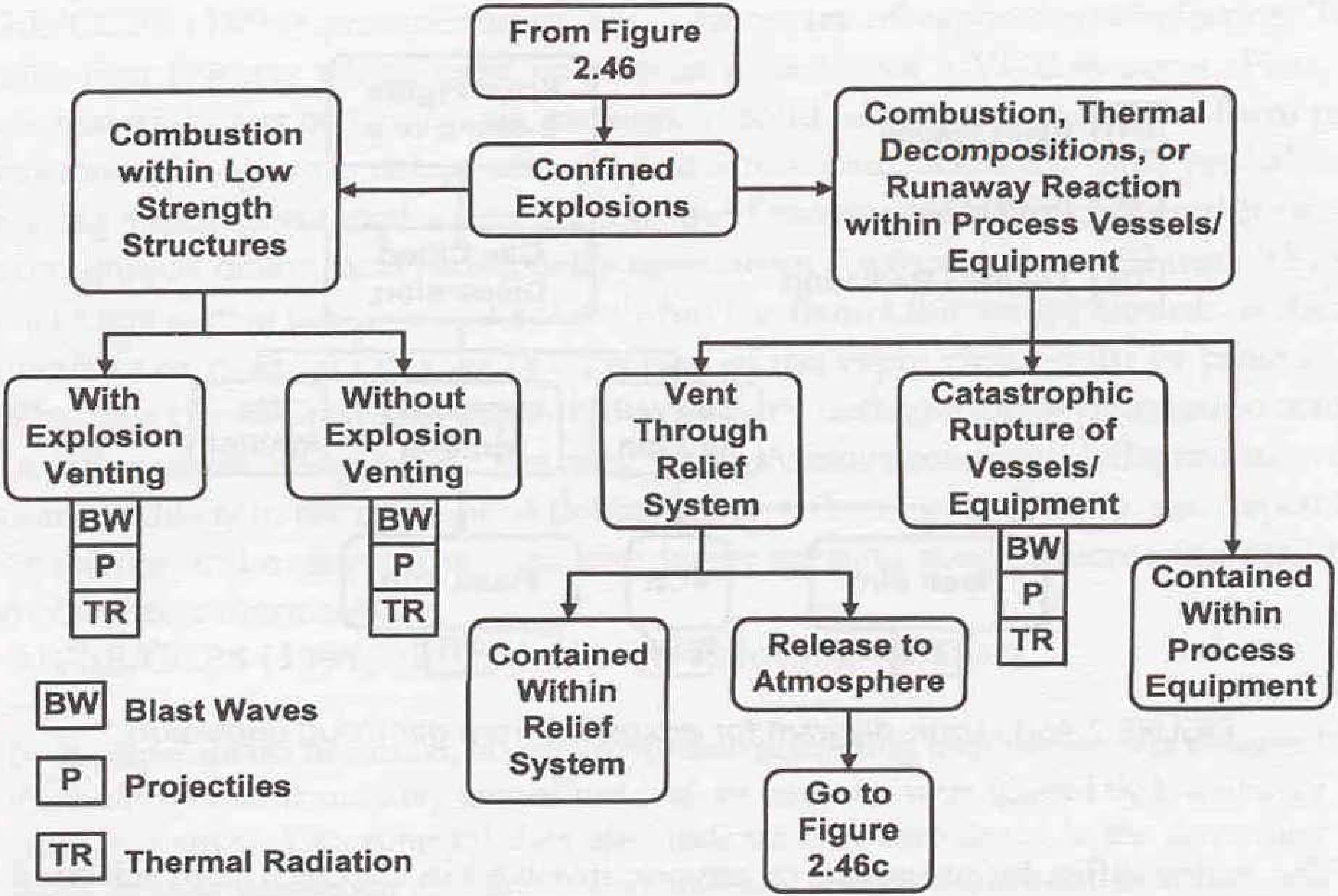

FIGURE 2.46b. Logic diagram for confined explosions.

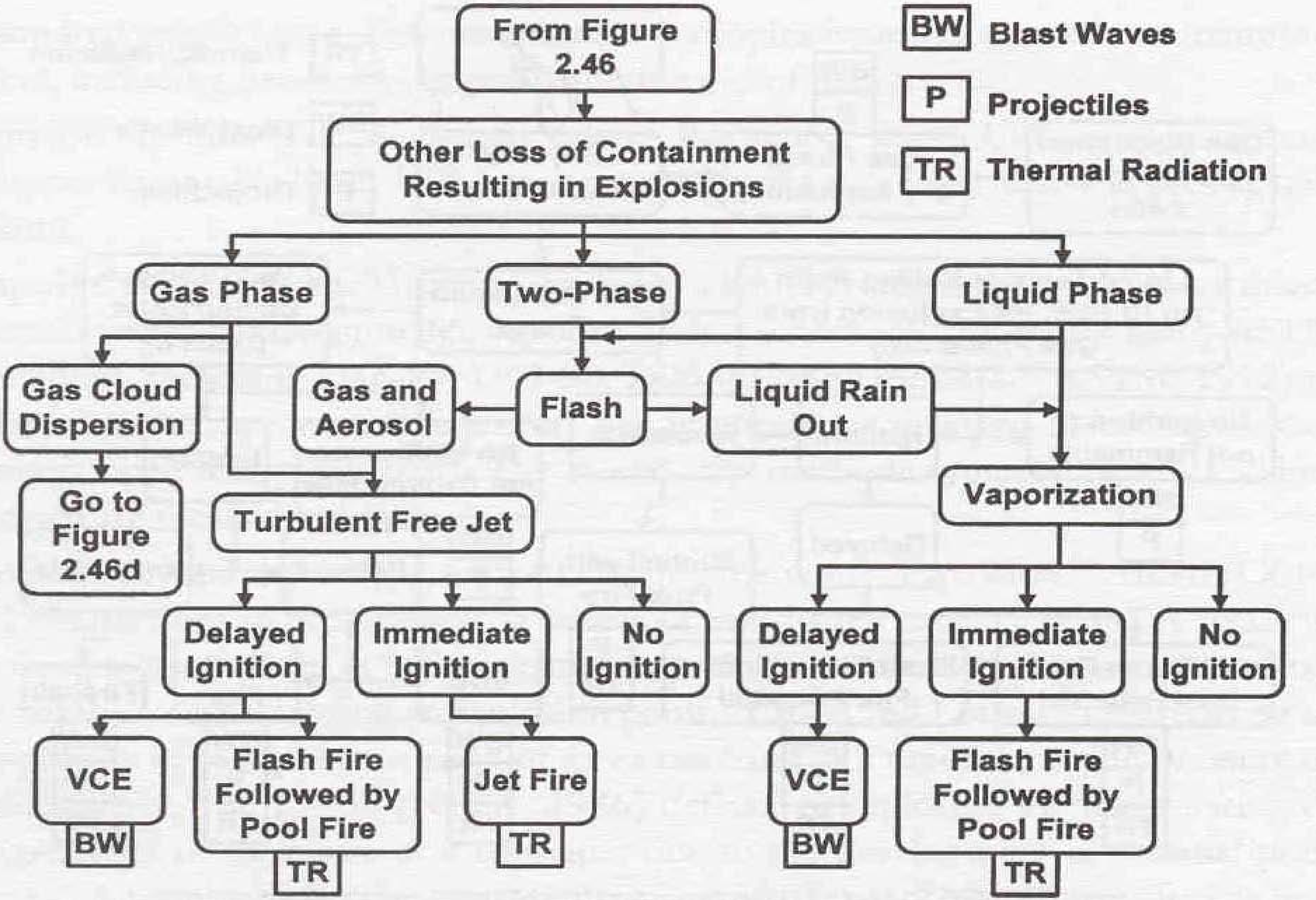

FIGURE 2.46c. Logic diagram for other losses of containment.

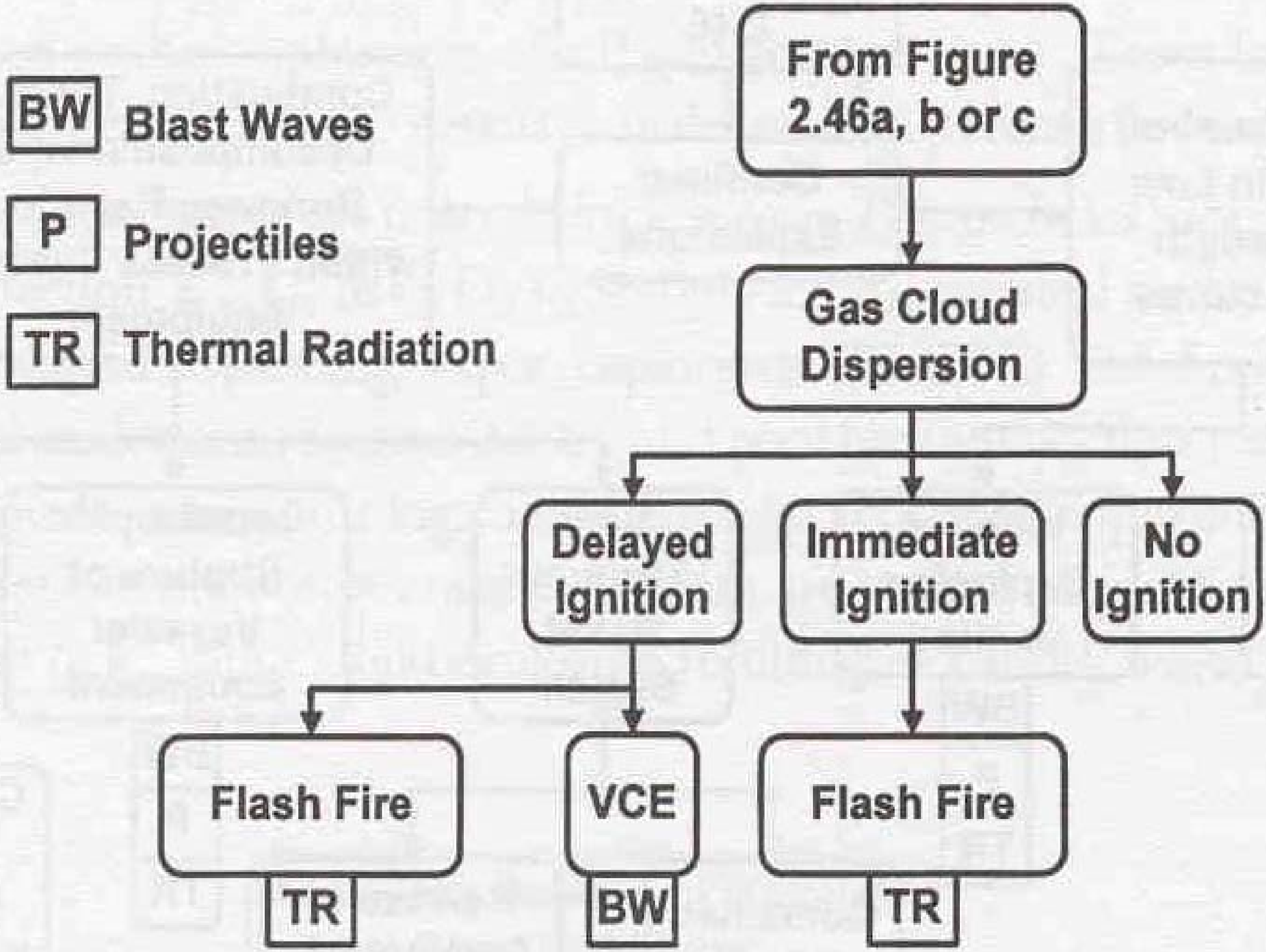

FIGURE 2.46d. Logic diagram for explosions from gas cloud dispersion.

Vapor Cloud Explosion(VCE)-1

- When a large amount of flammable vaporizing liquid or gas is rapidly released, a vapor cloud forms and disperses with surrounding air
- If this cloud is ignited before the cloud is diluted below its lower flammability limit(LFL), a VCE or flash fire will occur
- Models of VCEs
  - TNT equivalency model
  - TNO multi-energy model
  - Modified Baker model

Vapor Cloud Explosion(VCE)-2

- The parameters that affect VCE behavior
  - Quantity of material released
  - Fraction of material vaporized
  - Probability of ignition of the cloud
  - Distance travelled by the cloud prior to ignition
  - Time delay before ignition of cloud
  - Probability of explosion rather than fire
  - Existence of a threshold quantity of material
  - Efficiency of explosion
  - Location of ignition source with respect to release

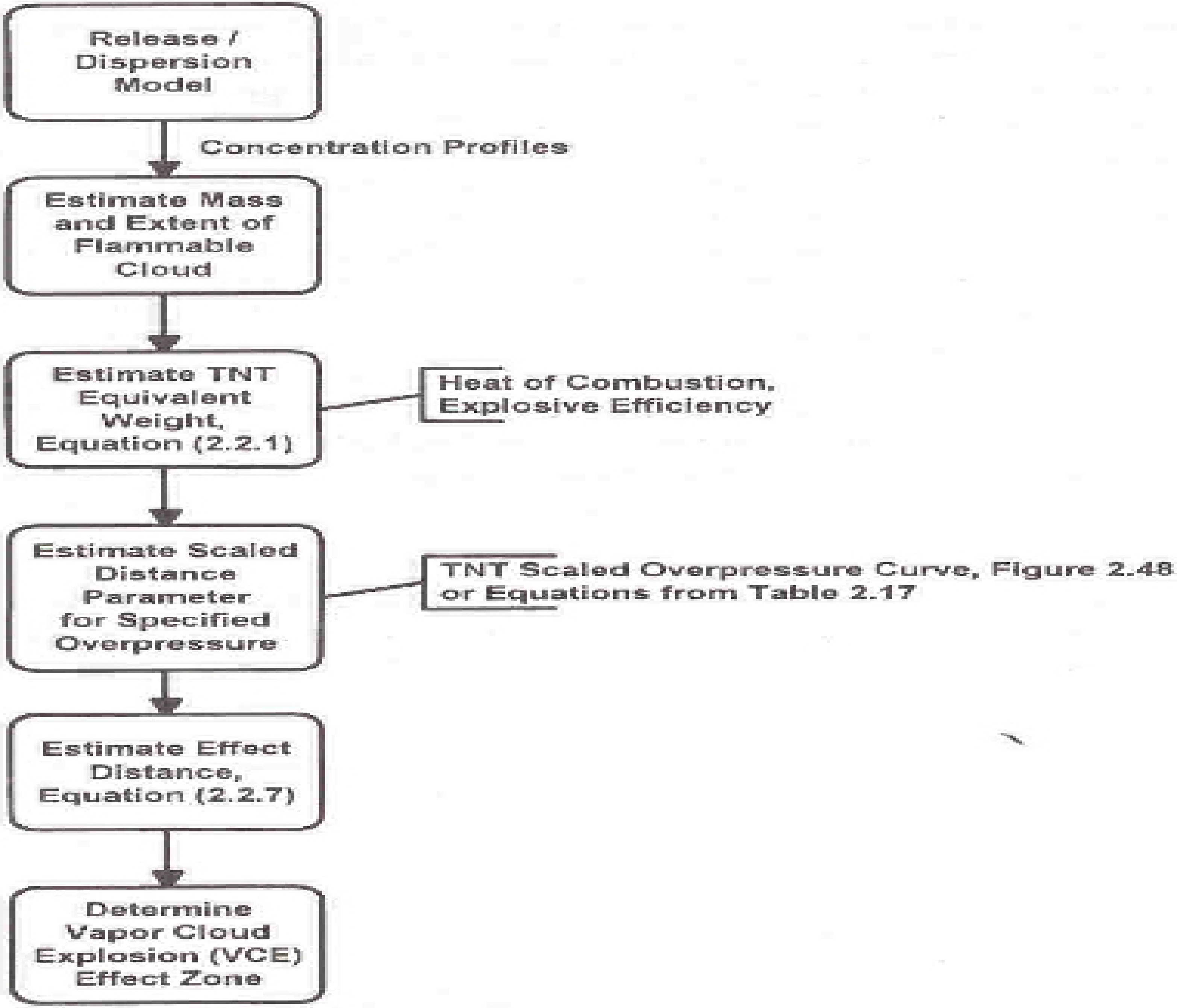

FIGURE 2.52. Logic diagram for the application of the TNT equivalency model.

Vapor Cloud Explosion(VCE)-3

- TNT equivalency model
  - Easy to use
  - Generally applied for many CPQRAs

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

- W is the equivalent mass of TNT(kg or lb)
- η is an empirical explosion efficiency(unitless)
- M is the mass of hydrocarbon(kg or lb)
- E_c is the heat combustion of flammable gas (kJ/kg or Btu/lb)
- E_{TNT} is the heat of combustion of TNT(4437-4765 kJ/kg or 1943-2049 Btu/lb)

Vapor Cloud Explosion(VCE)-4

- Overpressure can be estimated using an equivalent mass of TNT and using the distance from the ground zero point of the explosion

$$Z_e = \frac{r}{m_{TNT}^{1/3}}$$

- m_{TNT} is the equivalent mass of TNT
- R is the distance from the point of explosion
- Z_e is the scaled distance

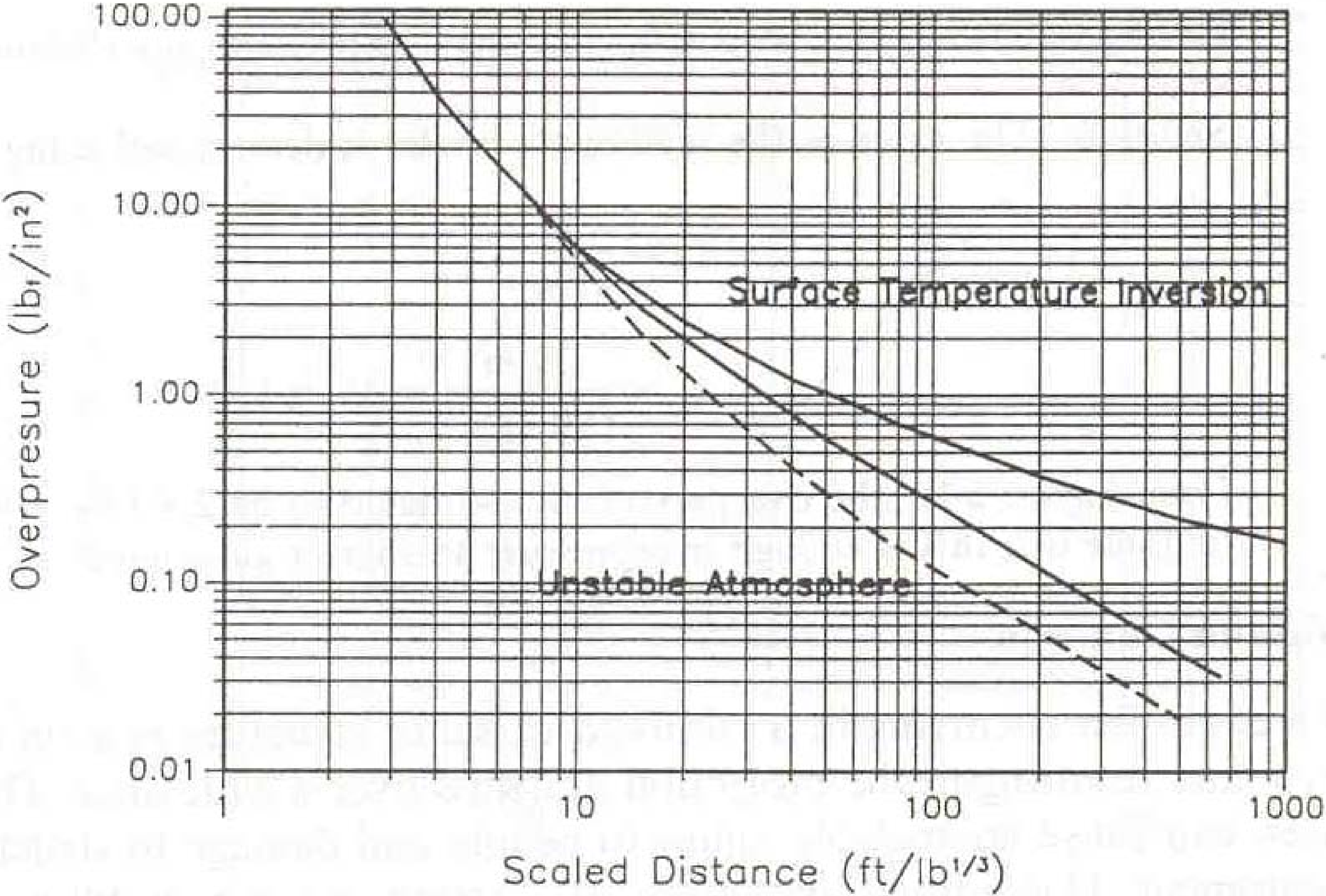

Figure 6-12 Correlation between overpressure and scaled distance, English engineering units.

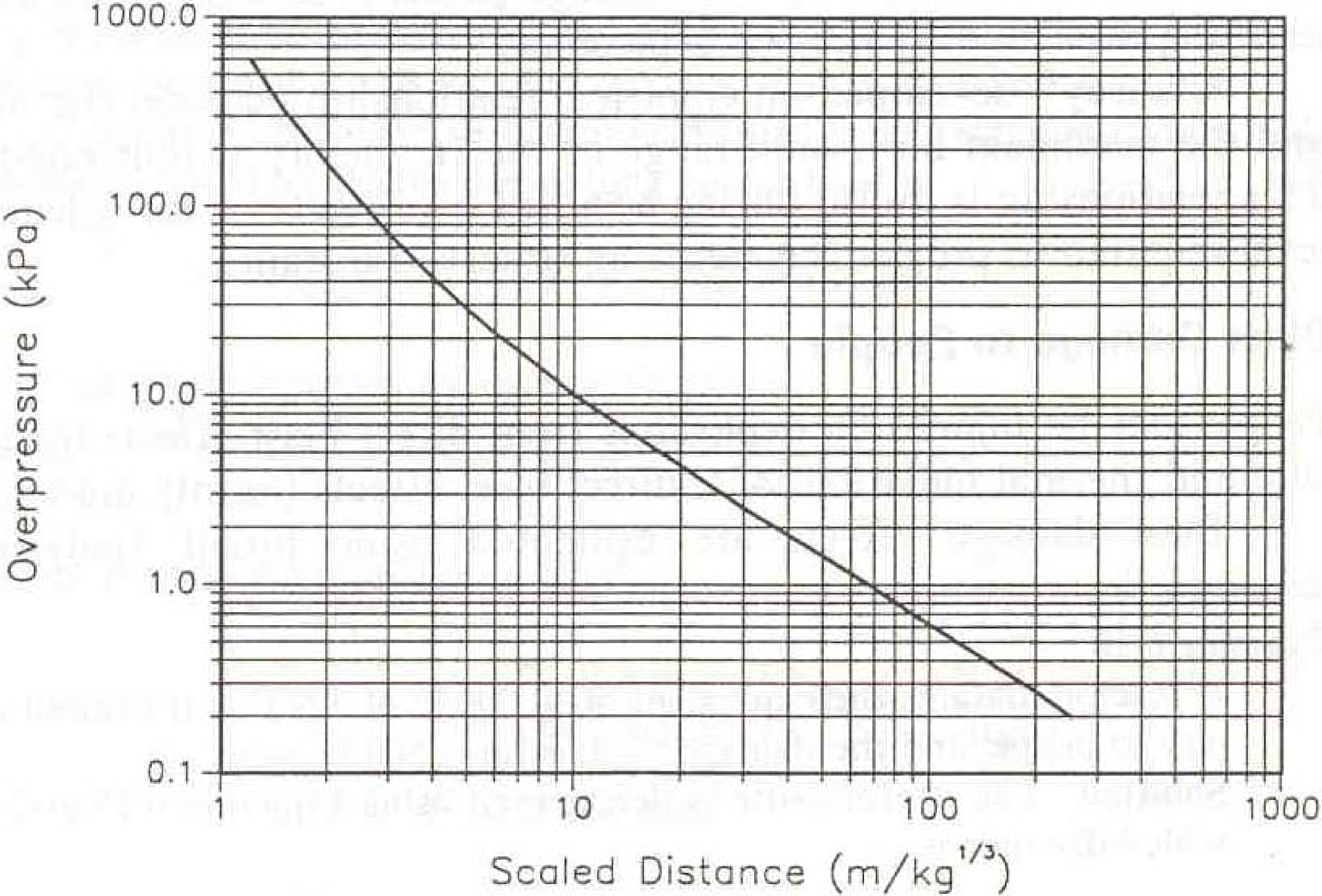

Figure 6-13 Correlation between overpressure and scaled distance, SI units.

TABLE 2.18a. Damage estimates for common structures based on overpressure (Clancey, 1972). These values should only be used for approximate estimates.

Pressure		Damage
psig	kPa	
0.02	0.14	Annoying noise (137 dB if of low frequency 10–15 Hz)
0.03	0.21	Occasional breaking of large glass windows already under strain
0.04	0.28	Loud noise (143 dB), sonic boom, glass failure
0.1	0.69	Breakage of small windows under strain
0.15	1.03	Typical pressure for glass breakage
0.3	2.07	"Safe distance" (probability 0.95 of no serious damage below this value); projectile limit; some damage to house ceilings; 10% window glass broken
0.4	2.76	Limited minor structural damage
0.5–1.0	3.4–6.9	Large and small windows usually shattered; occasional damage to window frames
0.7	4.8	Minor damage to house structures
1.0	6.9	Partial demolition of houses, made uninhabitable
1–2	6.9–13.8	Corrugated asbestos shattered; corrugated steel or aluminum panels, fastenings fail, followed by buckling; wood panels (standard housing) fastenings fail, panels blown in
1.3	9.0	Steel frame of clad building slightly distorted
2	13.8	Partial collapse of walls and roofs of houses
2–3	13.8–20.7	Concrete or cinder block walls, not reinforced, shattered
2.3	15.8	Lower limit of serious structural damage
2.5	17.2	50% destruction of brickwork of houses
3	20.7	Heavy machines (3000 lb) in industrial building suffered little damage; steel frame building distorted and pulled away from foundations
3–4	20.7–27.6	Frameless, self-framing steel panel building demolished; rupture of oil storage tanks
4	27.6	Cladding of light industrial buildings ruptured
5	34.5	Wooden utility poles snapped; tall hydraulic press (40,000 lb) in building slightly damaged
5–7	34.5–48.2	Nearly complete destruction of houses
7	48.2	Loaded train wagons overturned
7–8	48.2–55.1	Brick panels, 8–12 inches thick, not reinforced,fail by shearing or flexure
9	62.0	Loaded train boxcars completely demolished
10	68.9	Probable total destruction of buildings; heavy machine tools (7000 lb) moved and badly damaged; very heavy machine tools (12,000 lb) survive
300	2068	Limit of crater lip

Vapor Cloud Explosion(VCE)-5

- Overpressure impulse, i_P
  - Defined as the area under the positive duration
  - An important aspect of damage-causing ability of the blast on structures since it is indicative of the total energy contained within the blast wave

$$i_p = \int_0^{t_d} P dt$$

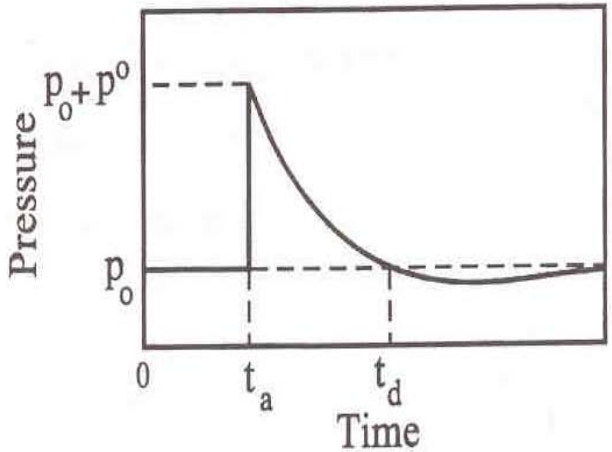

FIGURE 2.47. Typical pressure history for a TNT-type explosion. The pressure curve drops below ambient pressure due to a refraction at time t_d.

TABLE 2.18b. Damage Estimates Based on Overpressure for Process Equipment[a]

Equipment	Overpressure, psi																								
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10	12	14	16	18	20
Control house steel roof	A	C	D				N																		
Control house concrete roof	A	E	P	D			N																		
Cooling tower	B			F			O																		
Tank: cone roof		D				K							U												
Instrument cubicle			A			LM						T													
Fire heater				G	I					T															
Reactor: chemical				A				I					P					T							
Filter				H					F										V		T				
Regenerator						I				IP					T										
Tank: floating roof						K							U												D
Reactor: cracking							I							I							T				
Pine supports							P					SO													
Utilities: gas meter									Q																
Utilities: electronic transformer									H						I					T					
Electric motor										H								I							V
Blower										Q										T					
Fractionation column											R			T											
Pressure vessel: horizontal												PI						T							
Utilities: gas regulator												I								MQ					
Extraction column													I							V	T				
Steam turbine															I						M	S			V
Heat exchanger															I			T							
Tank sphere																I						I	T		
Pressure vessel: vertical																					I	T			
Pump																					I		V		

[a] See page 165 for the key to this table.

Key to Table 2.18b

A. Windows and gauges broken
B. Louvers fall at 0.2– 0.5 psi
C. Switchgear is damaged from roof collapse
D. Roof collapses
E. Instruments are damaged
F. Inner parts are damaged
G. Brick cracks
H. Debris—missile damage occurs
I. Unit moves and pipes break
J. Bracing falls
K. Unit uplifts (half tilted)
L. Power lines are severed
M. Controls are damaged
N. Block walls fall
O. Frame collapses
P. Frame deforms
Q. Case is damaged
R. Frame cracks
S. Piping breaks
T. Unit overturns or is destroyed
U. Unit uplifts (0.9 tilted)
V. Unit moves on foundation

- TNO multi-energy method
  - Assumes that blast modeling on the basis of deflagration combustion is a conservative approach
  - Energy of explosion is highly dependent on the level of congestion and less dependent on the fuel in the cloud

- The procedure for employing the multi-energy model to a vapor cloud explosion
  - Perform a dispersion analysis to determine the extent of the cloud
  - Conduct a field inspection to identify the congested areas
  - Identify potential source of strong blast present within the area covered by the flammable cloud
  - Estimate the energy of equivalent fuel-air charges
  - Estimate strengths of individual blasts
  - Once the energy quantities E and initial blast strengths of the individual equivalent fuel-air charges are estimated, the Sachs-scaled blast side on overpressure and positive-phase duration is calculated

Flash Fire

- Non-explosive combustion of a vapor cloud resulting from a release of flammable material into the open air
- Thermal radiation hazards from burning vapor clouds are considered less significant than possible blast effect
- Flash fire model
  - Based on flame radiation

Physical Explosion-1

- A Physical explosion relates to the catastrophic rupture of a pressurized gas filled vessel
- Rupture could occur for the following reasons
  - Failure of pressure regulating and pressure relief equipment
  - Reduction in vessel thickness due to
    - Corrosion
    - Erosion
    - Chemical attack
  - Reduction in vessel strength due to
    - Overheating
    - Material defects with subsequent development of fracture
    - Chemical attack
    - Fatigue induced weakening of the vessel
  - Internal runaway reaction
  - Any other incident results in loss of process containment

Physical Explosion-2

- A kind of Energy resulting from physical explosion
  - Vessel stretch and tearing
  - Kinetic energy of fragment
  - Energy in shock wave
  - "waste" energy (heating of surrounding air)

TABLE 2.22. Characteristics of Various Types of Physical Explosions

Type	Shock Wave Energy
Gas-filled vessel	Expansion of gas
Liquid-filled vessel Liquid temperature < Liquid boiling point	Expansion of gas from vapor space volume; liquid contents unchanged and runs out.
Liquid-filled vessel Liquid temperature > Liquid boiling point	Expansion of gas from vapor space volume coupled with flash evaporation of liquid.

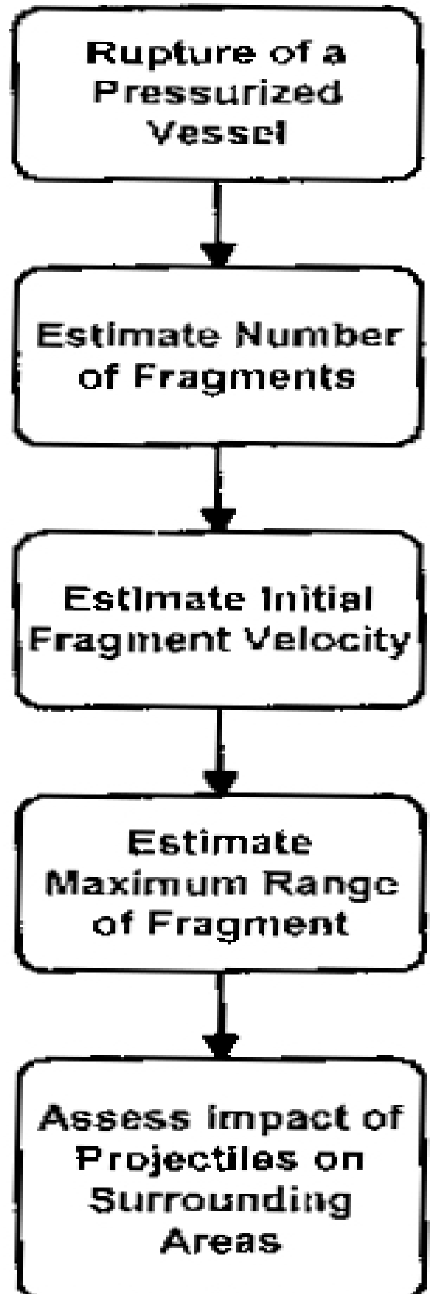

FIGURE 2.64. Logic diagram for the calculation of projectile effects for rupture of pressurized gas-filled vessels.

Physical Explosion-3

- Relate to calculation of a TNT equivalent energy and use of shock wave correlation
- Energy required to raise the pressure of the gas at constant volume from atmospheric pressure, P_0 to the initial or burst, pressure, P_1 (Brode, 1959)

$$E = \frac{(P_1 - P_0)V}{\gamma - 1}$$

  - E is the explosion energy(energy)
  - V is the volume of the vessel(volume)
  - γ is the heat capacity ratio for the expanding gas(unitless)

Physical Explosion-4

- Energy with isothermally expansion (Brown, 1985)

$$W = \left(1.39\times10^{-6}\,\frac{\mathrm{lb-mole\cdot lb-TNT}}{\mathrm{ft^3-BTU}}\right)V\left(\frac{P_1}{P_0}\right)R_g T_0 \ln\frac{P_1}{P_2}$$

- W is the energy(lb TNT)
- V is the volume of the compressed gas(ft^3)
- P_1 is the initial pressure of the compressed gas(psia)
- P_2 is the final pressure of expanded gas(psia)
- P_0 is the standard pressure(14.7 psia)
- T_0 is the standard temperature(492 R)
- R_g is the gas constant(1.987 Btu/lb-mole-R)
- $1.39*10^{-6}$ is a conversion factor(this factor assume that 2000 Btu=1 lb TNT)

Physical Explosion-5

- Energy considering thermodynamic availability (Crowl, 1992)
  - Available energy represents the maximum mechanical energy that can be extracted from a material as it moves into equilibrium with the environment

$$E = R_g T\left[\ln\left(\frac{P}{P_E}\right) - \left(1 - \frac{P_E}{P}\right)\right]$$

- P is the burst pressure
- T is the burst temperature
- P_E is the ambient pressure
- E is the maximum mechanical energy

Physical Explosion-6

- Pressure at the surface of the vessel for sphere burst

$$P_b = P_s\left[1 - \frac{3.5(\gamma - 1)(P_s - 1)}{\sqrt{(\gamma/M)(1+5.9P_s)}}\right]^{-2\gamma/(\gamma-1)}$$

- P_s is the pressure at the surface of the vessel(bar abs)
- P_b is the burst pressure of the vessel(bar abs)
- γ is the heat capacity ratio of the expanding gas(C_P/C_V)
- T is the absolute temperature of the expanding gas(K)
- M is the molecular weight of the expanding gas(mass/mole)

Physical Explosion-7

- AIChE/CCPS(1994) describe a number of techniques for estimating overpressure for a rupture of a gas filled container
  - Procedure
    - Collect data
      - The vessel's internal absolute pressure, P1
      - The ambient pressure, P0
      - The vessel's volume of gas filled space, V
      - The heat capacity ratio of the expanding gas, γ
      - The distance from the center of the vessel to the target, r
      - The shape of the vessel : spherical or cylindrical
    - Calculate the energy of explosion, E, using Brode equation
    - Determine the scaled distance, R, from the target

- Check the scaled distance
- Determine the scaled overpressure and scaled impulse using Figure 2.58 and 2.59
- Determine the final overpressure and impulse from the definition of the scaled variable
- Check the final overpressure
- Calculate the initial vessel radius
- Calculate the initial starting distance for the overpressure curve
- Calculate the initial peak pressure

BLEVE and Fireball-1

- BLEVE(Boiling Liquid Expanding Vapor Explosion)
  - Is a sudden release of a large mass of pressurized superheated liquid to the atmosphere
  - A special type of BLEVE involves flammable material, such as LPG
    - San Carlos, Spain(July 11, 1978)
    - Mexico city(November 19, 1984)
  - Effect of BLEVE
    - Blast effects
    - Fragments
    - Radiation

BLEVE and Fireball-2

- Fragment
  - Figure 2.70
    - Provide data for the number of fragment and the fragment range
    - Shows that roughly 80% of fragment fall within a 300 m range
  - Number of fragment = -3.77 + 0.0096[vessel capacity(m^3)]
    - Range of validity : 700-2500m^3

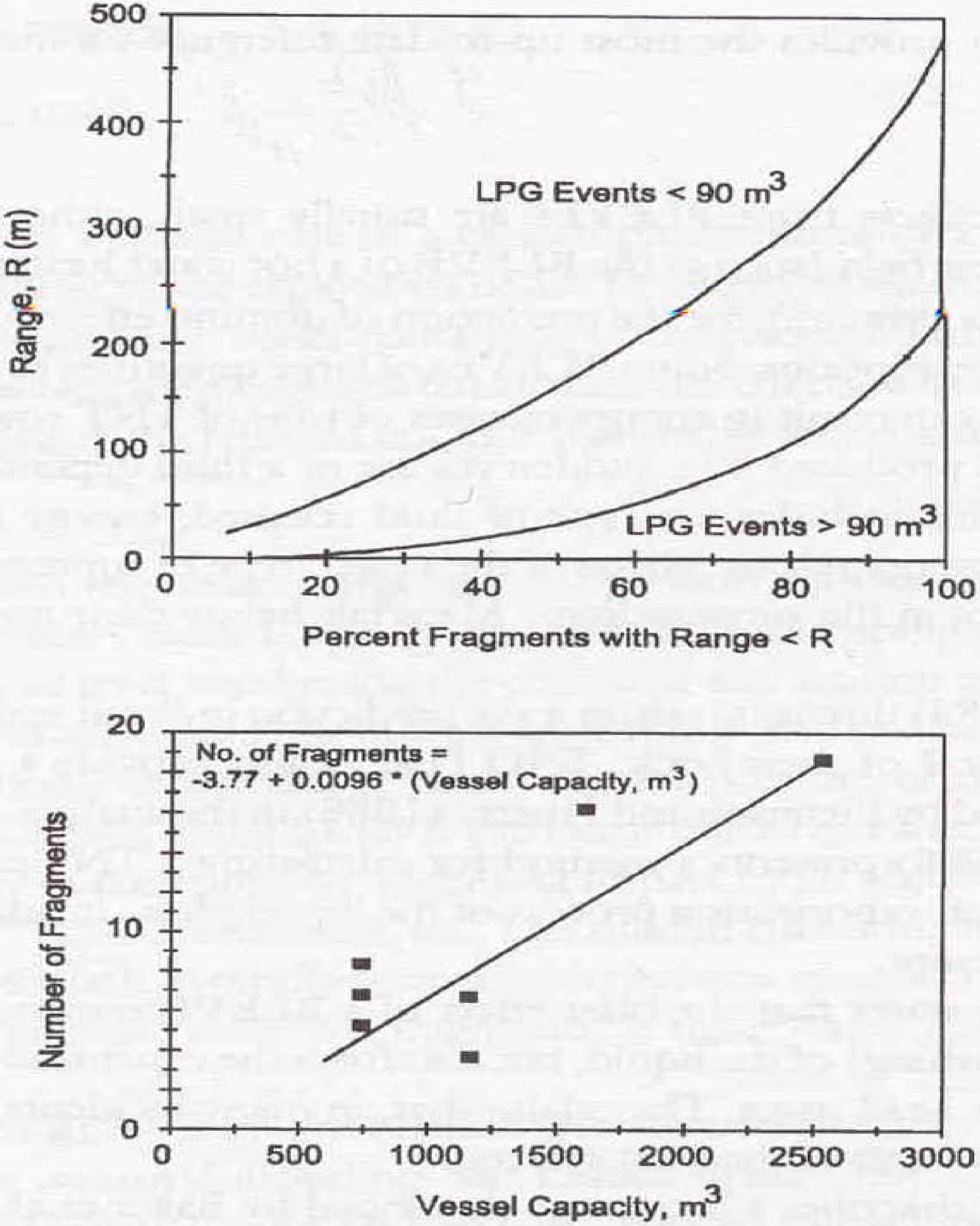

FIGURE 2.70. Correlations for the fragment range and number of fragments. (From Hodlen and Reeves, 1985.)

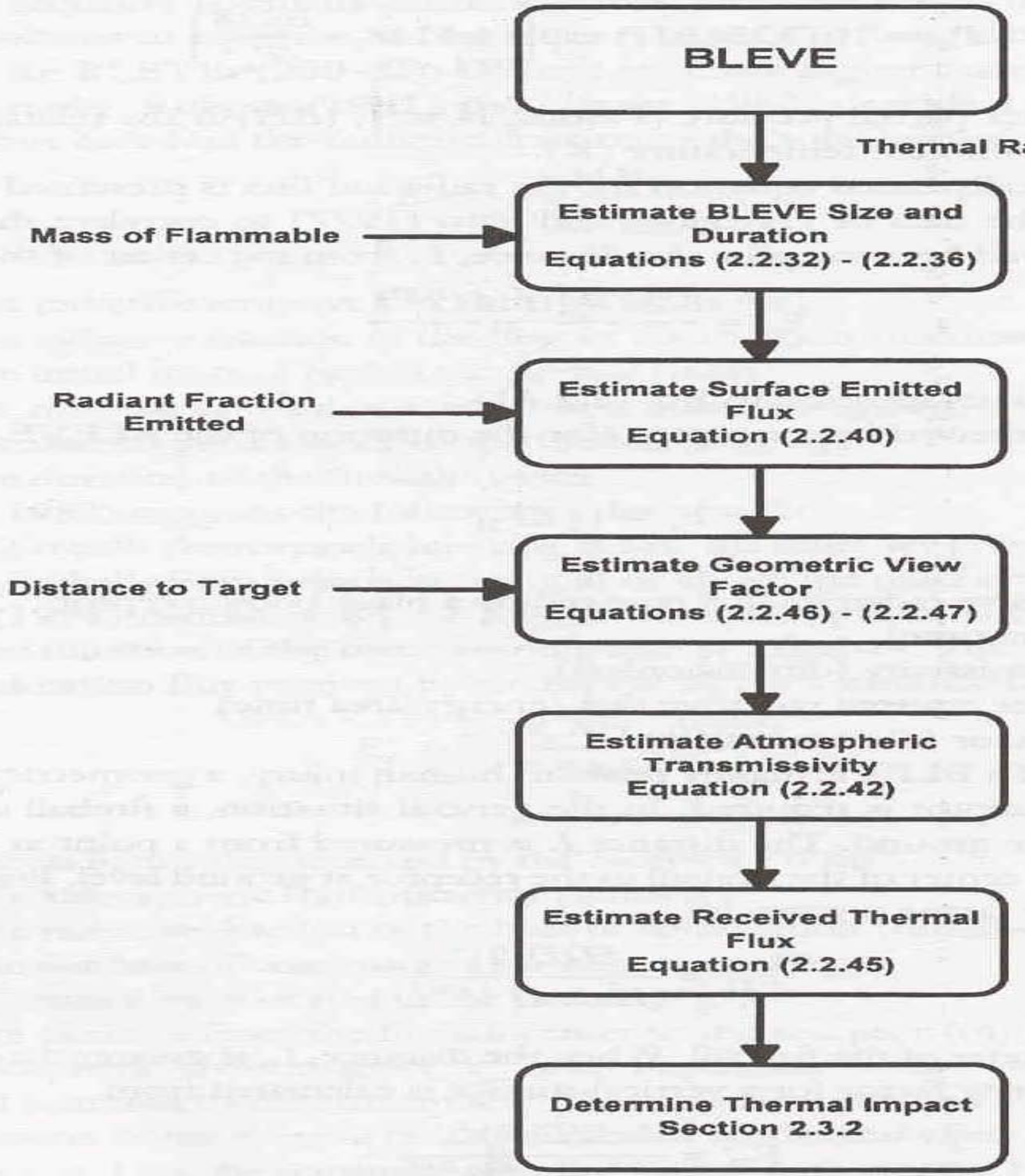

FIGURE 2.71. Logic diagram for calculation of BLEVE thermal intensity at a specified receptor.

BLEVE and Fireball-3

- Empirical equation for BLEVE fireball diameter, Duration and fireball height
  - Maximum fireball diameter(m)
    - $D_{max} = 5.8\ M^{1/3}$
  - Fireball combustion duration(s)
    - $t_{BLEVE} = 0.45\ M^{1/3}$ for $M < 30{,}000$ kg
    - $t_{BLEVE} = 2.6\ M^{1/6}$ for $M > 30{,}000$ kg
  - Center height of fireball(m)
    - $H_{BLEVE} = 0.75 D_{MAX}$
  - Initial ground level hemisphere diameter(m)
    - $D_{initial} = 1.3 D_{MAX}$
  - M is the initial mass of flammable liquid (kg)

BLEVE and Fireball-4

- Heat flux based on the radiative fraction of the total heat of combustion(Robert(1981) and Hymes(1983))

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

  - 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)
- Hymes(1983) suggest the following values for R
  - 0.3 for fireball from vessels bursting below the relief set pressure
  - 0.4 for fireball from vessels bursting at or above the relief set pressure

BLEVE and Fireball-5

- AIChE suggest an equation for the radiation flux received by a receptor, E_r at a distance L(for the duration of the combustion phase of a fireball)

$$E_r = \frac{2.2\tau_a R H_C M^{2/3}}{4\pi\pi_C^2}$$

- E_r is the radiative flux received by the receptor(W/m^2)
- τ_a is the atmospheric transmissivity(unitless)
- R is the radiative fraction of the heat of combustion(unitless)
- H_C is the net heat of combustion per unit mass(J/kg)
- M is the initial mass of fuel in the fireball(kg)
- X_C is the distance from the fireball center to the receptor(m)

BLEVE and Fireball-6

- Atmospheric transmissivity, τ_a
  - Fraction of thermal radiation result from absorbing and scattering by the atmosphere

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

    - 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)
  - Water partial pressure as a function of the relative humidity

$$P_W = 101325(RH)\exp\left(14.4114 - \frac{5328}{T_a}\right)$$

    - RH is the relative humidity(percent)
    - Ta is the ambient temperature(K)

BLEVE and Fireball-7

- Radiation received by a receptor(for the duration of the BLEVE incident)

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

- E_r is the emissive radiative flux received by a black body receptor(energy/area time)
- τ_a is the transmissivity(dimensionless)
- E is the durface emitted radiative flux(energy/area time)
- F_{21} is the view factor(dimensionless)

Confined Explosion-1

- Confined explosion
  - Deflagrations or other source of rapid chemical reaction which are constrained within vessels and buildings
  - Dust explosions and vapor explosion (deflagration or detonation) within low strength vessels and building are one major category
  - Calculation technique is based on the determination of the peak pressure

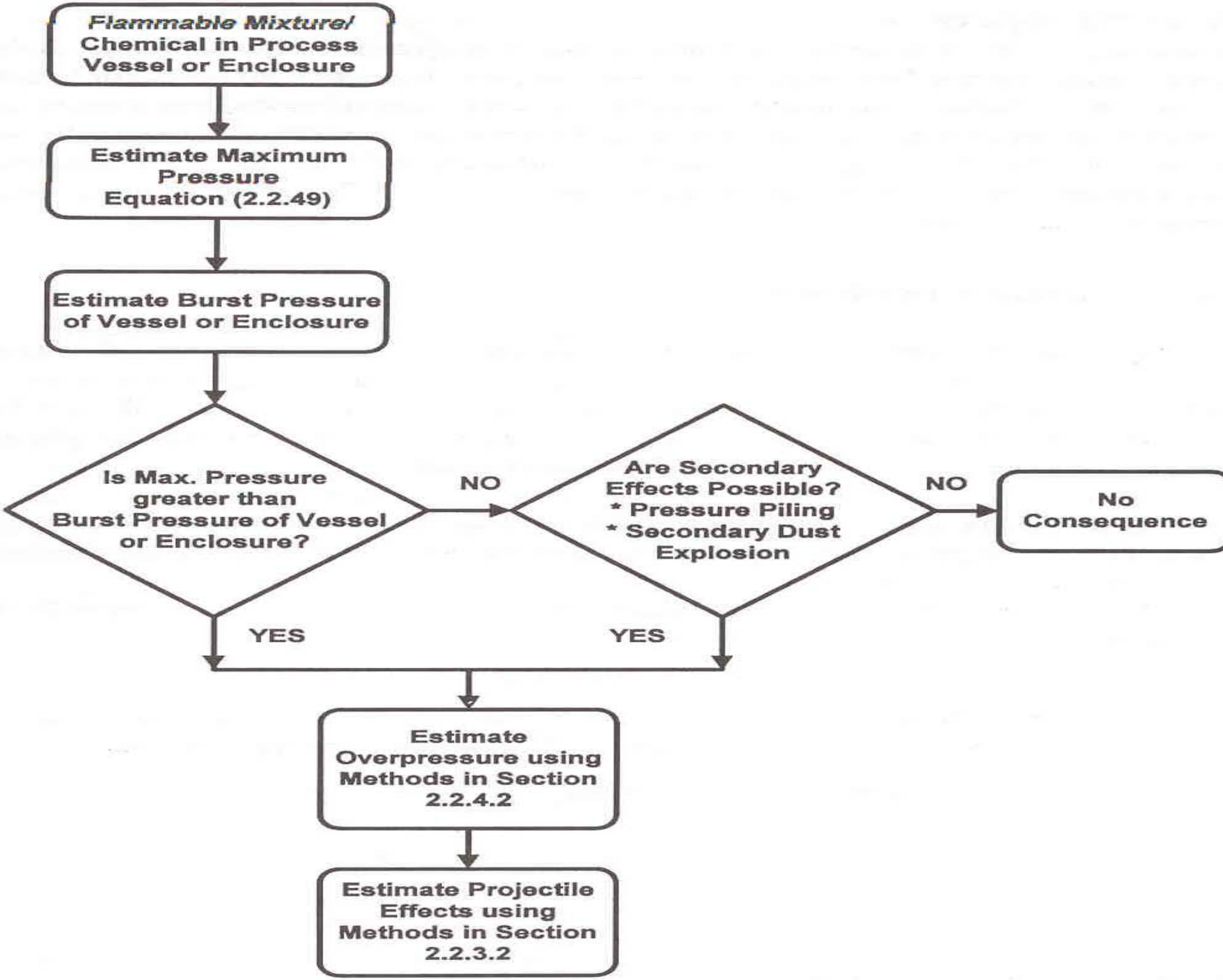

FIGURE 2.75. Logic diagram for confined explosion analysis.

Confined Explosion-2

- Maximum pressure rise as a result of a change in the number of moles and temperature(Lee, 1986)

$$\frac{P_{max}}{P_1} = \frac{n_2 T_2}{n_1 T_1} = \frac{M_1 T_2}{M_2 T_1}$$

- P_{max} is the maximum absolute pressure(force/area)
- P_1 is the initial absolute pressure(force/area)
- n is the number of moles in the gas phase
- T is the absolute temperature of the gas phase
- M is the molecular weight of the gas
- 1 is the initial state
- 2 is the final state

Pool Fire-1

- Pool fire
  - Tend to be localized in effect and are mainly of concern in establishing the potential for domino effects
  - Drainage is an important consideration in the prevention of pool fire
  - Important consideration are
    - The liquid must be drained to a safe area
    - The liquid must be covered to minimize vaporization
    - The drainage area must be far enough away from thermal radiation fire source
    - Adequate fire protection must be provided
    - Consideration must be provided for containment and drainage of fire water
    - Leak detection must be provided

Pool Fire-2

- Component of pool fire model
  - Burning rate
  - Pool size
  - Flame geometry including height, tilt and drag
  - Flame surface emitted power
  - Geometric view factor with suspect to the receiving source
  - Atmospheric transmissivity
  - Received thermal flux

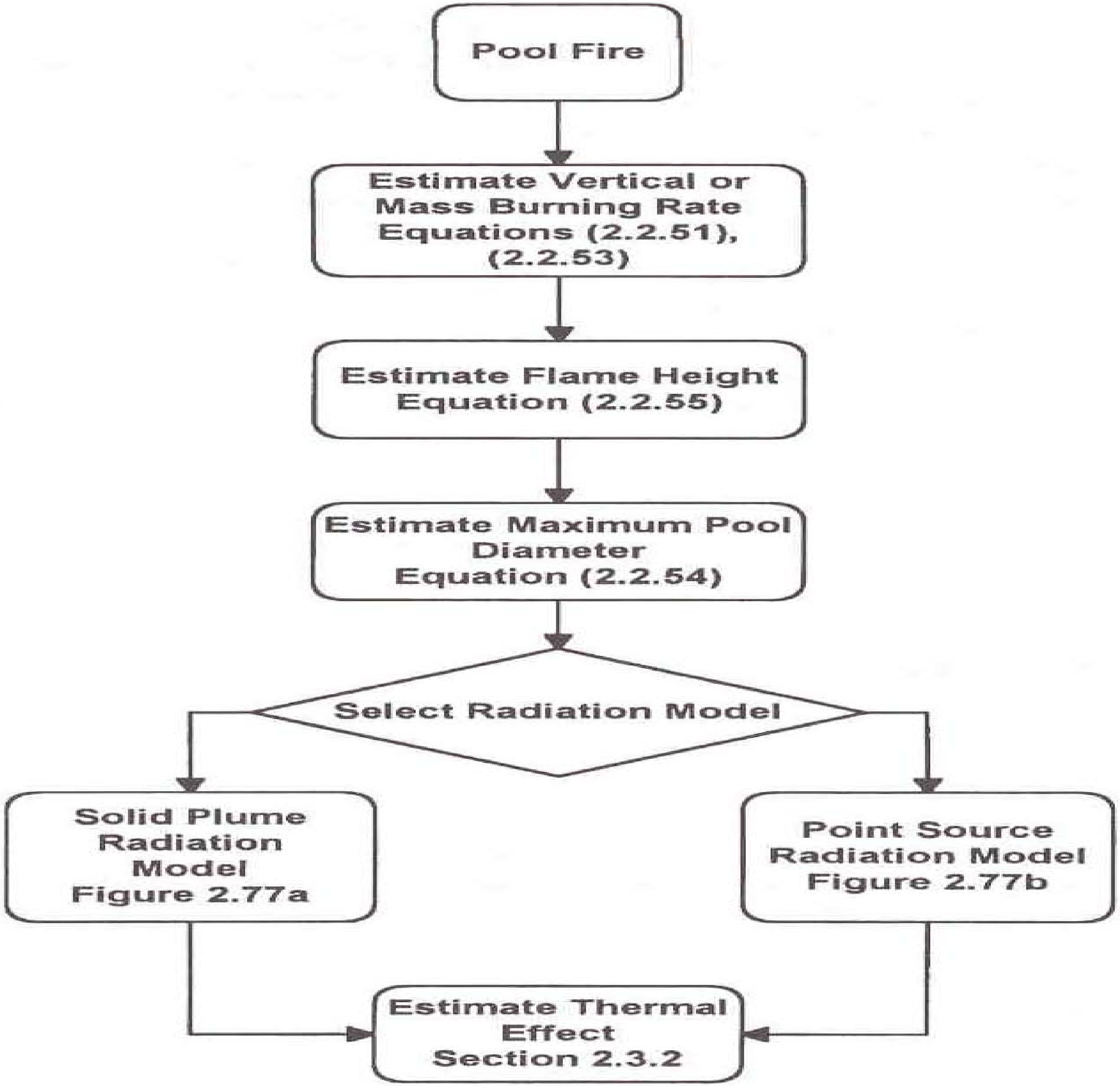

FIGURE 2.77. Logic diagram for calculation of pool fire radiation effects.

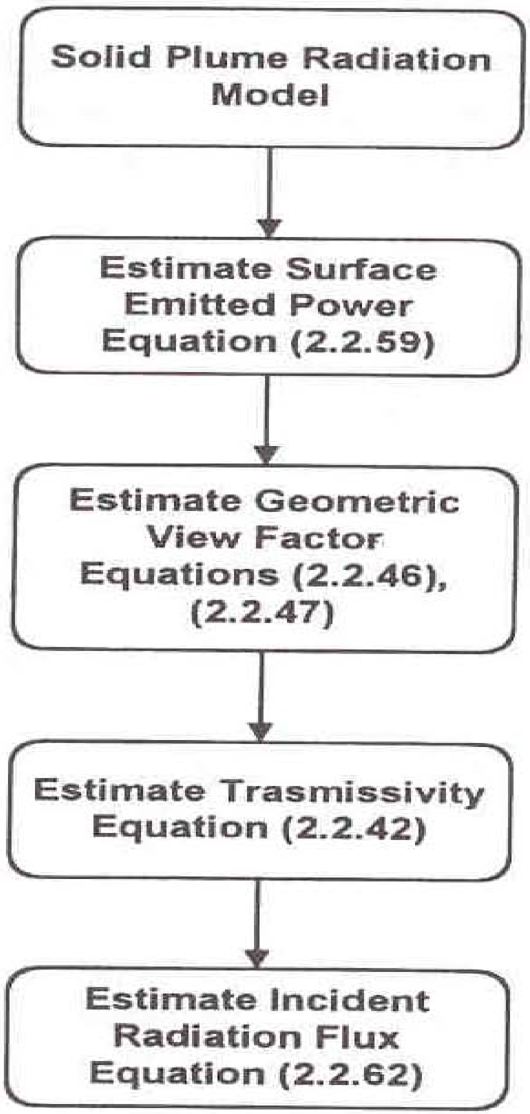

FIGURE 2.77a. Logic diagram for the solid plume radiation model.

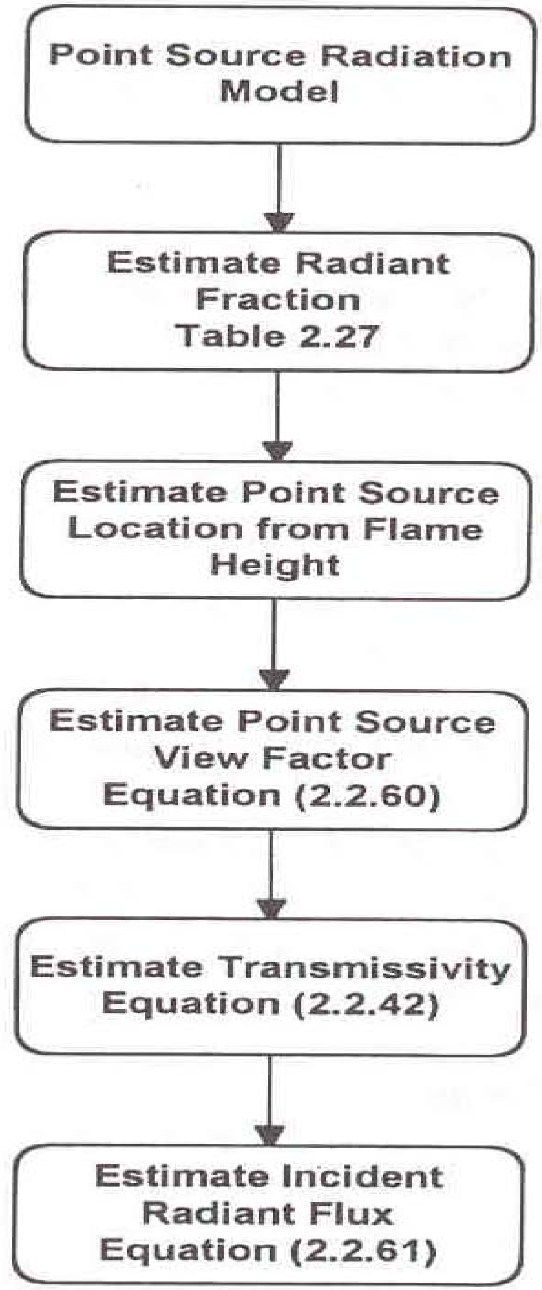

FIGURE 2.77b. Logic diagram for the point source radiation model.

Pool Fire-3

- Burning rate
  - Radiative heat transfer and the resulting burning rate increases with pool diameter

$$m_B = 1\times10^{-3}\frac{\Delta H_C}{\Delta H^*}$$

  - m_B is the mass burning rate(kg/m^2s)
  - ΔH_c is the net heat of combustion(energy/mass)
  - ΔH^* is the modified heat of vaporization at the boiling point of the liquid by following equation

$$\Delta H^* = \Delta H_V + \int_{T_a}^{T_{BP}} C_p dT$$

    - ΔH_v is the heat of vaporization at the ambient temperature(energy/mass)
    - C_p is the heat capacity of the liquid(energy/mass-deg)

Pool Fire-4

- Pool size
  - Pool size is fixed by the size of the release and by local physical barriers(e.g., dikes, sloped drainage area)

$$D_{max} = 2\sqrt{\frac{\dot{V}_L}{\pi \dot{y}}}$$

- D_{max} is the equilibrium diameter of the pool(length)
- V_L is the volumetric liquid spill rate(volume/time)
- y is the liquid burning rate(length/time)
  - Assume that burning rate is constant and that the dominant heat transfer is from flame

Pool Fire-5

- Flame height for circular pool fire (Thomas, 1963)

$$\frac{H}{D} = 42\left(\frac{m_B}{\rho_a\sqrt{gD}}\right)^{0.61}$$

- H is the visible flame height(m)
- D is the equivalent pool diameter(m)
- m_B is the mass burning rate(kg/m^2s)
- ρ_a is the air density($1.2 kg/m^3$ at 20C and 1 atm)
- g is the acceleration of gravity($9.81 m/s^2$)

Pool Fire-6

- Flame height based on large-scaled LNG test (Moorehouse, 1982)
  - Includes the effect of wind on flame length

$$\frac{H}{D} = 6.2\left[\frac{m_B}{\rho_a\sqrt{gD}}\right]^{0.254} u_{10}^{*\,-0.044}$$

- u_{10}^{*} is a nondimensional wind speed determined using

$$u_{10}^{*} = \frac{u_w}{\left[(g m_B D)/\rho_V\right]^{1/3}}$$

  - u_w is the measured wind speed at a 10 m height(m/s)
  - ρ_v is the vapor density at the boiling point of the liquid(kg/m^3)

Pool Fire-7

- Flame tilt and drag
  - These effect alter the radiation received at surrounding location
  - AGA(American Gas Association) suggest the following correlation

$$\cos\theta = 1 \quad \text{for} \quad u^* \leq 1$$

$$\cos\theta = \frac{1}{\sqrt{u^*}} \quad \text{for} \quad u^* \geq 1$$

- u* is the nondimensional wind speed at height of 1.6 m and θ is the flame tile angle

Pool Fire-8

- Surface emitted power
  - Two approach for estimating the surface emitted power
    - Point source model
    - Solid plume radiation model
  - Point source model
    - Based on the total combustion energy rate
    - Include smoke absorption of radiated energy
    - Estimating procedure
      - Calculate total combustion power(based on burning rate and total pool area)
      - Multiply by the radiation fraction to determine total power radiated(commonly use 0.15-0.35 by table 2.27)
      - Determine flame surface area(commonly use only the cylinder side area)
      - Divide radiated power by flame surface area

Pool Fire-9

- Solid plume radiation model
  - Considering amount of soot are generated, obscuring the radiating flame from the surroundings, and absorbing much of the radiation
  - As the diameter of the pool fire increases, the emitted flux decreases.
  - Model for sooty pool fire of high molecular weight hydrocarbon using these effect (Mudan and Croce, 1988)

$$E_{av} = E_m e^{-SD} + E_s\left(1 - e^{-SD}\right)$$

- E_{av} is the average emissive power(kW/m^2)
- E_m is the maximum emissive power of the luminous spots(approximately 140kW/m^2)
- E_s is the emissive power of smoke(approximately 20kW/m^2)
- S is the experimental parameter
- D is the diameter of the pool(m)

TABLE 2.27. The Fraction of Total Energy Converted to Radiation for Hydrocarbons (Mudan and Croce, 1988)

Fuel	Fraction
Hydrogen	0.20
Methane	0.20
Ethylene	0.25
Propane	0.30
Butane	0.30
C_5 and higher	0.40

Pool Fire-10

- Geometric view factor
  - For point source model
    - Assume that all radiation arises from a single point and is received by an object perpendicular to this

$$F_P = \frac{1}{4\pi\pi^2}$$

      - F_p is the point source view factor(length^{-2})
      - x is the distance from the point source to target(length)
  - For the solid plume model
    - The view factor provided in Figure 2.78 for untilted flame, figure 2.79 for tilted flame

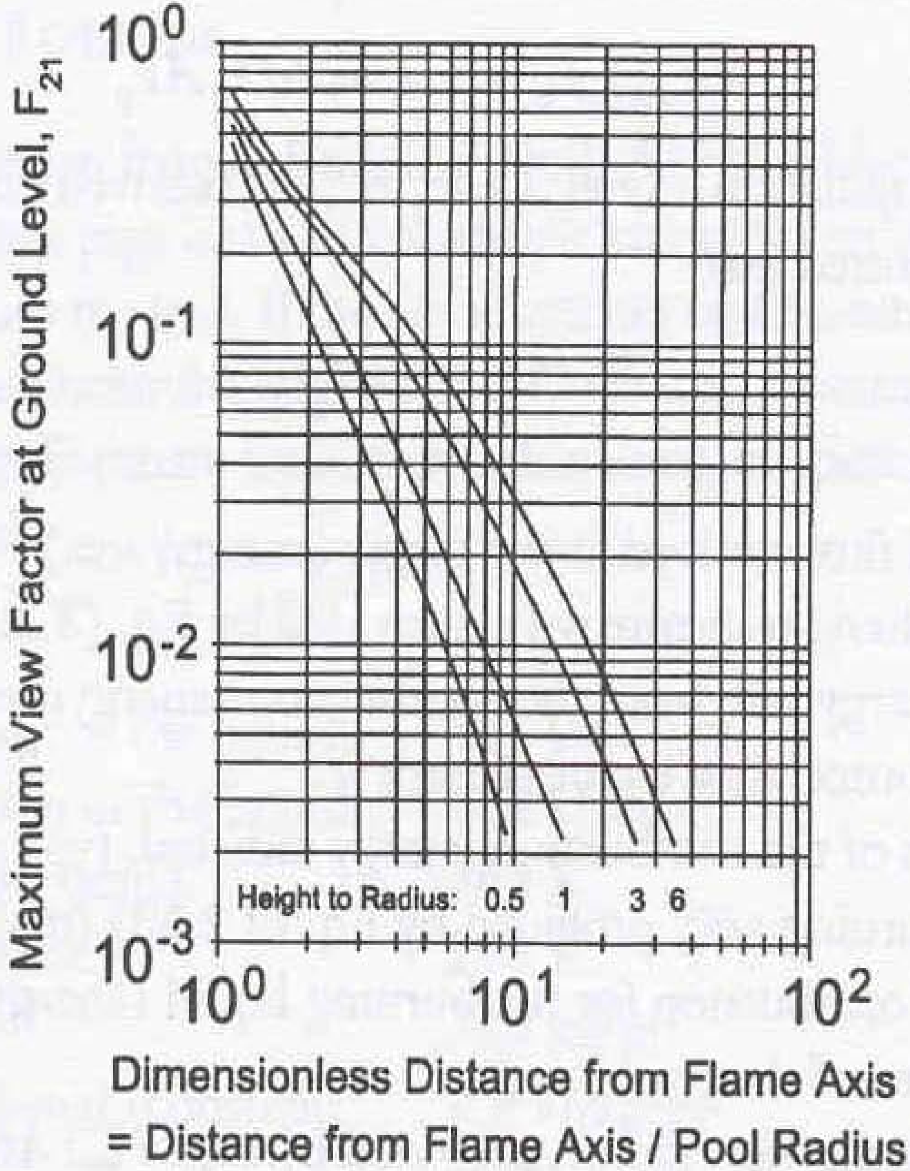

FIGURE 2.78. Maximum view factors for a ground-level receptor from a right circular cylinder (Mudan and Croce, 1988).

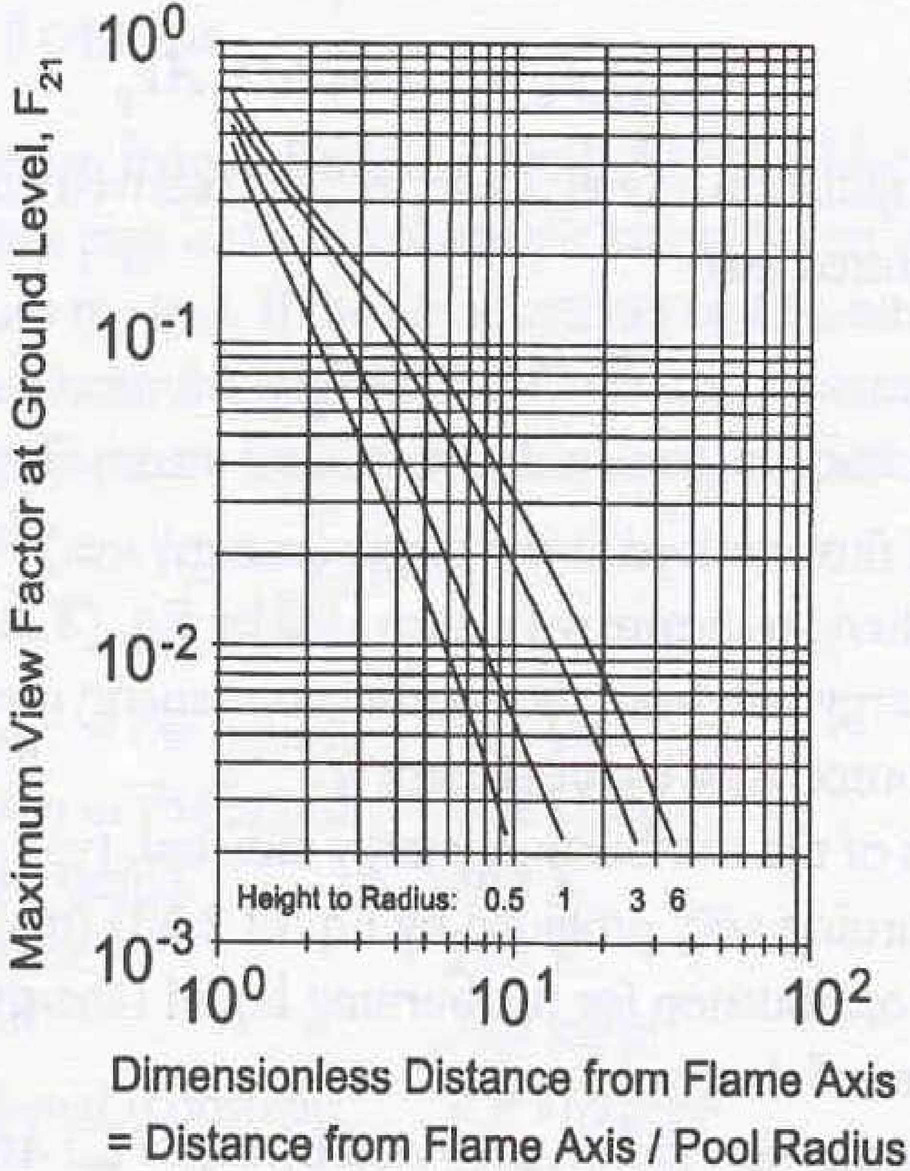

FIGURE 2.78. Maximum view factors for a ground-level receptor from a right circular cylinder (Mudan and Croce, 1988).

Pool Fire-11

- Received thermal flux
  - For point source model
    - Determined from of the total energy rate from the combustion process

$$E_r = \tau_a Q_r F_P = \tau_a \eta m_B \Delta H_c A F_P$$

  - For solid plume radiation model
    - Based on correlations of the surface emitted flux

$$E_r = \tau_a \Delta H_c F_{21}$$

      - E_r is the thermal flux received at the target(energy/area)
      - τ_a is the atmospheric transmissivity(uintless)
      - Q_r is the total energy rate from the combustion(energy/time)
      - F_p is the point source view factor(length^{-2})
      - η is the fraction of the combustion energy radiated, typically 0.15 to 0.35
      - m_B is the mass burning rate(mass/area-time)
      - ΔHc is the heat of combustion for burning liquid(energt/mass)
      - A is the total area of the pool(length^2)
      - F_{21} is the solid plume view factor

Jet Fire

- Jet fire
  - Typically result from the combustion of a material as it is being released from a pressurized process unit
  - API method(1996)
    - Based on the radiant fraction of total combustion energy, which is assumed to rise from a point source along jet flame path
  - Mudan and Croce(1988)
    - Provide the model to calculate the flame height(equation 2.2.63)
  - Radiative heat flux
    - Using a procedure similar to the point source method described for pool fires

$$E_r = \tau_a Q_r F_P = \tau_a \eta \dot{m} \Delta H_c F_P$$

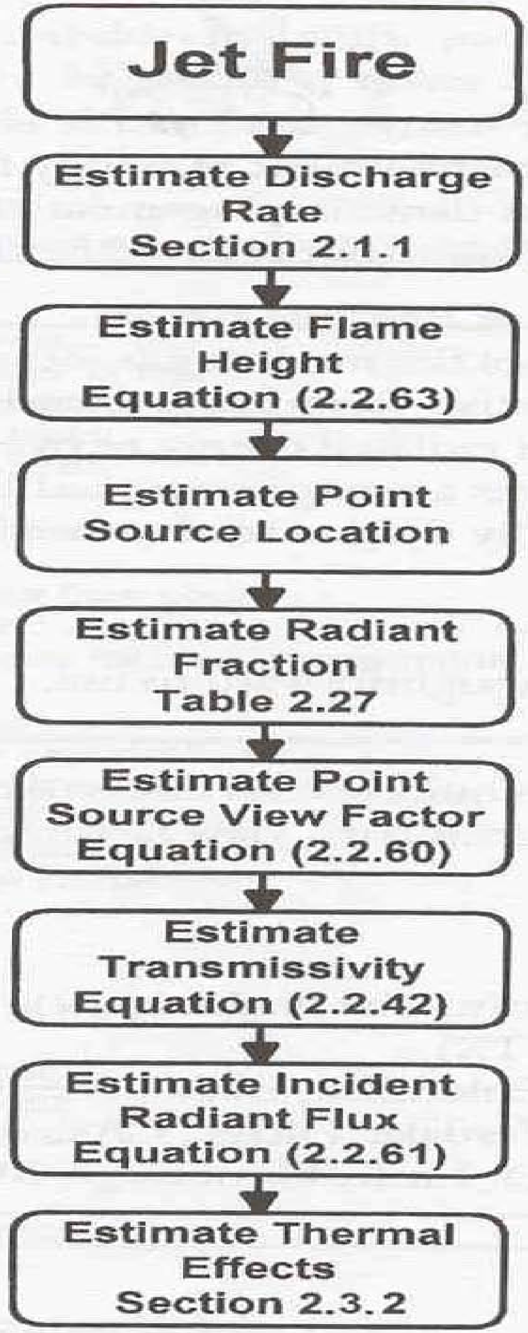

FIGURE 2.82. Logic diagram for the calculation of jet fire radiation effects.

Effect Model

- Effect model
  - To calculate the effect on human beings, consequences may be expressed as deaths or injuries and property such as structure and buildings
  - Predicts effects on people or structures based on predetermined criteria
  - The probit method reflects a generalized time-dependent relationship for any variable that has a probabilistics outcome that can be defined by a normal distribution
    - Can be applied toxic, thermal and explosion effect

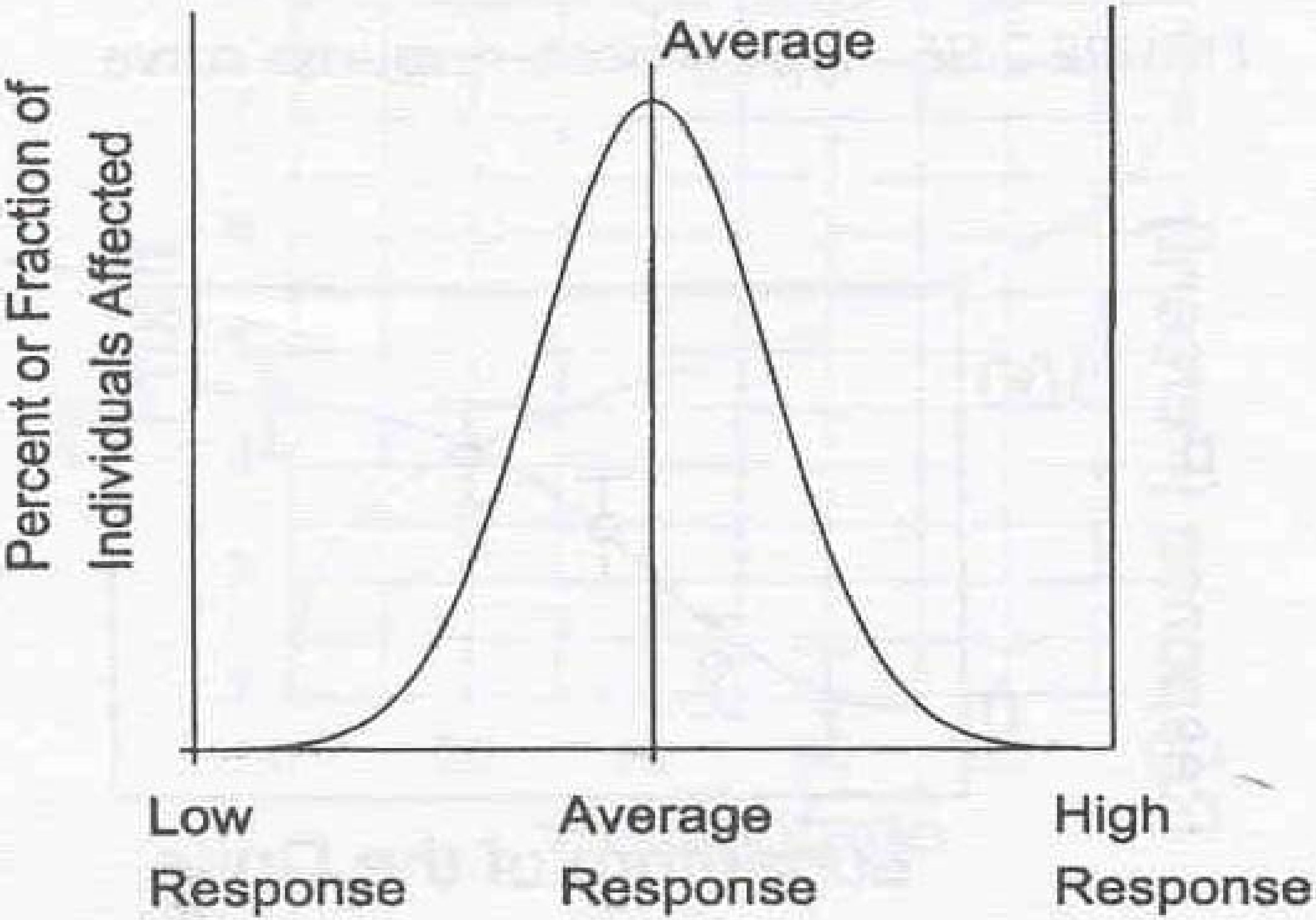

FIGURE 2.85. Typical Gaussian or bell-shaped curve.

Dose-Response Function

- Dose-response function
  - Difficult to evaluate precisely the human caused by an acute, hazardous exposure due to following reason
    - Humans experience a wide range of acute adverse health effects including irritation, narcosis, asphyxiation, organ system damage and death
    - There is a high degree of variation in response among individuals in typical population
      - Such as age, health etc.
  - Figure 2.85 explain the relation percent of individual affected and response
    - Within one standard deviation, 68% of the individual organisms response, in case of two standard deviation, 95.5 %of the total individual

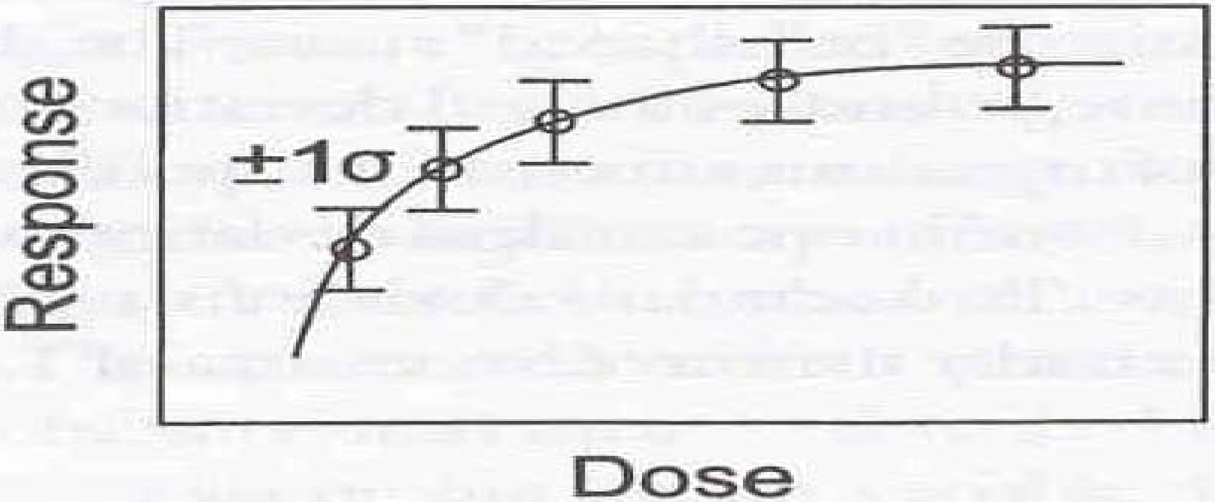

FIGURE 2.86. Typical dose–response curve.

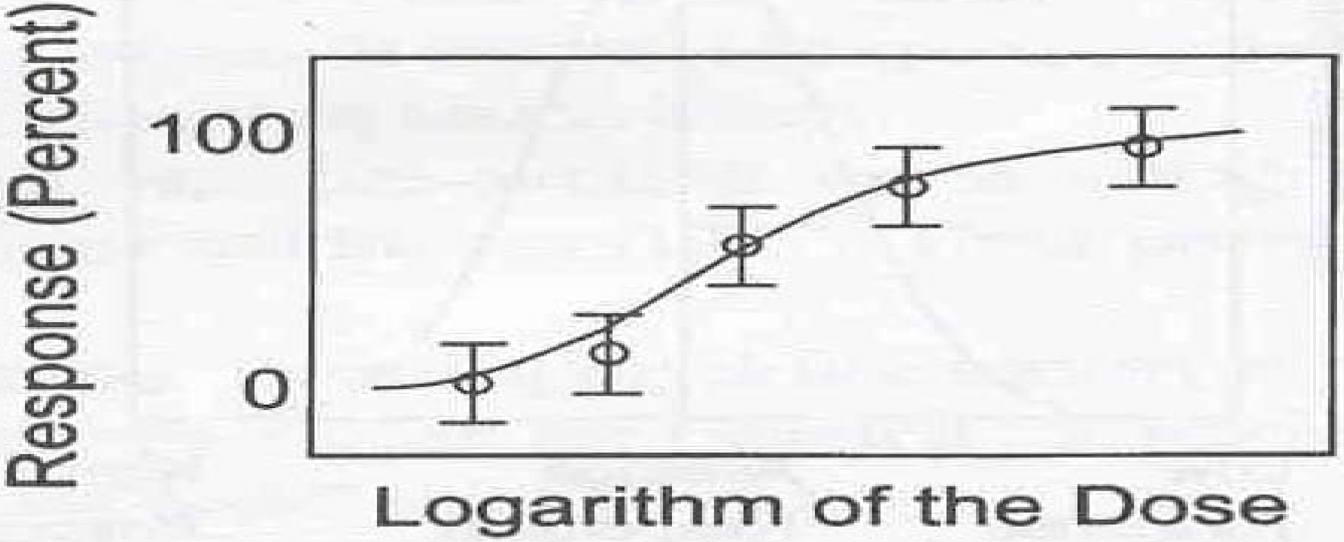

FIGURE 2.87. Typical response versus log(dose) curve.

Probit Function

- Probit function
  - Available for a variety of exposures including exposure to toxic materials, heat, pressure, radiation, impact and sound
  - General form of probit equation

$$Y = k_1 + k_2 \ln V$$

- Y is the probit variable
- k_1 and k_2 is the constants

TABLE 2.28. Conversion from Probits to Percentages

%	0	1	2	3	4	5	6	7	8	9
0	—	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33
%	**0.0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
99	7.33	7.37	7.41	7.46	7.51	7.58	7.65	7.75	7.88	8.09

Toxic Gas Effect-1

- Toxic effect model
  - Assess the consequences to human health as a result of exposure to a known concentration of toxic gas for a known period of time
  - Toxicologic criteria and methods
    - Emergency Response Planning Guidelines for Air Contaminant (ERPGs) issued by AIHA(American Industrial Hygiene Association)
    - Immediately Dangerous to Life or Health (IDLH) established by NIOSH(National Institute for Occupational Safety and Health)
    - Emergency Exposure Guidance Levels (EEGLS) and Short-Term Public Emergency Guidance Levels (SPEGLs) issued by National Academy of Science
    - Threshold Limit Values (TLVs) established by ACGIH(American Conference of Governmental Industrial Hygienists)
    - Permissible Exposure Limit (PELs) promulgated by OSHA(Occupational Safety and Health Administration)

Toxic Gas Effect-2

- ERPGs
  - Provide a consequence of exposure to a specific substance
    - ERPG1
      - Maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hr without experiencing any symptoms other than mild transient adverse health effects or without perceiving a clearly defined objectionable odor
    - ERPG2
      - Maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hr without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action
    - ERPG3
      - Maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hr without experiencing or developing life-threatening health effects

TABLE 2.29. Emergency Response Planning Guidelines, ERPGs (AIHA, 1996). All values are in ppm unless otherwise noted. Values are updated regularly.

Chemical	ERPG-1	ERPG-2	ERPG-3
Acetaldehyde	10	200	1000
Acrolein	0.1	0.5	3
Acrylic Acid	2	50	750
Acrylonitrile	NA	35	75
Allyl Chloride	3	40	300
Ammonia	25	200	1000
Benzene	50	150	1000
Benzyl Chloride	1	10	25
Bromine	0.2	1	5
1,3-Butadiene	10	50	5000
n-Butyl Acrytate	0.05	25	250
n-Butyl Isocyanate	0.01	0.05	1
Carbon Disulfide	1	50	500
Carbon Tetrachloride	20	100	750
Chlorine	1	3	20
Chlorine Trifluouride	0.1	1	10
Chloroacetyl Chloride	0.1	1	10
Chloropicrin	NA	0.2	3
Chlorosulfonic Acid	2 mg/m^3	10 mg/m^3	30 mg/m^3
Chlorotrifluoroethylene	20	100	300
Crotonaldehyde	2	10	50
Diborane	NA	1	3
Diketene	1	5	50
Dimethylamine	1	100	500
Dimethylchlorosilane	0.8	5	25
Dimethyl Disulfide	0.01	50	250
Epichlorohydrin	2	20	100
Ethylene Oxide	NA	50	500
Formaldehyde	1	10	25
Hexachlorobutadiene	3	10	30
Hexafluoroacetone	NA	1	50
Hexafluoropropylene	10	50	500
Hydrogen Chloride	3	20	100
Hydrogen Cyanide	NA	10	25
Hydrogen Fluoride	54	20	50
Hydrogen Sulfide	0.1	30	100
Isobutyronitrile	10	50	200
2-Isocyanatoethyl Methacrylate	NA	0.1	1
Lithium Hydride	25 μgm/m^3	100 μgm/m^3	500 μgm/m^3
Methanol	200	1000	5000

(continued)

Toxic Gas Effect-3

- IDLHs
  - Defined as a condition "that poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment"
  - Currently available for 380 materials
- EEGLs and SPEGLs
  - EEGL is define as a concentration of a gas, vapor or aerosol that is judged to be acceptable and that will allow healthy military personnel to perform specific tasks during emergency conditions lasting from 1 to 24 hr
  - SPEGLs defined as acceptable concentrations for exposures of members of the general public

Toxic Gas Effect-4

- TLV-STEL
  - Maximum concentration to which workers can be exposed for a period of up to 15 minutes without suffering
    - Intolerable irritation
    - Chronic or irreversible tissue change
    - Narcosis of sufficient degree to increase accident proneness
- PEL
  - Similar to the ACGIH criteria for TLV-TWAs since they are also based on 8-hr time-weighted average exposure
- Toxic endpoints
  - Used for air dispersion modeling of toxic gas released as part of the EPA Risk Management Plan(RMP)
  - Use ERPG2 or LOC(Level of Concern) by Emergency Planning and Community Right-to-Know Act

TABLE 2.32. Probit Equation Constants for Lethal Toxicity

The probit equation is of the form

$$Y = a + b \ln(C^n t_e)$$

where

Y is the probit
a, b, n are constants
C is the concentration in ppm by volume
t_e is the exposure time in minutes

Substance	U.S. Coast Guard (1980)			World Bank (1988)		
	a	b	n	a	b	n
Acrolein	−9.931	2.049	1	−9.93	2.05	1.0
Acrylonitrile	−29.42	3.008	1.43			
Ammonia	−35.9	1.85	2	−9.82	0.71	2.00
Benzene	−109.78	5.3	2			
Bromine	−9.04	0.92	2			
Carbon Monoxide	−37.98	3.7	1			
Carbon Tetrachloride	−6.29	0.408	2.50	0.54	1.01	0.5
Chlorine	−8.29	0.92	2	−5.3	0.5	2.75
Formaldehyde	−12.24	1.3	2			
Hydrogen Chloride	−16.85	2.00	1.00	−21.76	2.65	1.00
Hydrogen Cyanide	−29.42	3.008	1.43			
Hydrogen Fluoride	−25.87	3.354	1.00	−26.4	3.35	1.0
Hydrogen Sulfide	−31.42	3.008	1.43			
Methyl Bromide	−56.81	5.27	1.00	−19.92	5.16	1.0
Methyl Isocyanate	−5.642	1.637	0.653			
Nitrogen Dioxide	−13.79	1.4	2			
Phosgene	−19.27	3.686	1	−19.27	3.69	1.0
Propylene Oxide	−7.415	0.509	2.00			
Sulfur Dioxide	−15.67	2.10	1.00			
Toluene	−6.794	0.408	2.50			

Thermal Effects

- Two approaches are used
  - Simple tabulations or charts based on experimental results
  - Theoretical models based on the physiology of skin burn response
  - Probit model(Eisenberg, 1975)

$$Y = -14.9 + 2.56 \ln\left(\frac{tI^{4/3}}{10^4}\right)$$

- Y is the probit
- t is the duration of exposure(sec)
- I is the thermal radiation intensity(W/m^2)

TABLE 2.33. Exposure Time Necessary to Reach the Pain Threshold (API, 1966a)

Radiation intensity ($Btu/hr/ft^2$)	kW/m^2	Time to pain threshold (s)
500	1.74	60
740	2.33	40
920	2.90	30
1500	4.73	16
2200	6.94	9
3000	9.46	6
3700	11.67	4
6300	19.87	2

TABLE 2.34. Recommended Design Flare Radiation Levels Excluding Solar Radiation (API, 1996a)

Permissible design level (K)		
Btu/hr/ft²	kW/m²	Conditions[a]
5000	15.77	Heat intensity on structures and in areas where operators are not likely to be performing duties and where shelter from radiant heat is available, for example, behind equipment
3000	9.46	Value of K at design flare release at any location to which people have access, for example, at grade below the flare or on a service platform of a nearby tower. Exposure must be limited to a few seconds, sufficient for escape only
2000	6.31	Heat intensity in areas where emergency actions lasting up to 1 min may be required by personnel without shielding but with appropriate clothing
1500	4.73	Heat intensity in areas where emergency actions lasting several minutes may be required by personnel without shielding but with appropriate clothing
500	1.58	Value of K at design flare release at any location where personnel are continuously exposed

[a] On towers or other elevated structures where rapid escape is not possible, ladders must be provided on the side away from the flare, so the structure can provide some shielding when K is greater than 200 Btu/hr/ft^2 (6.31 kW/m^2).

TABLE 2.35. Effects of Thermal Radiation (World Bank, 1985)

Radiation intensity (kW/m^2)	Observed effect
37.5	Sufficient to cause damage to process equipment
25	Minimum energy required to ignite wood at indefinitely long exposures (nonpiloted)
12.5	Minimum energy required for piloted ignition of wood, melting of plastic tubing
9.5	Pain threshold reached after 8 sec; second degree burns after 20 sec
4	Sufficient to cause pain to personnel if unable to reach cover within 20 s. however blistering of the skin (second degree burns) is likely; 0% lethality
1.6	Will cause no discomfort for long exposure

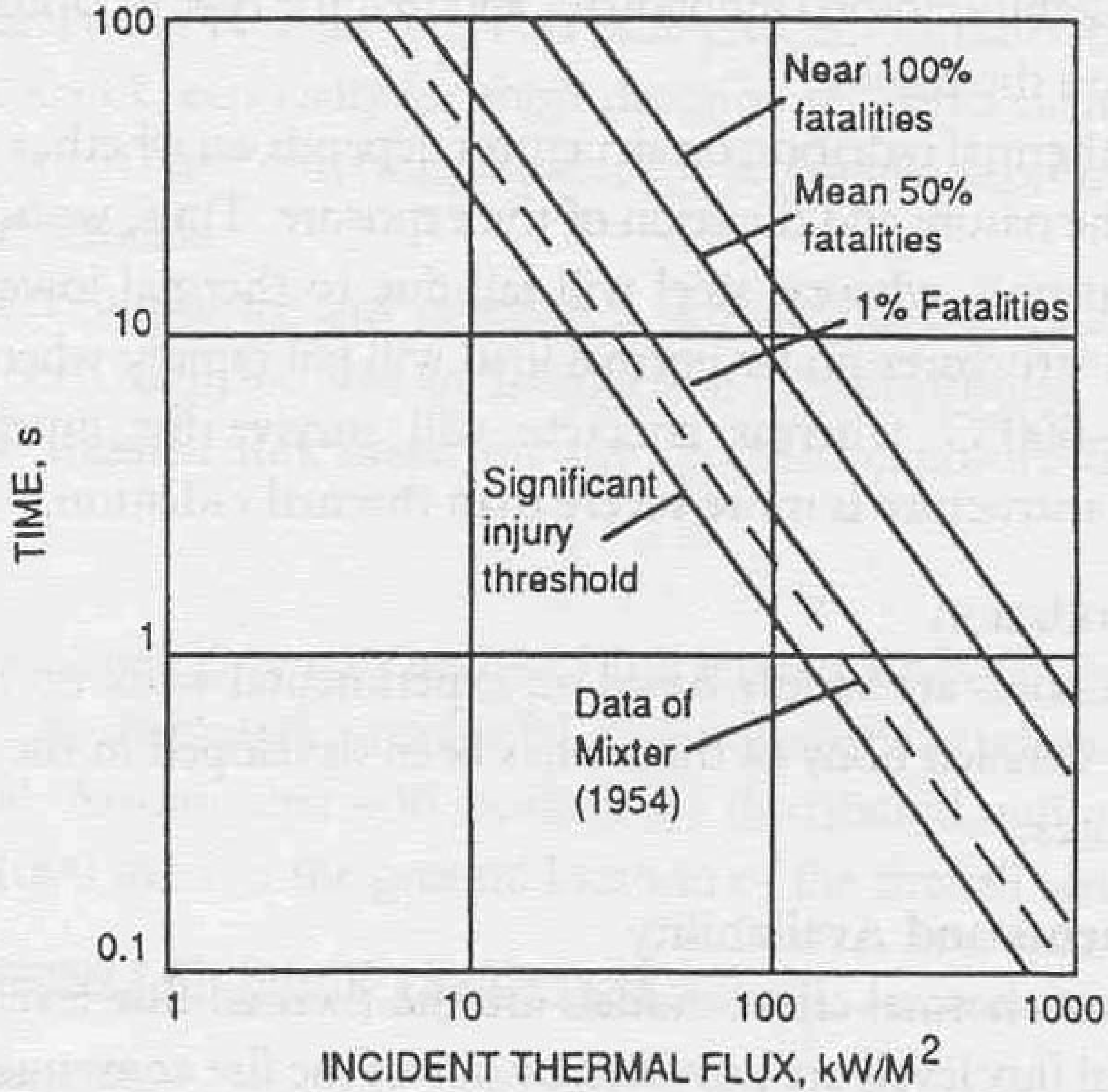

FIGURE 2.95. Serious injury/fatality levels for thermal radiation (Mudan, 1984).

Explosion Effects

- Explosion effect
  - Based on either the blast overpressure alone, or a combination of blast over pressure, duration and/or specific impulse
  - Structure

$$Y = -23.8 + 2.92\ln(P^0)$$

    - Y is the probit
    - P^0 is the peak overpressure(Pa)
    - Table 2.18a and 2.18b provide an estimate of damage expected as a function of the overpressure
  - People

$$Y = -77.1 + 6.91\ln(P^0)$$

Evasive Action

- Evasive action
  - Include evacuation, escape, sheltering and heroic medical treatment

TABLE 2.36. Benefits of Evasive Actions[a]

Hazard effect	In shelter	Escape	Escape to shelter[b] (after occurrence)	Evacuation[c] (after occurrence)
Thermal radiation				
Pool fire	Very beneficial	Very beneficial	Very beneficial	Very beneficial
Fet fire	Very beneficial	Very beneficial	Very beneficial	Very beneficial
BLEVE				
At instant BLEVE takes place	Very beneficial if shelter is far enough away from blast effects	Limited benefit (escape time limited)	Limited benefit (escape time too limited) fireball may exceed escape speed	No benefit (no evacuation time)
Pre-BLEVE	Very beneficial if shelter is far enough away from blast effects	Beneficial	Beneficial	Limited benefit (limited evacuation time, e.g., 10–30 min)
Flash fire	Limited benefit (due to vapor ingress)	Limited benefit (flame may exceed escape speed)	Limited benefit (flame may exceed escape speed)	No benefit (no evacuation time)
Explosion				
Overpressure	Increased risk of collapse of structure at lower overpressure (rather than direct fatality)	Very limited benefit (no escape time)	Very limited benefit (no escape time)	No benefit (no evacuation time)
Missiles	Limited benefit (protection from primary missiles but secondary missiles may be generated)	No benefit (no escape time)	No benefit (no escape time)	No benefit (no evacuation time)
Toxic exposure	Very beneficial (if forced ventilation is not used)	Beneficial if escape is rapid (depends on size of cloud and wind speed)	Beneficial if escape is rapid (depends on size of cloud and wind speed)	Benefits uncertain during a release

[a] The type of clothing (wool, polyester, cotton, etc.) being worn by exposed personnel influences the impact of heat radiation on the individual

[b] Escape prior to an incident is equivalent to being in shelter.

[c] Evacuation is beneficial prior to an incident where warning is given and escape time is available (but impact of rapid evacuation must be considered against possible benefits