Chapter 5

Exposure Profile Modeling

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EXPOSURE PROFILE MODELING 5

5.1 INTRODUCTION

Exposure Profile Modeling is Step 5 in the risk-informed, performance-based fire protection process. This chapter provides an introduction to the approach and methods for quantifying the exposure profile at the target, establishing consequence levels, and developing fire protection system (FPS) performance response parameters.

Step 5, which is highlighted in Fig.5.1, provides key input for Step 6, Fire Protection Performance Success, and Step 7, Risk Estimation and Comparison with Risk Tolerance.

Fig. 5.1: Risk-Informed, Performance-Based Fire Protection Steps

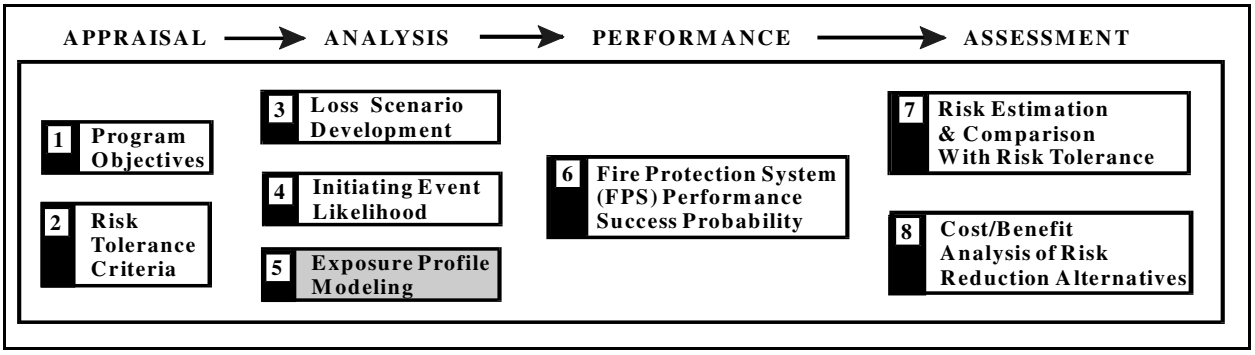


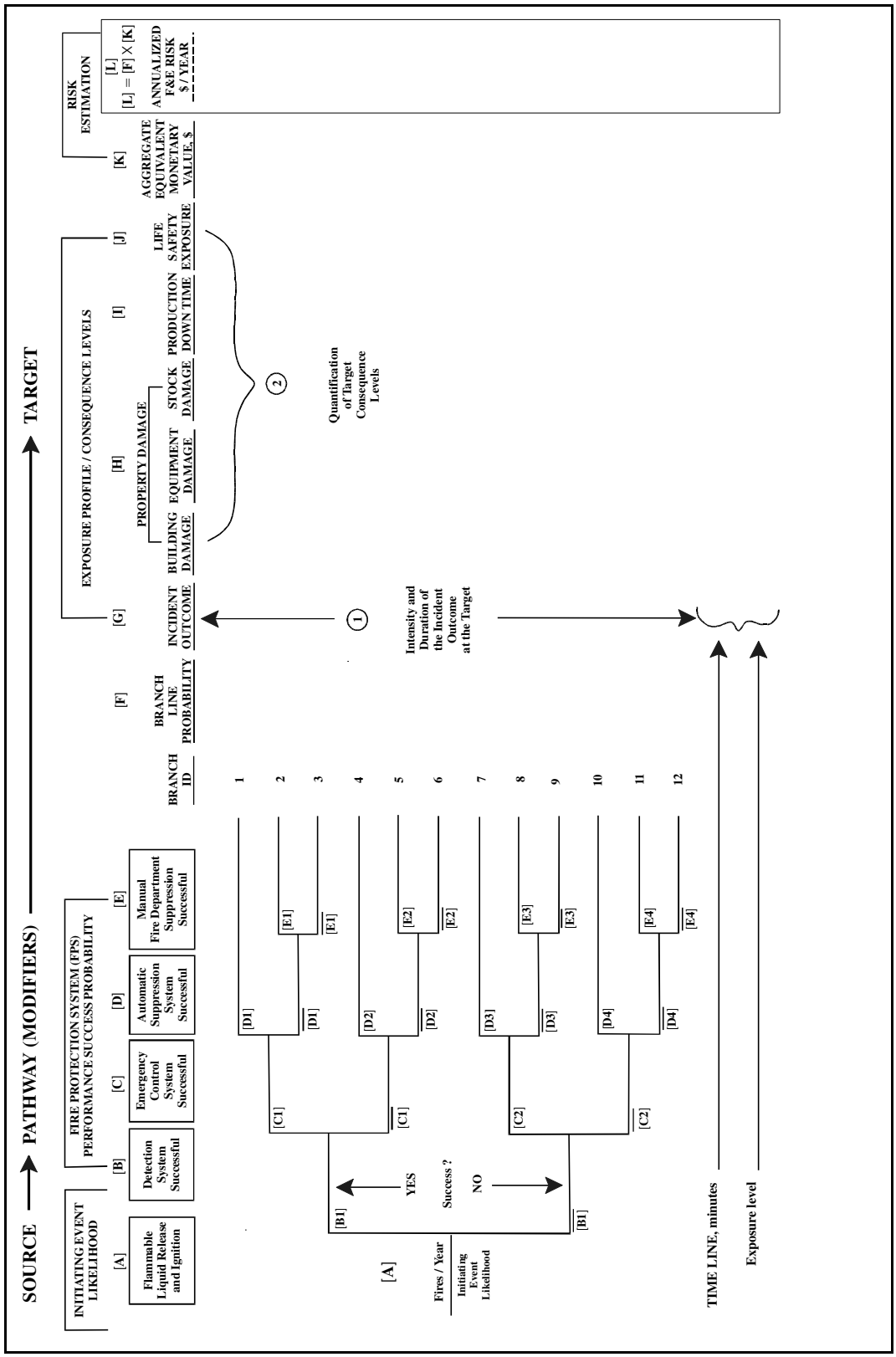
Figure 5.2 presents the general event tree fire risk modeling framework, indicating the area covered in this chapter, which is the quantification of the exposure and consequences at the target. As illustrated in Fig. 5.2, exposure and consequence evaluation involves:

① Quantification of the fire or explosion incident outcome in terms of exposure intensity versus time as seen by the target

② Quantification of the target consequence levels, including:

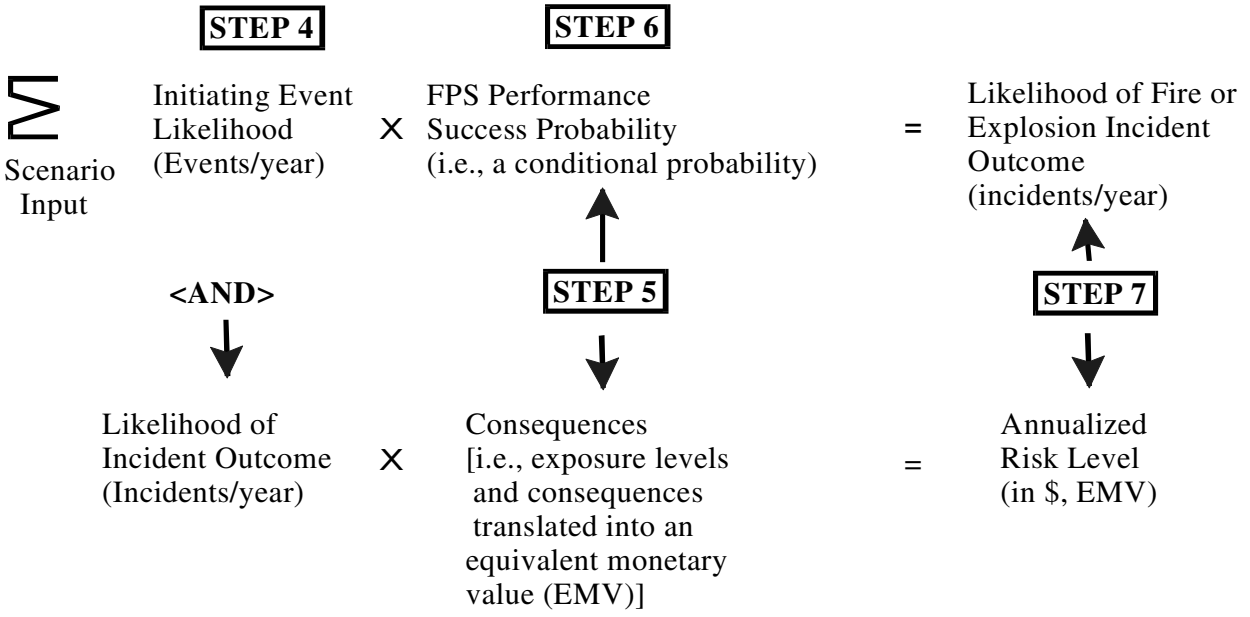
- Property damage
- Production down time
- Life safety exposure

Fig. 5.2: General Fire Risk Event Tree Structure



Risk Estimation Refresher

Exposure profile modeling, Step 5, is a key factor in developing consequence levels and establishing FPS performance success parameters:



Step 4: Initiating Event Likelihood: Provides the quantification of initiating fire events using a structured analysis approach that includes historical data, fault tree analysis (FTA), and engineering judgement.

Step 5: Exposure Profile Modeling: Provides an exposure profile of the fire or explosion source intensity versus time (at the target), which is a primary input for evaluating FPS performance and consequential outcomes.

Step 6: FPS Success Probability: Based on the input from Steps 4 and 5, the conditional probability (a number between 0 and 1) of the FPS is estimated based on performance measures that include response effectiveness, availability, and operational reliability.

Step 7: Risk Estimation and Comparison: The annualized risk level is the product of Steps 4, 5, and 6. The annualized risk is usually expressed as an EMV to allow cost/benefit analysis of risk reduction alternatives (Step 8) if the risk tolerance criteria are exceeded.

5.1.1 Exposure Profile Modeling Approach

To have fire risk, there must be:

- A target that has value and is vulnerable to loss
- An exposure from a fire or explosion incident that exceeds the damage threshold limits of the target

The general modeling approach used for exposure assessment involves the following:

1. Determine the vulnerability of the target or targets. Vulnerability is defined in terms of threshold damage limits (TDLs). TDLs are potential failure limits of the target subsystems and components (equipment, operators, structure, etc.) when exposed to fire or explosion impacts. Based on the TDLs of the target components, system-based exposure damage limits can be established.
2. Characterize the initiating fire or explosion source intensity. For fire scenarios, developing and quantifying the initiating source heat release rate (HRR) in a credible manner is a key consideration in the initial development of the exposure profile. The HRR is used to estimate flame height, radiant heat flux, and fire plume size and intensity, all of which affect the exposure at the target.
3. Model the event tree scenario fire or explosion incident outcome. Pool fires, torch fires, unconfined spill fires, flash fires, BLEVE fireballs, solid materials, and storage configurations can be modeled to evaluate radiant heat flux, temperatures, and smoke concentration intensities at the target. Unconfined vapor cloud explosions and confined explosions can be modeled to evaluate potential explosion overpressures at the target.
4. Establish exposure profile consequence levels. By relating the incident outcome modeling to the target's TDLs, potential consequence levels for property damage (equipment, stock, structure) and life safety exposure can be established. This is commonly presented in terms of a graphical exposure profile presentation.
5. Develop FPS response parameters. Based on the exposure profile, response times for detection systems, emergency shutdown systems, and automatic and manual fire suppression system, can be established and shown in the event tree time line. These response times are then used in the FPS performance success probability evaluation (Step 6).

An exposure profile is a graphical representation of what the target may be subject to in terms of source intensity and duration, based on a specific event tree scenario. Figure 5.3 presents an example of the relationship between the fire risk event tree and a fire exposure profile. As shown below the event tree, the exposure profile is a dynamic, time-related graphical depiction of the fire growth and propagation based on a defined initiating event and assuming an uncontrolled scenario (i.e., branch line 12 in Fig. 5.3 indicates a sequence of unsuccessful FPS stages). Developing this type of graphical exposure profile provides a tool for evaluating the exposure and potential consequence levels at the target versus time.

Fig. 5.3: Illustration of Relationship Between the Fire Event Tree Analysis and Fire Exposure Profile

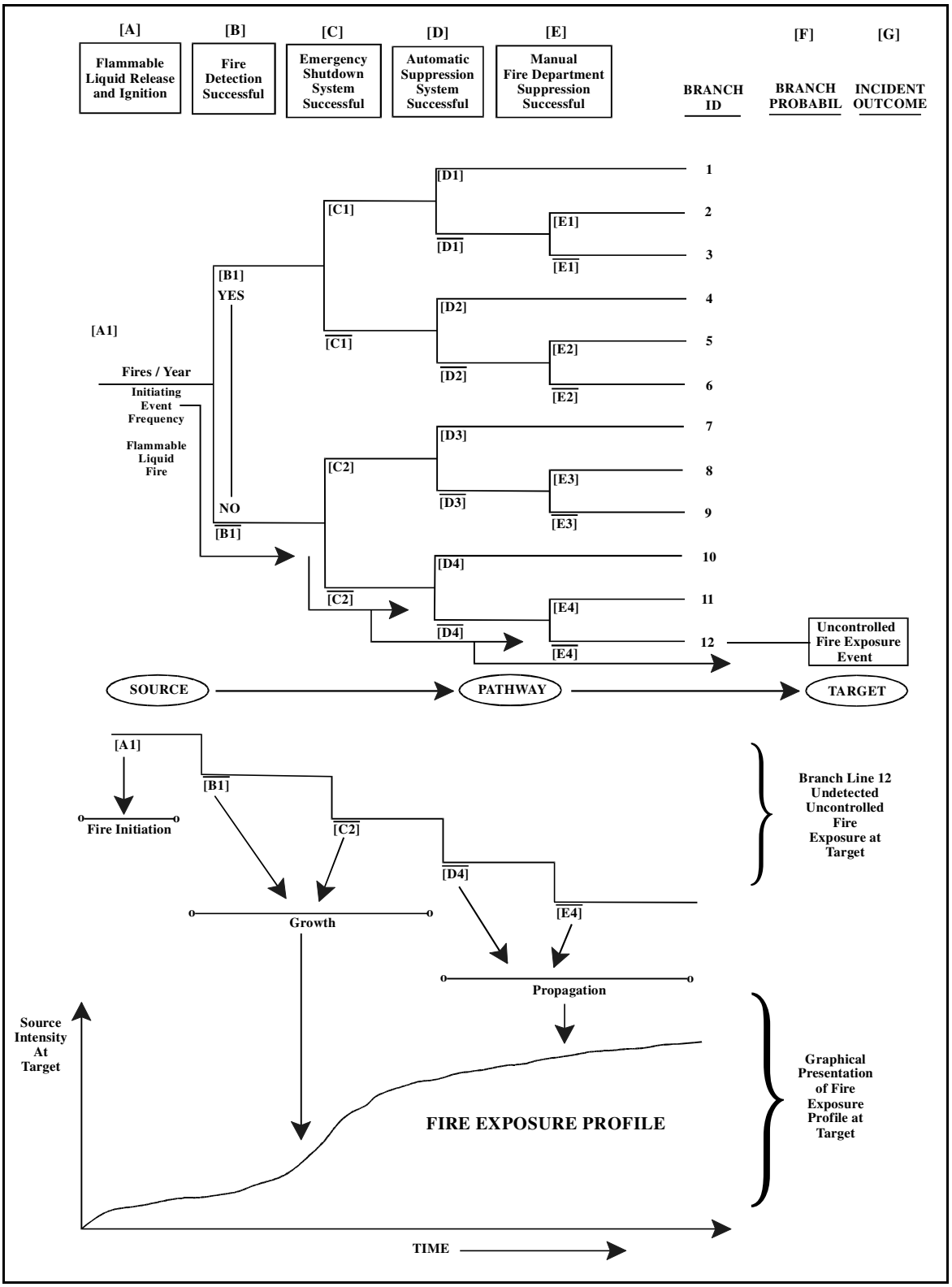
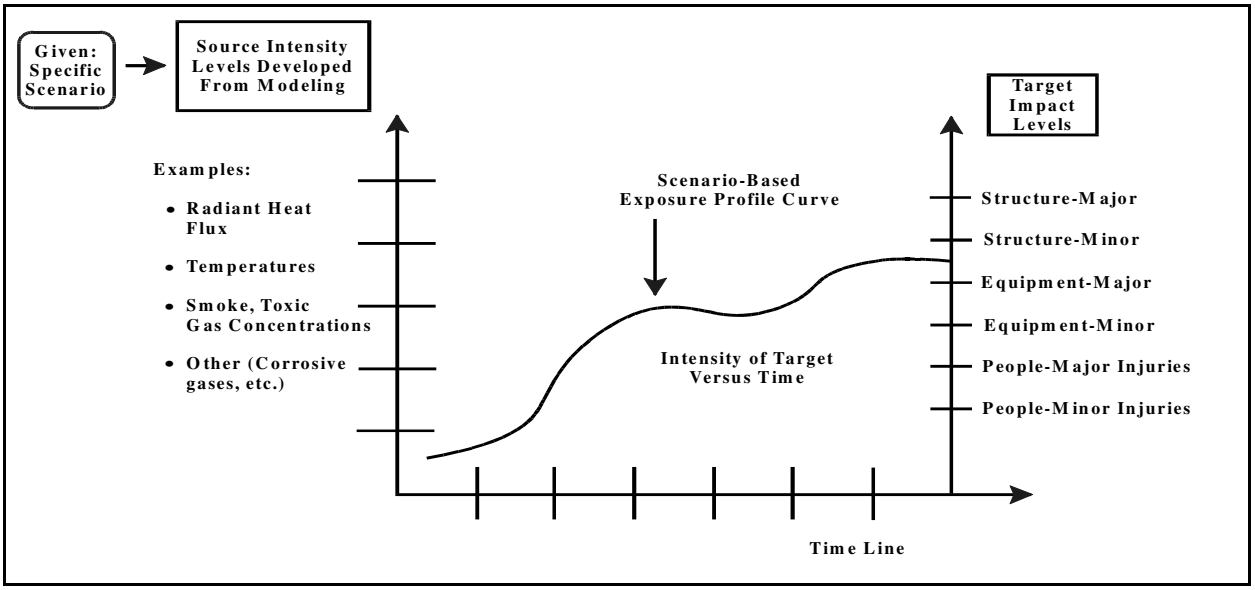


Figure 5.4 presents a general example of a fire exposure profile illustrating that the fire exposure assessment could include multiple exposure concerns such as radiant heat flux, temperatures, concentration levels of smoke, toxic gases, corrosive gases, etc. Based on the source intensity pathway (transport) modeling and the target TDLs, the impact and consequence levels at the target can be estimated.

Fig. 5.4: General Example-Fire Exposure Graphical Profile



Fire and Explosion Dynamics

This chapter introduces the methodology of exposure profile modeling as related to event tree analysis (ETA) and is not intended to provide detailed information on fire and explosion dynamics and modeling techniques. At least one member of the project team performing the risk-informed, performed-based assessment should have expertise in the theory, applications, and limitations of fire and explosion modeling approaches. Two indispensable references are listed in the following box.

Fire and Explosion Dynamics and Modeling References

- The SFPE Handbook of Fire Protection Engineering, Published by the Society of Fire Protection Engineers and the National Fire Protection Association, Quincy, MA.[1]
- Guidance for Consequence Analysis of Chemical Releases, Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, N.Y., 1999.[2]

5.2 TARGET THRESHOLD DAMAGE LIMITS

The first step in the exposure profile modeling process is to establish target TDLs. TDLs provide a vulnerability measurement tool by establishing ranges and limits of target component and system damage potential from fire or explosion exposures.

As depicted in Fig. 5.5, the TDL evaluation focuses on defined target boundaries, which can include people, equipment, and structural aspects.

Fig. 5.5: Example Target Vulnerability Evaluation Approach

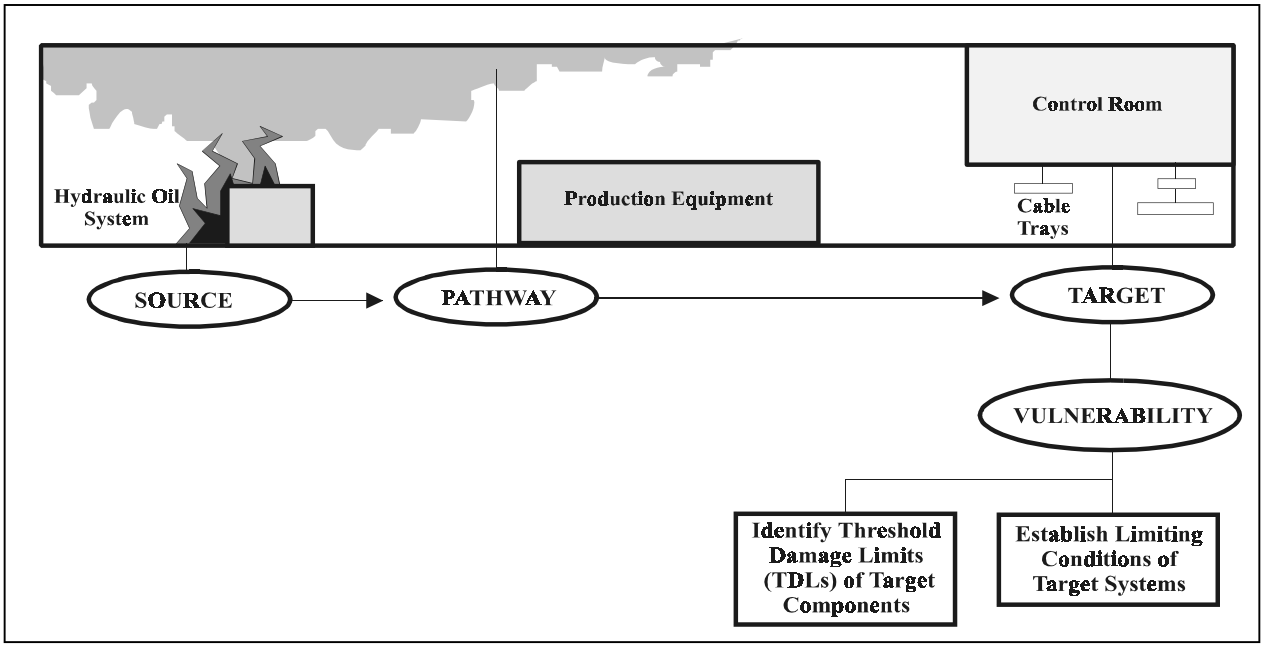


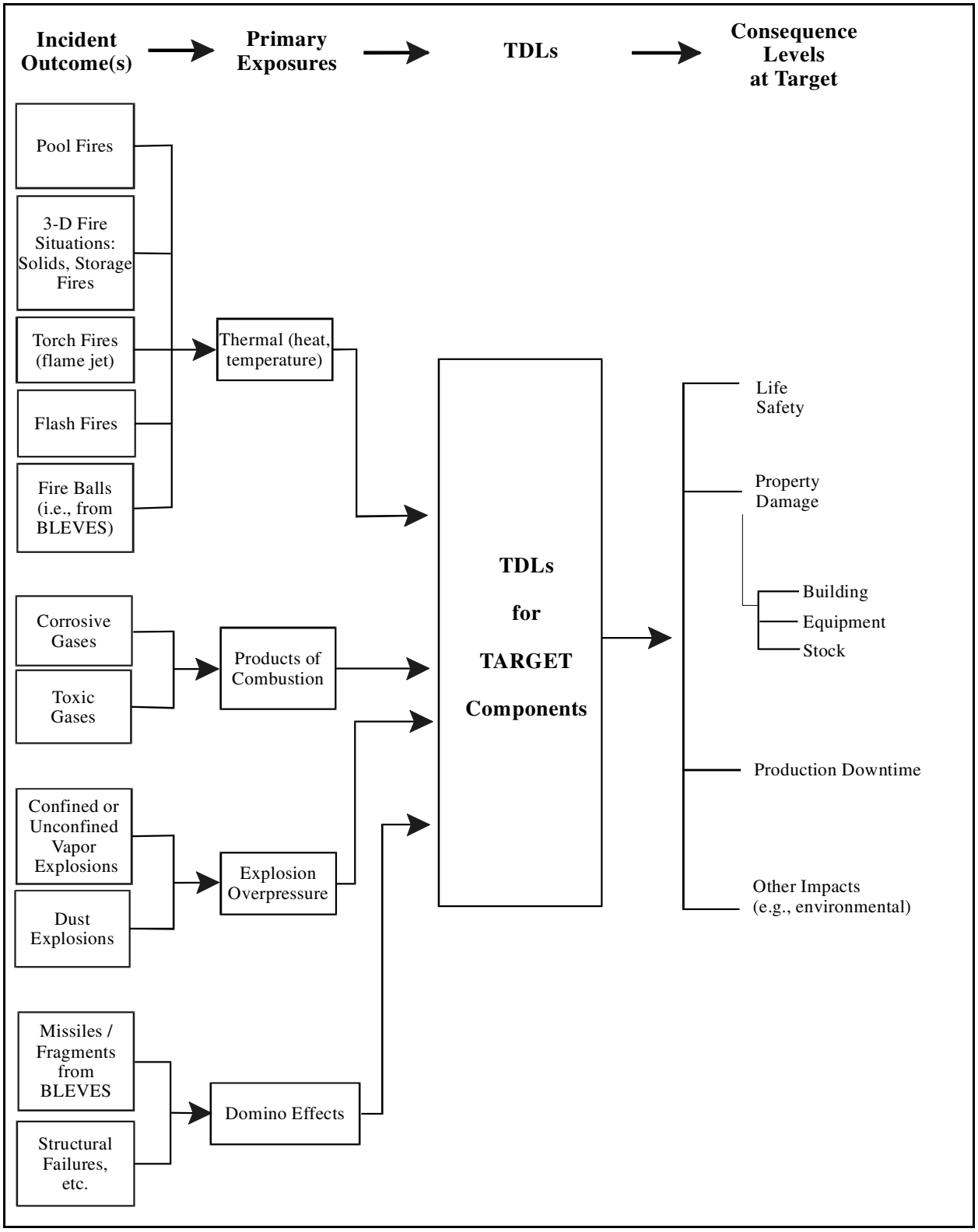
Figure 5.6 depicts primary exposures related to incident outcomes. Primary exposures include:

- Thermal effects
- Products of combustion
- Explosion overpressure effects
- Domino effects

TDLs provide the link between fire and explosion (F&E) incident outcomes and potential consequence levels at the target including:

- Life safety (injuries, fatalities)
- Property damage (equipment, stock, structure)
- Production downtime
- Other impacts (e.g., environmental)

Fig. 5.6: Example: Linking Incident Outcome with TDLs and Consequence Levels



The TDL can be defined as the exposure level below which a significant adverse effect is not expected. As part of the analysis, the adverse effect must be defined. This can include loss of some level of functional performance (50% loss of yield strength from a steel column, loss of electric signal cable integrity, loss of operator vision from smoke, etc.), secondary effects (structural collapse of an assembly, flame spread through a cable tray, operator incapacitation, etc.), repair/replacement costs, or a combination of these.

The general process for TDL evaluation of a target includes:

- Identify the TDLs for the target components. This may involve the use of data based on tests or experience or the use of deterministic models to estimate damage vulnerability.
- Establish limiting conditions for damage thresholds of the "system." This involves recognizing the weak link components within the target boundaries that could cause performance failure.

5.2.1 Life Safety Exposure and TDLs

Life safety exposures of primary concern include:

- Heat effects (radiant, convective)
- Toxic products of combustion (CO, HCN, HCl, etc.) and oxygen levels
- Visibility (smoke density versus escape)
- Overpressure (from explosion incidents)

For a fire occurring inside an enclosed area, there are two primary exposure concerns. One is the radiant heat emitting from the flame or from a descending hot smoke layer. The other is the convective heat released from the fire plume and transferred through heated smoke and hot gases moving and expanding through the area. The following tables and figures presented in this section provide some general TDL data related to radiant heat and convective temperatures.

Radiant Heat

Table 5.1 summarizes human exposure limits from various radiant heat levels.[3]

Table 5.1: Exposure at Different Incident Levels of Thermal Radiation

RADIANT HEAT (kW/m^2)	HUMAN EXPOSURE LIMITS*
35 – 37.5	100% lethality in 1 min; 1% lethality in 10 seconds
25.0	100% lethality in 1 min; significant injury in 10 seconds
12.5 – 15.0	1% lethality in 1 min; first degree burns in 10 seconds
9.5	Pain threshold reached after 8 seconds; second-degree burns after 20 seconds
4.0 – 5.0	Sufficient to cause pain to personnel if unable to reach cover within 20 seconds; however, blistering of the skin (second-degree burns) is likely; 0% lethality
1.6	Causes no discomfort for long exposure
* With exposed skin	

Figure 5.7 provides graphical interpretations of some incident thermal heat flux levels versus injury/fatality potential.[4]

Fig. 5.7: Injury/Fatality Levels for Thermal Radiant Heat Flux

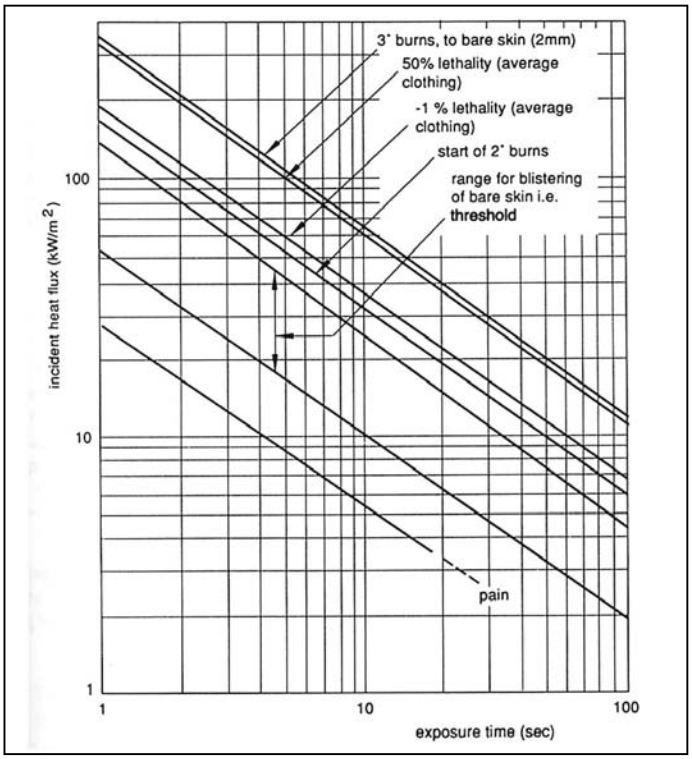


Table 5.2 provides some data from the U.S. Department of Transportation (DOT), UK, and New South Wales regulatory agencies.[5]

Table 5.2: Expected Damage for Various Thermal Radiation Levels

	Thermal Radiation Level (kW/m^2)		
EXPOSURE	US DOT	UK	New South Wales
1. Causes pain after 1 min of exposure	—	—	2.1
2. Will cause pain in 15 – 20 seconds and injury (second-degree burns) after 30 seconds	5	6.3	4.7
3. Significant chance of fatality for extended exposure; high chance of injury after exposures of less than 30 seconds. Buildings made of cellulosic materials may suffer minor damage after prolonged exposure	12.5	10	12.6
4. Extended exposure results in fatality; there is a chance of fatality for instantaneous exposure. Buildings that are made of cellulosic materials or not fire resistant will suffer damage after short exposures. Fire-resistant structures and metal may suffer damage after prolonged exposure	21.0	—	23.0
5. Significant chance of fatality for people with instantaneous exposure. Fire-resistant structures suffer damage after short duration. Buildings of cellulosic materials ignite spontaneously. Metal fatigue after short to medium exposure	31.5	—	35.0

Purser [1, 6] suggests a tenability limit inside buildings from radiant flux from the hot smoke/gas layers at ≤ 2.5 kW/m^2 (this corresponds to an upper gas layer temperature of approximately 200°C).

Convective Heat Exposure

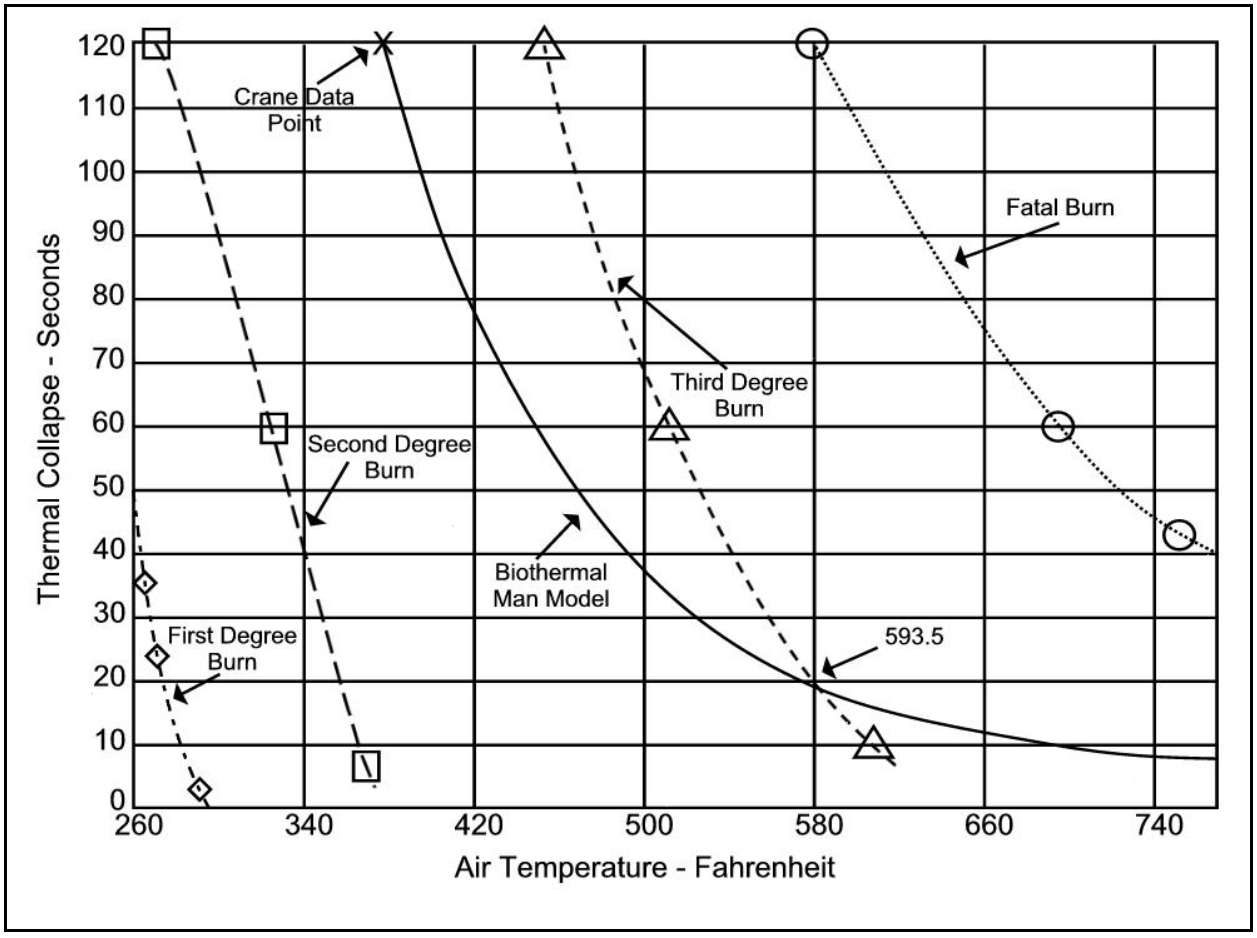
In fire tests conducted by the National Research Council of Canada (NRCC), 300°F (149°C) was taken as the maximum survivable breathing air temperature. A temperature this high can be endured for only a short period and not at all in the presence of moisture. Research has indicated the effects of elevated temperature levels on the human individual in relation to the establishment of human tenability limits for full-scale fire tests at five residential dwellings with the following values. [6, 7, 8]

260°F: difficult breathing
300°F: mouth breathing very difficult, temperature limit for escape

320°F: rapid, unbearable pain with dry skin
360°F: irreversible injury in 30 seconds
400°F: respiratory system tolerance time less than 4 min with wet skin

Some investigators have indicated that the maximum air temperature that can be tolerated by the human respiratory tract is approximately 203°C (400°F) (Fig.5.8). As a result of their review and model studies these investigators established the upper limit of thermal exposure for occupants in aircraft fire incidents to be at an air temperature of 309°C (593.5°F). This temperature is the temperature at which an individual suffers third-degree burns with a 20 second exposure, and escape is estimated impossible.[7]

Fig. 5.8: Air Temperature Hazard Limits for Aircraft Occupants



Effects of Oxygen Depletion

Tables 5.3 and 5.4 provide some data on oxygen depletion effects on humans, which is an important concern when evaluating fire exposure within an enclosed area.[9]

Table 5.3: Effects of Oxygen Depletion

PERCENT OF OXYGEN IN AIR	SYMPTOMS
20	Normal
17	Respiration volume increases, muscular coordination diminishes, attention and thinking clearly requires more effort
12 – 15	Shortness of breath, headache, dizziness, quickened pulse, efforts fatigue quickly, muscular coordination for skilled movements lost
10 – 12	Nausea and vomiting, exertion impossible, paralysis of motion
6 – 8	Collapse and unconsciousness occurs
6 or below	Death in 6 to 8 min
Source: Kimmerle, George, "Aspects and Methodology for the Evaluation of Toxicological Parameters During Fire Exposure," ***JFF/Combustion Toxicology***, Vol.1, February 1974.	

Table 5.4: Four Stages of Asphyxiation

1st Stage:	21 – 14% oxygen by volume, increased pulse and breathing rate with disturbed muscular coordination
2nd Stage:	14 – 10% oxygen by volume, faulty judgment, rapid fatigue, and insensitivity to pain
3rd Stage:	10 – 6% oxygen by volume, nausea and vomiting, collapse, and permanent brain damage
4th Stage:	Less than 6% by volume, convulsion, breathing stopped, and death
Source: "Cryogenics Safety Manual," British Cryogenics Council, London, 1970	

Toxic Products of Combustion

Injury or death can result from toxic products of combustion. Some gases of concern include carbon monoxide (CO), hydrogen cyanide (HCN), and hydrogen chloride (HCl).

Evidence appears to suggest a simple rule-of-thumb for estimation of CO doses likely to be hazardous to humans. Any exposure in which the product of concentration (ppm) × time (minutes) exceeds about 30,000 ppm-min is likely to be dangerous. Thus, a 5 – min exposure to 6000 ppm of carbon monoxide would be expected to be hazardous and possibly incapacitating to many people, as shown in Table 5.5.[6]

Table 5.5: Some Limiting Conditions for Toxic Products of Combustion

CHEMICAL PRODUCTS	5 – MIN EXPOSURE		30 – MIN EXPOSURE	
	INCAPACITATION	DEATH	INCAPACITATION	DEATH
Carbon monoxide	6000 ppm	12,000 ppm	1400 ppm	2500 ppm
Low oxygen	< 13%	< 5%	< 12%	< 7%
Carbon dioxide	> 7%	> 10%	> 6%	> 9%

Pryor has indicated the following physiological effects on human individuals from carbon monoxide, a reduced oxygen level, and carbon dioxide with all the values presented in percentages by volume: [6, 7, 8]

- Carbon monoxide (numbers indicate percent by volume in air)
  - 0.15, headache after 15 min, collapse after 30 min, death after 1 hr
  - 0.20, headache after 10 min, collapse after 20 min, death after 45 min
  - 0.30, maximum "safe" exposure for 5 min, danger of collapse in 10 min
  - 0.60, headache and dizziness in 1 to 2 min, danger of death in 10 to 15 min
  - 1.28, immediate effect, unconscious after 2 to 3 breaths, danger of death in 1 to 3 min
- Anoxia — reduced oxygen (numbers indicate percent by volume in air)
  - 11, headache, dizziness, early fatigue, tolerance time 30 min
  - 9, shortness of breath, quickened pulse, slight cyanosis, nausea, tolerance time 5 min
  - 7, above symptoms become serious, stupor sets in, unconsciousness occurs, tolerance time 3 min
  - 6, heart contractions stop 6 to 8 min after respiration stops
  - 3-2, death occurs within 45 sec
- Carbon dioxide (numbers indicate percent by volume in air)
  - 10, approaches threshold of unconsciousness in 30 min
  - 12, threshold of unconsciousness reached in 5 min
  - 15, exposure limit 1 min
  - 20, unconsciousness occurs in less than 1 min

Thus, when conditions reach a point where the temperature is above 300°F, the CO is above 1%, the CO_2 is above 12%, and/or the O_2 is below 7%, then the exposed person's ability to escape under their own power is severely threatened.

Other toxic and corrosive combustion products of concern include gases such as hydrogen cyanide and hydrogen chloride.

Hartzell's chapter on combustion products and their effects on life safety in reference [8] and Purser's chapter on toxicity of combustion products in reference [1] provide very good information on these subjects.

Visibility Through Smoke

Visibility through smoke has a great effect on the ability of occupants to safely exit from a fire. The factors that affect visibility are the amount of smoke particulate in the path of vision and the physiological effects on the eyes, which may affect decision making. Scherfig defined the safety criteria for evacuation in terms of visibility thresholds. The author proposes a rule that persons during egress must have a visibility of at least 3 m in the primary fire compartment and 10 m in escape routes.[6]

Studies of aircraft fire hazard environments have developed escape times based on the reduced visibility created in a crash fire incident. Investigators established from studies with human subjects that it was possible for an individual to find an exit with tactile sensations from a distance of 34 ft (10.2 m) in total darkness.[7]

Smoke generation is very much a function of the fire growth rate and HRR. From a life safety perspective, it is important that a hazardous dose of smoke or toxic combustion products either never be generated (i.e., rapid detection and fire extinguishment) or be prevented from reaching building occupants (i.e., smoke control and ventilation systems).

5.2.2 Property Threshold Damage Limits

Target elements subject to property damage from fire or explosion exposures include:

- Equipment
- Stock
- Structure

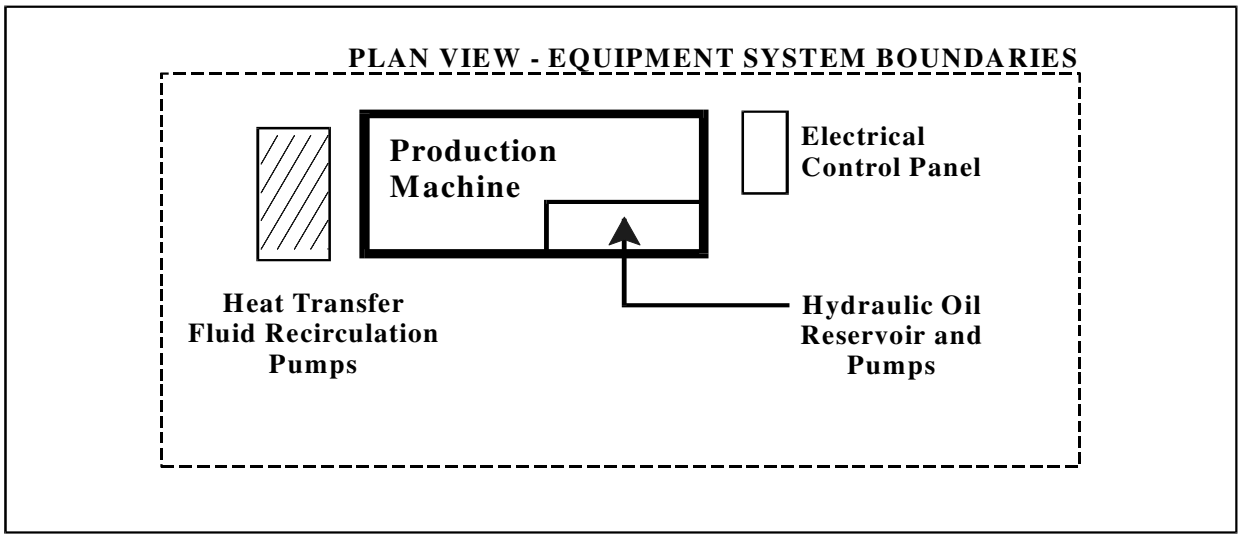
Damage potential for these property elements is generally approached by evaluating each with defined boundaries and components. The steps include:

1. Break down the significant system components (i.e., significant from a fire damage potential perspective) and describe component materials.
2. Develop component level TDL information from available data sources, which might include:
   - Manufacturer's data
   - Experience
   - Modeling
   - Testing

Equipment

When evaluating the damage potential to equipment, the equipment system boundaries, components, construction materials, process mediums, and controls must be defined. For example, Fig. 5.9 presents a general illustration of a production unit where the equipment system boundaries include the production machine, electrical control panel, heat transfer fluid recirculation pumps, and hydraulic oil reservoir and pumps.

Fig. 5.9: Example of Defining Equipment System Boundaries



There are a number of ways to break down system components with various levels of detail. For example purposes, Table 5.6 illustrates a descriptive format that includes component category, materials description, and a remarks column, based on Fig. 5.9.

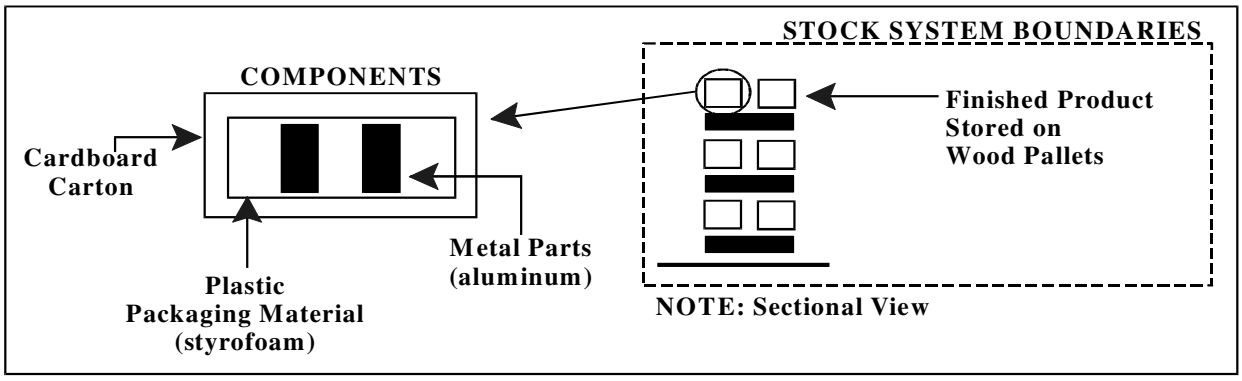
Table 5.6: Example Table for Equipment Component Breakdown and Description

EQUIPMENT SUBSYSTEM	SUBSYSTEM COMPONENTS	MATERIAL DESCRIPTION	REMARKS
Electrical control panel	• Electrical relays • Electrical wiring	• Plastic relays and circuit boards • PVC insulated wiring	• Industrial grade, watertight control panel provided
Production machine	• Machine press and extruder • Machine hydraulic system – reservoir, pumps, piping – flexible hose connections – hydraulic fluid	• Heavy steel components • Steel components • Rubber hoses • Low hazard hydraulic fluid	• Refer to manufacturer's data sheets on seals, gaskets, rubber hoses • Refer to material safety data sheet (MSDS) on hydraulic fluid
Heat transfer fluid recirculation pumps	• Pumps, piping • Heat transfer fluid	• Steel components • Organic fluid	• Refer to manufacturer's data sheet • Refer to MSDS sheet on heat transfer fluid

Stock

A similar approach for component breakdown and material description can be taken with stock. Stock can include raw materials, in-process inventory, or finished product storage. System boundary considerations for stock include the storage and retrieval mechanisms (i.e., steel racks, wood pallets, automated inventory system, etc.). Figure 5.10 presents a simplistic illustration of palletized finished product storage.

Fig. 5.10: Example of Defining Stock System Boundaries



Structures

The term structural components, as used in this section, includes structural supports, building materials, and building penetrations (doors, windows, direct and cable penetrations, etc.) Figure 5.11 presents a simplified example of defining structure boundaries. Table 5.7 provides an example of breaking down structural components.

Fig. 5.11: Example of Defining Structure System Boundaries

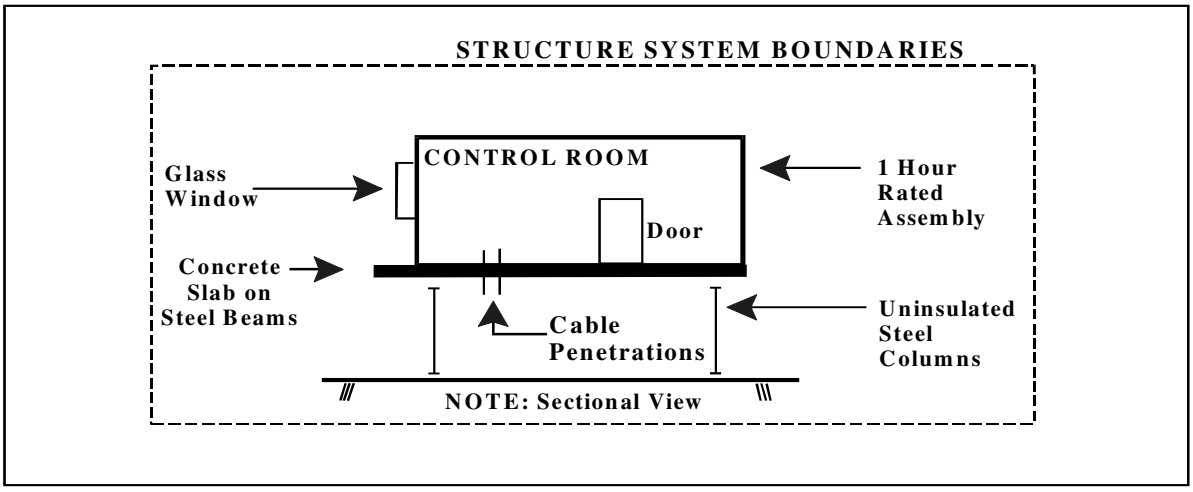


Table 5.7: Example Table for Structure Component Breakdown and Description

STRUCTURE SUBSYSTEM	SUBSYSTEM COMPONENTS	MATERIAL DESCRIPTION	REMARKS
Supports: steel columns & beams	• Uninsulated load bearing steel columns & beams		See diagram X for details
Supports: concrete floor	• Concrete slab on uninsulated steel beams		See diagram Y for details
Compartmentation: control room roof and walls	• 1 hr rated assembly per U.L. Directory	Walls and Roof: ⅝ inch gypsum board or steel studs	
Compartment penetration	• Window • Door • Cables	• Plain glass window • ¾ hr rated fire door • Cable penetration filled with 1 hr rated penetration sealant	

Following the breakdown of system components and material description, the next step is to develop TDL data. First-order TDL estimates involve the use of generic data and engineering judgement to estimate TDLs for specific equipment, stock, or structural components under evaluation.

Primary exposures of interest when evaluating component damage potential from fires or explosions include:

- Thermal effects (i.e., radiant heat, temperature)
- Explosion overpressure effects
- Products of combustion (i.e., corrosive gases)

Radiant Heat Exposure

The effect of thermal radiation on equipment and structures depends on whether they are combustible and the nature and duration of the exposure. Thus, wooden materials will fail due to combustion, whereas steel will fail due to thermal lowering of the yield stress. Many steel structures under normal load will fail rapidly when raised to a temperature of 500 – 600°C, whereas concrete will survive for much longer. Flame impingement is generally more severe than thermal radiation. Table 5.8 provides some generic damage data.[3]

Table 5.8: Example of Some Thermal Radiation Damage Levels

INCIDENT HEAT FLUX (KW/M²)*	DAMAGE TO EQUIPMENT	REMARKS
35.0 – 37.5	Damage to process equipment	Generally includes steel tanks, chemical process equipment, industrial machinery
25.0	Minimum energy to ignite wood at indefinitely long exposure without a flame	
18.0 – 20.0	Plastic cable insulation degrades	
12.5 – 15.0	Minimum energy to ignite wood with a flame; melts plastic tubing	
* Based on an average 10 min exposure time		

Table 5.9 from reference [6] provides a listing of some critical radiant heat flow values.

Table 5.9: Some Critical Values of Received Radiation I_{RC}

I_{RC} (kW/m²)	OUTCOME
> 9	Breakage of ordinary glass and ignition of fabrics if in contact with sparks or embers
≥ 21	Ignition of timber if in contact with sparks or embers
≥ 42	Spontaneous ignition of timber

NOTE: (notes are from reference [6])
- Scherfig used 15 kW/m² as the acceptable threshold level for preventing spread from one structure to other exposed structures.
- Barnett and Simpson defined a threshold level as 10 kW/m² for plastic cladding, 12.5 kW/m² for timber cladding, and 25 kW/m² for spontaneous ignition of items just inside the neighbor's windows of the exposed building.

Table 5.10 lists some radiant heat flux critical ignition levels for some materials.

Table 5.10: Radiant Heat Flux Required for Ignition (10 min exposure)

HEAT FLUX ITEM	(BTU/FT^2 SEC)	(KW/M^2)
Paper	1.8	20.4
Wood	2.8	32
Polyurethane	1.6	18
Polyethylene	1.8	20
Nylon	2.6	29
Polystyrene	1.6	18
Polypropylene	1.8	20
Polymethyl methacrylate	1.6	18
Polyvinyl chloride	1.85	21
Reference: Factory Mutual Research Corporation		

Tables 5.11 and 5.12 present data on the effects of temperature on some selected materials from reference [10].

Table 5.11: Effect of Temperature on Selected Materials

MATERIAL	TYPICAL EXAMPLES	DAMAGE CONDITIONS	APPROXIMATE TEMPERATURE (°C)
Polystyrene	Thin wall food containers, foam, light shades, handles, curtain hooks, radio casings	Collapse Softens Melts and flows	120 120 – 140 150 – 180
Polyethylene	Bags, films, bottles, buckets, pipes	Shrivels Softens and melts	120 120 – 140
Polymethyl methacrylate	Handles, covers, skylights, "glazing"	Softens Bubbles	130 – 200 250
PVC	Cables, pipes, ducts, linings, profiles, handles, knobs, house ware, toys, bottles	Degrades Fumes Browns Chars	100 150 200 400 – 500
Cellulose	Wood, paper, cotton	Darkens	200 – 300
Solder	Plumbing joints	Melts	250
Lead	Plumbing Sanitary installations, toys	Melts, sharp edges rounded Drop formation	300 – 350
Aluminum and alloys	Fixtures, casings, brackets, small mechanical parts	Softens Melts Drop formation	400 600 650
Glass	Glazing, bottles	Softens, sharp edges rounded Flows easily, viscous	500 – 600 800
Silver	Jewelry, spoons, cutlery, etc.	Melts Drop formation	900 950
Brass	Locks, taps, door handles, clasps	Melts (particularly at edges) Drop formation	900 – 1000 950 – 1050
Copper	Wiring, cables, ornaments	Melts	100 – 1100
Cast iron	Radiators, pipes	Melts Drop formation	1100 – 1200 1150 – 1250
Zinc	Sanitary installations, gutter, down pipes	Drop formation Melts	400 420
Bronze	Windows, fittings, door bells, ornamentation	Edges rounded Drop formation	900 900 – 1000
Paint	—	Deteriorates Is destroyed	100 250
Wood	—	Ignites	240

Table 5.12: Ignition Temperatures of Various Materials (Average Values)

MATERIAL	IGNITION TEMPERATURE[a] (°C)	Auto-Ignition Temperature[b] (°C)
Wood	280 – 310	200 – 260
Wool	240	—
Paper	230	230
Cotton fabrics	230 – 270	255
Polymethyl methacrylate	280 – 300	450 — 460
Rigid polyurethane foam	310	415
Polyethylene	340	350
Polystyrene	345 – 360	455 – 495
Polyester (glass fiber filled)	350 – 400	480
Polyvinyl chloride (PVC)	390	455
Polyamide (Nylon)	420	425 – 450
Phenolic resins (glass fiber filled)	520 – 540	570 – 580

Notes are from reference [10].

[a] The temperature to which material has to be heated for sustained combustion to be initiated from a pilot source.

[b] The temperature at which the heat evolved by a material decomposing under the influence of heat is sufficient to bring about combustion without the application of an external source of ignition. This tends to be higher than the ignition temperature.

Reference: 1990 Fire Safety Journal [10]

Electrical Cables

With electrical cables, there are various levels of failure; pyrolosis of the cable, ignition of the cable insulation, and electrical failure. Table 5.13 provides a general listing of critical heat flux and temperatures.[11] "Critical" is defined as the point at which sustained cable pyrolosis and ignition is not expected to occur. In general, this would be below the point of loss of electrical integrity through the cable.

Table 5.13: Electrical Cable – Critical Failure Points

GENERAL CABLE TYPE	CRITICAL HEAT FLUX (kw/m2)	CRITICAL TEMPERATURE (°C)
PE/PVC	18	478
XPE/Neoprene	22	516
EPR/Hypolor	19	488
Reference: EPRI – Electric Cable Study [11]		

Electronic Equipment

There are three types of fire damage to electronic equipment: thermal damage, damage due to combustion products, and damage due to the decomposition products of the fire suppression agent. Damage thresholds for electronic equipment have been measured for a number of common combustion products. Reference [12] indicates that for electronic equipment exposed to individual combustion products for 22 hr at a relative humidity of 75% resistors, capacitors, wire, connectors, integrated circuits, relays, and transistors the following damage thresholds were found:

- 100 ppm HCl
- 1000 ppm HF
- 1000 ppm NO_2
- > 1000 ppm SO_2

By employing rapid detection and rapid agent discharge, fires can be extinguished while still in their incipient stages, and the formation of combustion products can be limited to levels below damage thresholds.[12]

Glass

The following criteria can be used to define glass breakage:[6]

- Breakage temperatures on the exposed side of glazing were 150 to 175°C for plain glass and 350°C for both heat strengthened and tempered glass (Kim and Taber).[6]
- Breakage temperature of interior ordinary glass is 100°C for tempered glass, 270°C (Guaglia). (Frantzich, Jonsson, and Rantatalo used a single value of 300°C).[6]

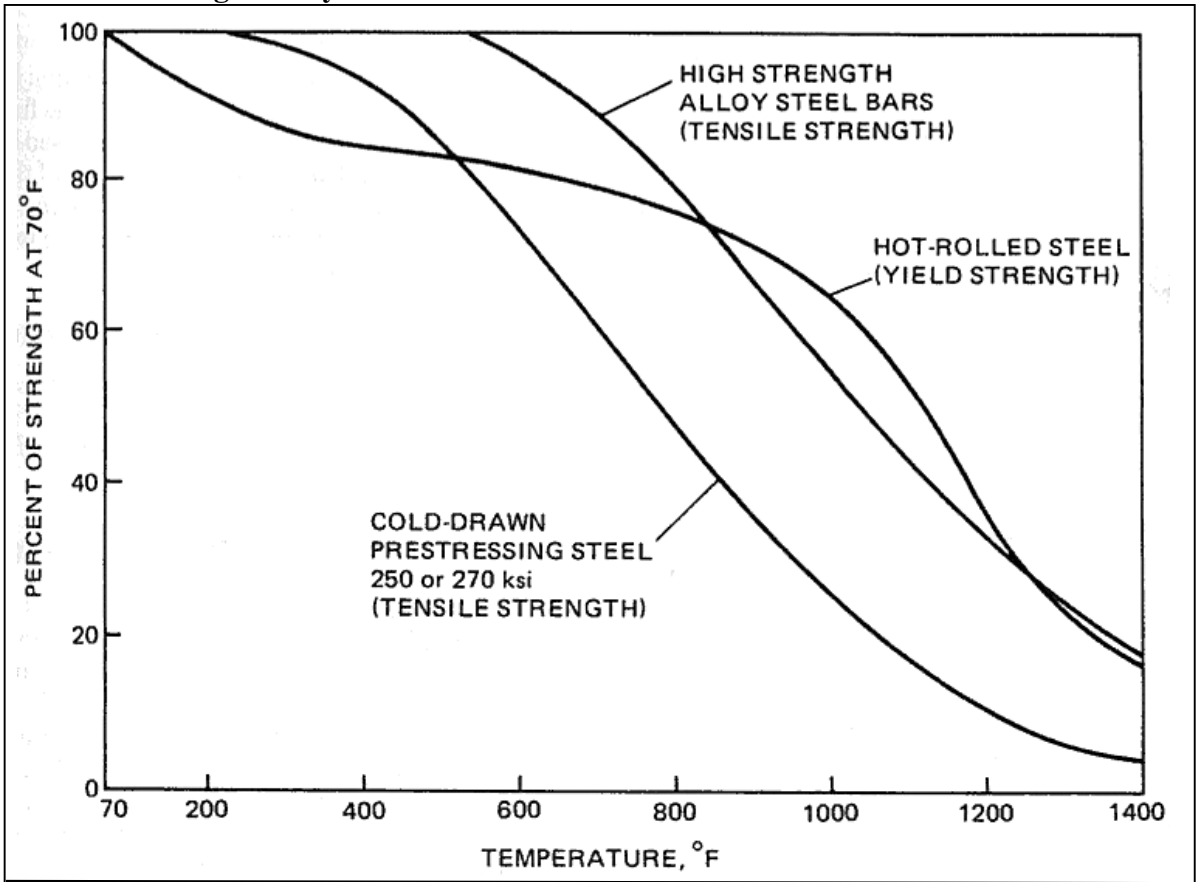
Steel

Steel has three characteristics that are of concern under fire conditions:[13]

- Steel expands substantially when heated
- Steel substantially loses strength when heated to temperatures in excess of 900° to 1000°F (480° to 540°C)
- Steel transmits heat readily

According to reference [13], the strength of mild steel actually increases up to about 600°F (315°C). Beyond that temperature, a decrease in strength occurs until about 1100°F (600°C) when the strength of steel is reduced to a point where it is not sufficient to carry the dead load, and the steel member fails. Bar joists and steel trusses are particularly subject to failure due to rapid overheating of thin steel members. The consequences in the case of bar joists may not be serious because large supporting beams that are protected can maintain the overall structural integrity of the building. However, localized overheating of a small section of a large steel truss system can cause major building collapse. In addition, heat can be transmitted through steel to combustible material that is otherwise unexposed to fire, such as steel deck roof insulation and contents of tanks and bins.[13] Figure 5.12 from reference [14] presents some strength-temperature relationships for steel. Table 5.14 presents critical steel failure temperatures from the ASTM E-119 standard.

Fig. 5.12: Strength-Temperature Relationships for Hot-Rolled, Cold-Drawn, and High-Strength Alloy Steels



Reference: SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995. Reprinted with permission of the Society of Fire Protection Engineers

Table 5.14: Critical Temperatures Defined as Failure Points in the ASTM E-119 Standard

ELEMENT	MAXIMUM SINGLE TEMPERATURE, °F	ARITHMETIC MEAN TEMPERATURE, °F
Steel columns (no load)	1,200	1,000
Steel beams	1,300	1,100
Alternate (no load)	1,200	1,000
Reinforcing steel	1,100	1,100
Prestressing steel	800	800
Floor-roof slabs	1,300	1,100

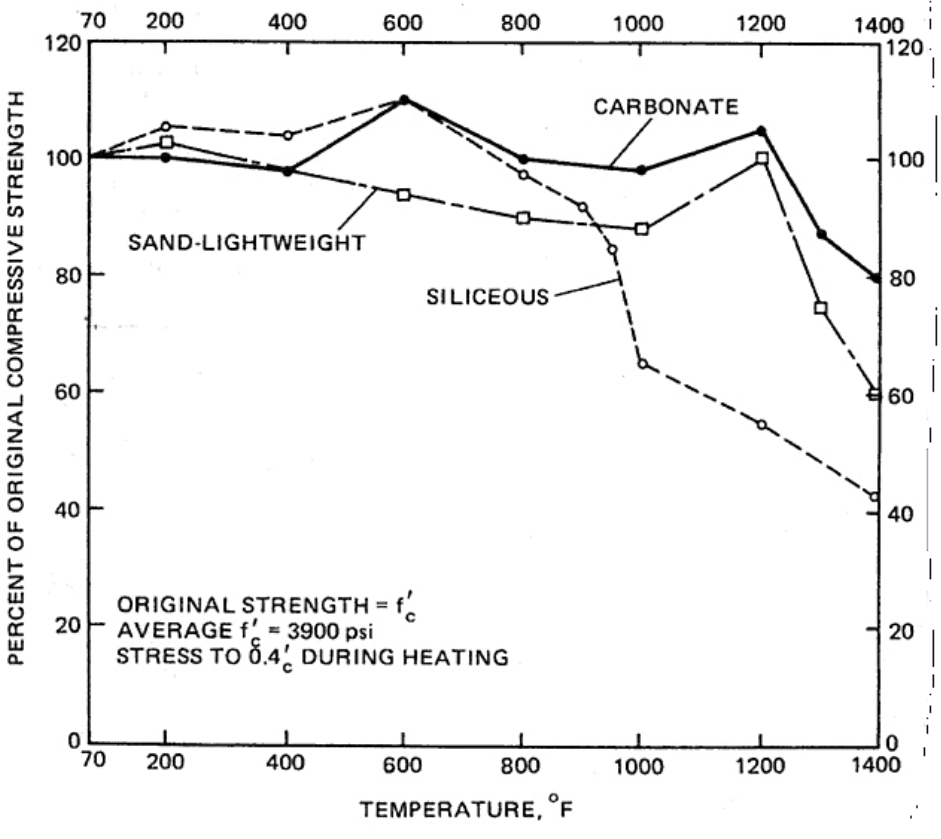
Concrete

Fire alone seldom causes failure of concrete or masonry structural components. Failure is more often due to loss of support of stresses indirectly resulting from the fire. For example reference [13] indicates:

- Masonry walls can be pushed over by expanding concrete or steel members, toppling or expanding storage, or explosion pressures
- Exposed steel-supporting trusses, beams, or columns can fail if not protected by water spray or insulation
- Floors can be overloaded by water-soaked storage
- Spalling can occur due either to expansion of moisture or to thermal expansion of the outer surface in concrete under compression as in columns, walls, or prestressed structural members.

Figure 5.13 from reference [14] presents strength-temperature relationships for some concrete types.

Fig. 5.13: Strength-Temperature Relationships for Carbonate, Siliceous, and Sand-Lightweight Aggregate Concretes



Reference: SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995. Reprinted with permission of the Society of Fire Protection Engineers

Figure 5.13 illustrates that the compressive strength of concrete remains relatively unchanged up to 900°F. Above 900°F, the compressive strength of the siliceous aggregate concrete starts to decrease rapidly and is considered ineffective at temperatures above 1200°F, where the compressive strength has been reduced by approximately 50% of the value at normal temperatures. For carbonate and lightweight aggregates, compressive strength remains relatively unchanged up to 1200°F and is not considered ineffective until it reaches a temperature of 1400°F.[14]

Example TDL Worksheet

Table 5.15 presents an example of applying TDL data to the equipment system boundaries previously presented in Fig. 5.9.

Table 5.15: Example Thermal TDL Estimates for Equipment in Example Fig. 5.9

FROM TABLE X SUBSYSTEM COMPONENTS	MATERIAL DESCRIPTION	TDL RADIANT HEAT FLUX KW/M²	TDL TEMPERATURE (°C)	REMARKS
Electrical Control Panel				
• Electrical relays	• Plastic relays and circuit boards	18	350	
• Electrical wiring	• PVC insulated wiring	18 – 21	478	
Production Machine				
• Machine press and extruder	• Heavy steel components	35	600	
• Machine hydraulic system	• Steel components, pump seals, mechanical joint rubber gaskets	30 – 35	550	
– Reservoir, pumps, piping				
– Flexible hose connections	• Rubber hoses	20 – 22	516	
– Hydraulic fluid	• Low hazard hydraulic fluid		460	Hydraulic fluid ignition temperature
Heat Transfer Fluid Recirculation Pumps				
• Pumps, piping	• Steel components, pump seals, mechanical joint rubber gaskets	35	600	
• Heat transfer fluid	• Organic fluid		370	Organic fluid ignition temperature
First-order estimates for example purposes only.				

Table 5.16 presents an example of applying TDL data to the structure system boundaries previously presented in Fig. 5.11.

Table 5.16: Example Thermal TDL Estimate for Structure Example in Fig. 5.11

FROM TABLE Z SUBSYSTEM COMPONENTS	MATERIAL DESCRIPTION	TDL RADIANT HEAT FLUX KW/M^2	TDL TEMPERATURE (°C)	REMARKS
Steel columns • Uninsulated load bearing columns		35 – 37.5	600	
Floor • Concrete slab on uninsulated steel beams		35 – 37.5	600 Steel beams 760 Concrete	
Control room roof and walls • 1 hr rated assembly per U.L. Directory	Walls and roof: ⅝ in. gypsum board or steel studs	*	*	* Assumed 45 min effective fire resistance
Compartment penetrations • Window • Door • PVC cables	• Plain glass window • ¾ hr rated fire door • Cable penetration filled with 1 hr rated penetration sealant	9 *	150 – 175 *	* Assumed 45 min effective fire resistance
First-order estimates for example purposes only.				

Modeling and Computer Simulation

Structure instability and potential collapse poses not only a property damage exposure but an exposure to people exiting the facility and emergency responders entering the facility. Depending on the scope and level of detail needed in the fire or explosion risk assessment study, the use of analytical modeling methods and computer simulation may be warranted. Detailed description of these methods is beyond the scope of this chapter. References in the following box address this topic.

Some References – Analytical Modeling Methods

- Mike, J. "Analytical Methods for Determining Fire Resistance of Steel Members," *The SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, Quincy, MA.[1]
- Fleischman, C. "Analytical Methods for Determining Fire Resistance of Concrete Members," *The SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, Quincy, MA.[1]
- White, R. "Analytical Methods for Determining Fire Resistance of Timber Members," *The SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, Quincy, MA.[1]

Several textbooks on heat transfer address the problem of transient temperature distribution within bodies of various geometrical configurations and under different conditions of heating. The response of a target (i.e., time to damage) to an imposed heat flux depends on the thermal characteristics of the target. Two types of heat transfer analysis are briefly considered here for the case of a constant heat flux imposed at the surface of the target:

- The lumped capacity, or thermally thin, solid analysis
- The semi-infinite, or thermally thick, solid analysis

The thermally thin solid is representative of targets with negligible internal resistance to heat flow, such that the temperature can be considered uniform throughout the solid. Fire detection devices and steel structural members are normally modeled as thermally thin solids.

Application of the lumped capacity approach is appropriate when the Biot number is small, (which is generally true for materials of high thermal conductivity, k, or when the material is thin) the material is considered thermally thin, and the transient heat conduction within the solid is fast compared to heat transfer to its surface.

$$\text{The Biot number} = \frac{hL}{k}$$

$$\text{Where L is the characteristic length} = \frac{\text{Volume}}{\text{Surface Area}}$$

and h is the applied heat transfer coefficient

When the Biot number is less than 0.1, the temperature distribution within the material may be neglected and the material may then be considered to have a uniform temperature at any moment in time and the use of thermally thin analysis is valid.

Thermally Thin Solid Analysis

An energy balance at the surface of a thermally thin solid exposed to an incident heat flux can be expressed as:

$$q'' = pc_p\left(\frac{V}{A_s}\right)\frac{dT}{dt}$$

where

q'' = Total incident heat flux (Kw/m^2)
p = Density of the target material (kg/m^3)
c_p = Specific heat of the target material (kJ/kg-°K)
$\frac{V}{A_s}$ = Volume to surface area ratio of the target (m)
$\frac{dT}{dt}$ = Rate of temperature change of the target (°K/s)

For a constant incident heat flux, this equation can be solved for the time (t_d) to achieve a damage or detection temperature, T_d as:

$$t_d = pc_p\frac{V}{A_s}\left(\frac{T_d - T_a}{q''}\right)^2$$

T_a = ambient temperature, °K

Semi-Infinite Solid Analysis

The semi-infinite analysis is used for targets with substantial internal resistance to heat flow. For this case, thermal gradients arise within the material, with the surface temperature rising more quickly than internal temperatures under imposed heat flux conditions due to the internal resistance of the target material to heat transfer. Grouped electrical cables can be modeled as semi-infinite solids.

When a semi-infinite or thermally thick solid is subjected to a constant heat flux at its surface, the surface temperature changes with time as:

$$T_s - T_o = 2q''\sqrt{\frac{t}{\pi kpc_p}}$$

q'' = Total incident heat flux (Kw/m^2)
k = Thermal conductivity (Kw/m°K)
p = Material density (kg/m^3)
c_p = Specific heat(J/kg-°K)
t = Time (s)
T_s = Surface temperature, °K
T_o = Initial temperature, °K

This equation can be rearranged to solve for the time, t_d, needed for the surface temperature to increase to a damage temperature, T_d:

$$t_d = \frac{\pi}{4}(kpc_p)\left(\frac{T_d - T_o}{q''}\right)^2$$

Finite Element Heat Transfer Modeling

Finite element analysis computer models allow the engineer to evaluate the impact of a fire on a two- or three-dimensional surface such as a fire barrier, steel beam, and/or column. These models break the surface to be modeled into a two- or three-dimensional grid and solve the general heat conduction equation. General heat transfer finite element programs have been available for many years and can provide very good heat flux and temperature profile results assuming that adequate thermal property data for the materials being modeled are available. In the application of finite element heat transfer models to fires, special attention must be given to characterizing the conditions (radiant and convective heat flux) to which the modeled surface is exposed. This characterization is often based on other fire modeling results or experimental data. [1]

Fires – T3 is a three dimensional heat transfer model applicable to analyzing fire barriers and structural elements. The Society of Fire Protection Engineers (SFPE) have developed a useful guide for this model called Fires – T3: A Guide for Practicing Engineers.[36]

5.2.3 Explosion Overpressure Effects

Explosion effects are commonly separated into a number of classes. The main division is between direct and indirect effects. Sometimes, direct effects are referred to as primary effects, and indirect effects as secondary effects.

The main direct, primary effect to humans from an explosion is the sudden increase in pressure that occurs as a blast wave passes. It can cause injury to pressure-sensitive human organs, such as ears and lungs.

Indirect primary effects include fragments originating from the explosion source, for example, a pressure vessel. In general, those fragments have a high velocity. The impact of fragments and debris from sources not originating from the explosion source are secondary effects. Secondary fragments result when the blast tears off parts of structures, for example, bricks, roof tiles, and glass. Such fragments, except for glass, are relatively blunt and have low velocities. Glass window panes and fragments, however, are small, sharp, and sometimes have high velocities. Thus, they are capable of causing injuries at much greater distances from explosion centers than usually result from other secondary fragments. Building collapse can be regarded as a secondary effect, although it is not commonly grouped within any specific class.[13]

The level of injury or damage caused by a blast wave is primarily a function of the strength of the blast wave when it reaches a person or object. The strength of the blast wave at any given time and location is typically referred to as the overpressure, or peak positive overpressure (i.e., the maximum increase in the localized air pressure). The rate at which the localized air pressure increases and then decreases as the blast wave travels past a given location can also affect the level of injuries or damages.[2, 4]

The following tables provide some approximate values of blast wave overpressure that may cause given levels of property damage or human injury:

- Table 5.17 presents some general characteristic damage range for buildings, equipment, and people.[3]
- Tables 5.18 and 5.19 from reference [15] present data on building response and occupant effects.
- Table 5.20 presents some typical overpressure effects on unprotected people.[2, 4, 9]
- Table 5.21, from reference [16], presents explosion blast overpressure effects on oil refinery equipment

Table 5.17: Explosion Overpressure Damage Impacts [3]

OVERPRESSURE (PSIG)	CHARACTERISTIC DAMAGE	
	To Equipment	To People
2.5 – 5	Heavy damage to buildings and to process equipment	1% death from lung damage >50% eardrum rupture >50% serious wounds from flying objects
1 – 2.4	Repairable damage to buildings and damage to the facades of dwellings	1% eardrum rupture 1% serious wounds from flying objects
.5 – 1	Glass damage	Injury from flying glass
.15 – .30	Glass damage to about 10% of panes	Slight injury from flying glass

Table 5.18: Building Response and Occupant Vulnerability to Selected Blast Overpressures [15]

BUILDING TYPE	PEAK SIDE-ON OVERPRESSURE, PSI (BAR)	CONSEQUENCES	VULNERABILITY OF OCCUPANTS (PROBABILITY OF SERIOUS INJURY OR FATALITY)
Woodframe	1.0 (0.069)	Isolated buildings overturn. Roofs and walls collapse	0.1
	2.0 (0.14)	Complete collapse	0.4
	5 (0.34)	Total destruction	1.0
Steel frame/metal siding pre-engineered	1.5 (0.10)	Sheeting ripped off and internal walls damaged. Danger from falling objects	0.4
	2.5 (0.17)	Building frame stands, but cladding and internal walls destroyed as frame distorts	0.4
	5 (0.34)	Total destruction	1.0
Unreinforced masonry bearing wall	1.0 (0.069)	Partial collapse of walls that have no breakable windows	0.1
	1.25 (0.085)	Walls and roof partially collapse	0.2
	1.5 (0.10)	Complete collapse	0.6
	3 (0.21)	Total destruction	1.0

Table 5.19: Airblast Effects on Personnel [15]

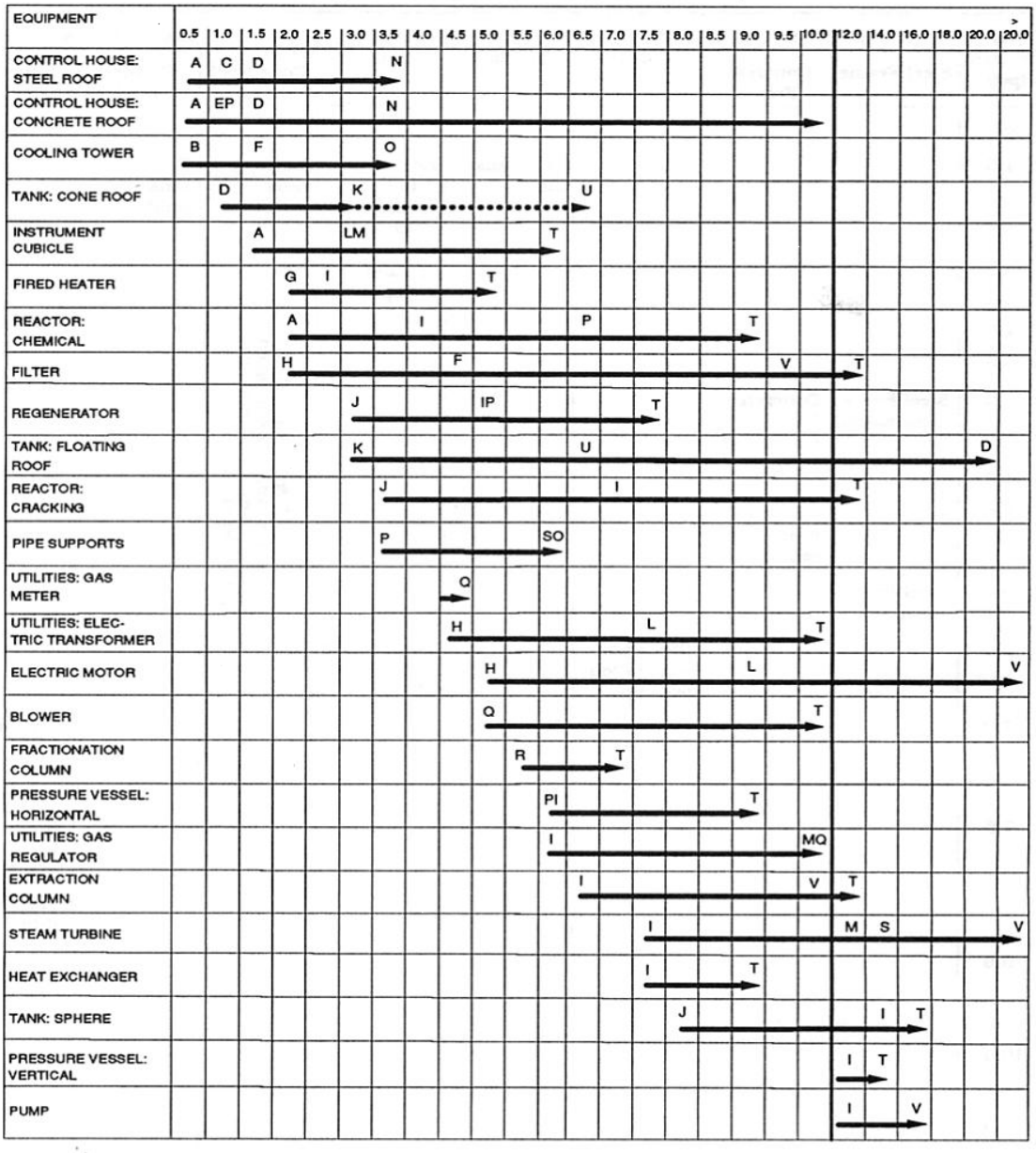
EFFECTS ON PERSONNEL	PEAK PRESSURE
Severe injury or death to personnel from direct blast, building collapse, or bodily translation	12 psi
Personnel are likely to be injured seriously due to blast, fragments, debris, and bodily translation. Unstrengthened buildings will suffer damage approaching total destruction	8 psi
Personnel injuries of a serious nature are expected from fragments, debris, firebrands, or other objects. Damage to unstrengthened buildings will be of a serious nature and approximately 50% or more of the total replacement cost	3.5 psi
Building occupants may suffer temporary hearing loss or injury from secondary blast effects such as building debris and impact after translation. Personnel in the open are not expected to be killed or seriously injured directly by the blast, though some injuries from fragments and debris are possible. Unstrengthened buildings can be expected to sustain damage approximating 20% of their replacement cost	2.3 psi
Building occupants may suffer injury from secondary effects such as building debris. Unstrengthened buildings can be expected to sustain damage approximating 10% of the replacement cost	1.7 psi
Personnel are provided a high degree of protection from death or serious injury, injuries that do occur are likely to be caused by glass breakage and building debris. Unstrengthened buildings can be expected to sustain damage up to about 5% of their replacement cost	1.2 psi

Table 5.20: Typical Overpressure Effects on Unprotected People

RESPONSE	THRESHOLE OVERPRESSURE (PSI)
Eardrum rupture	5
Fatal head injury	8
Serious lung damage	10
Fatal bodily injury	11

Table 5.21: Blast Overpressure Effects on Oil Refinery Equipment [16]

Blast Overpressure Effects On Vulnerable Refinery Parts



Code

A. Windows and gauges break
B. Louvers fall at 0.3-0.5 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 fails
K. Unit uplifts (half-filled)
L. Power lines are severed
M. Controls are damaged
N. Block walls fail
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 filled)
V. Unit moves on foundation

5.3 TIME LINE PARAMETERS AND CONSEQUENCE LEVELS

After identifying TDLs for target components, the next steps involved in developing an exposure profile include:

1. Evaluating target TDLs, both thermal and nonthermal, based on system functional requirements
2. Modeling the fire or explosion source intensity at the target with graphical depiction of the results
3. Establishing damage limiting conditions for the target and developing event tree time line parameters
4. Categorizing event tree consequence levels

5.3.1 Evaluating System Functional Requirements

When a target is evaluated to determine vulnerability from a defined fire or explosion scenario, the functional requirements from both an operational and safety perspective must be defined. The first task is defining or describing the functional requirements of the target system under normal operating conditions and abnormal emergency (i.e., fire exposure) conditions. This provides an understanding of how the target components contribute to the system's functional success.

The best way to further describe this is by using an example with defined target system boundaries, such as Fig. 5.14.

Fig. 5.14: Example Control Room Target System Boundaries

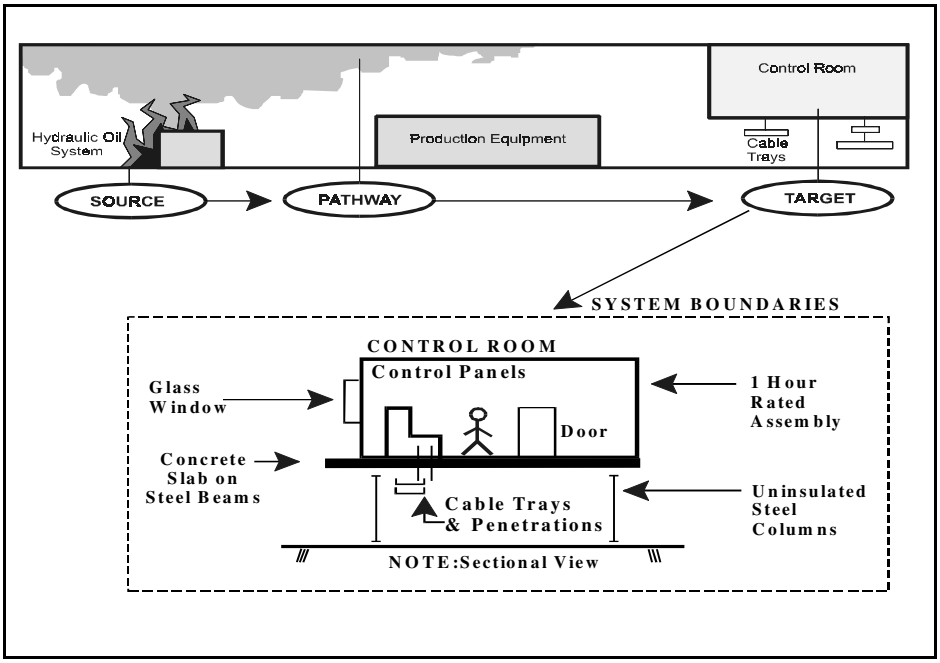


Table 5.22 was constructed to further develop this example. In the first columns, the control room subsystems and components are listed in terms of relative vulnerability from fire exposure based on the general knowledge of component TDLs. The other columns in this example worksheet include:

- Primary function – normal operations
- Functional requirements – emergency conditions
- Loss of Functional Requirement
  - Thermal limits
  - Nonthermal limits
  - Other exposure limits

It is very important to define the primary functions of target subsystems and components during normal operations. Knowing the design intent allows one to evaluate design alternatives if the proposed design potentially affects fire safety. In our example, Fig. 5.14, the control room is elevated, located in the production area, and has a glass window for the operators to view the production operations from the control room. If this was a proposed design, the use of additional instrumentation and cameras to view production operations and the location of the control room outside of the production area might be a good alternative to reduce fire and smoke exposure to operations and high-value digital control system equipment.

Functional requirements during emergency conditions, shown in the third column of Table 5.22 are associated with primary functions during normal operations. Functional requirements set the foundation for establishing the TDLs that could cause “loss of function” (shown in the last three columns of Table 5.22).

An interesting functional requirement in Table 5.22 is that one operator must remain in the control room to safely shut down production equipment (item 1), which could take 5 – 10 min. Therefore, the thermal and nonthermal TDLs should be related to this requirement. The control room DCS equipment (item 3) and electrical cables (item 4) must maintain electrical signal and power integrity during shut down of production equipment.

The last three columns in Table 5.22 are for establishing the thermal, nonthermal, and other exposure TDLs. (TDLs were discussed in Sect.5.2.)

Table 5.22: Example Worksheet, Loss of Function From Fire Exposure

CONTROL ROOM SUBSYSTEMS / COMPONENTS	PRIMARY FUNCTION – NORMAL OPERATIONS	FUNCTIONAL REQUIREMENTS – EMERGENCY CONDITIONS	LOSS OF FUNCTION FROM FIRE EXPOSURE		
			THERMAL LIMITS	NONTHERMAL LIMITS	OTHER EXPOSURES / LIMITS
1. OPERATORS Two operators — one constantly in Control Room	Operation, control, and monitoring of production equipment	One operator must remain in Control Room for 5 – 10 min to shutdown production equipment. Other employees may immediately evacuate	q_R = 2.5 kw/m^2 T_L = 260°F (127°C)	CO = 3,000PPM* O_2 = 13% *(Tolerable exposure for 5 min; danger of collapse 10 min.)	Visibility 18 ft pathway visibility thru smoke
2. CONTROL ROOM WINDOW Plain glass — no fire rating	Provides view of production area from control room	Prevent passage of smoke and combustion products into control room during emergency shutdown	q_R = 9 kw/m^2 T_L = 320°F (160°C) Window failure from 5 – 10 min exposure	—	
3. CONTROL ROOM EQUIPMENT Electronic control panels and computer DCS consoles	Automatic operation and monitoring of production equipment	Maintain DCS integrity for reliable shutdown of production operations	q_R = 15 – 18 kw/m^2 T_L = 350°F (177°C) Start of DCS malfunctioning	HCl = 100 PPM	Smoke density/ particulate 0.02kg/m^3
4. CABLES ENTERING CONTROL ROOM THRU FLOOR PVC cables; 30 min rated penetration sealant	Power and signal interface between control room and production equipment	Maintain electrical integrity during shutdown of production equipment	q_R = 18 kw/m^2 T_L = 860°F (460°C)	—	
5. COMPARTMENT ASSEMBLY 1 hr rated walls and ceiling per U.L. Fire Resistance Directory	Control room DCS equipment compartmented to provide temperature, humidity, dust, noise control	Maintain a 1-hr rated fire barrier between the control room DCS equipment and the production area equipment	Assumed 45 min effective fire resistance	—	Weak link in compartment integrity is plain glass viewing window
6. STEEL SUPPORTS Uninsulated steel columns and beams	Support concrete floor and control room compartment Control room elevated to provide operator view of entire production area	Maintain the structural integrity of the control room during fire emergencies	q_R = 35-38 kw/m^2 T_L = 1100°F (593°C) For 10 – 15 min exposure time	—	

q_R = radiant heat flux limit DCS = digital Control System
T_L = exposure temperature limit

5.3.2 Modeling Fire Source Intensity

After compiling and evaluating target TDLs based on functional requirements, the next task is to quantify and graphically depict the source fire intensity-time exposure as "seen" by the target. Modeling methods and computer tools are addressed in Sect. 5.4. For the purpose of continuing with the target control room example (Fig. 5.14, Table 5.22) and maintaining focus on developing limiting damage conditions, time lines, and event tree consequence levels, we will assume the following set of graphical fire modeling results were developed:

- Exposure to target control room subsystems
  - Hot smoke layer temperature
  - Smoke layer height above floor
  - Total incident heat flux
- Exposure to control room operator
  - O_2/CO in smoke layer
  - Visibility distance through smoke layer
- Exposure to control room DCS equipment
  - Smoke concentration
  - HCl corrosive gas concentration

Exposure to Target Subsystems

Figure 5.15 provides a simplified graphical depiction of potential thermal exposure to the target control room. "Tg" represents the temperature of the hot smoke layer that could impinge on the control room wall and viewing window; "$\dot{q}r$" represents the potential radiant heat exposure from the flame to various target components (i.e., steel columns, cable trays); and "h_1" represents the distance of the descending hot smoke layer above the floor.

Fig. 5.15Thermal Exposure to Control Room Target

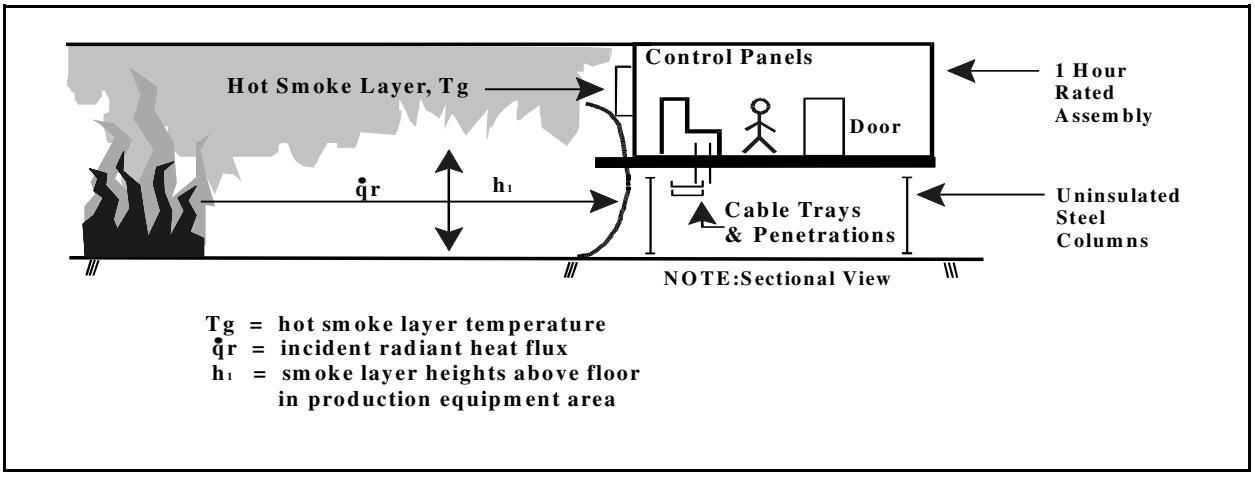
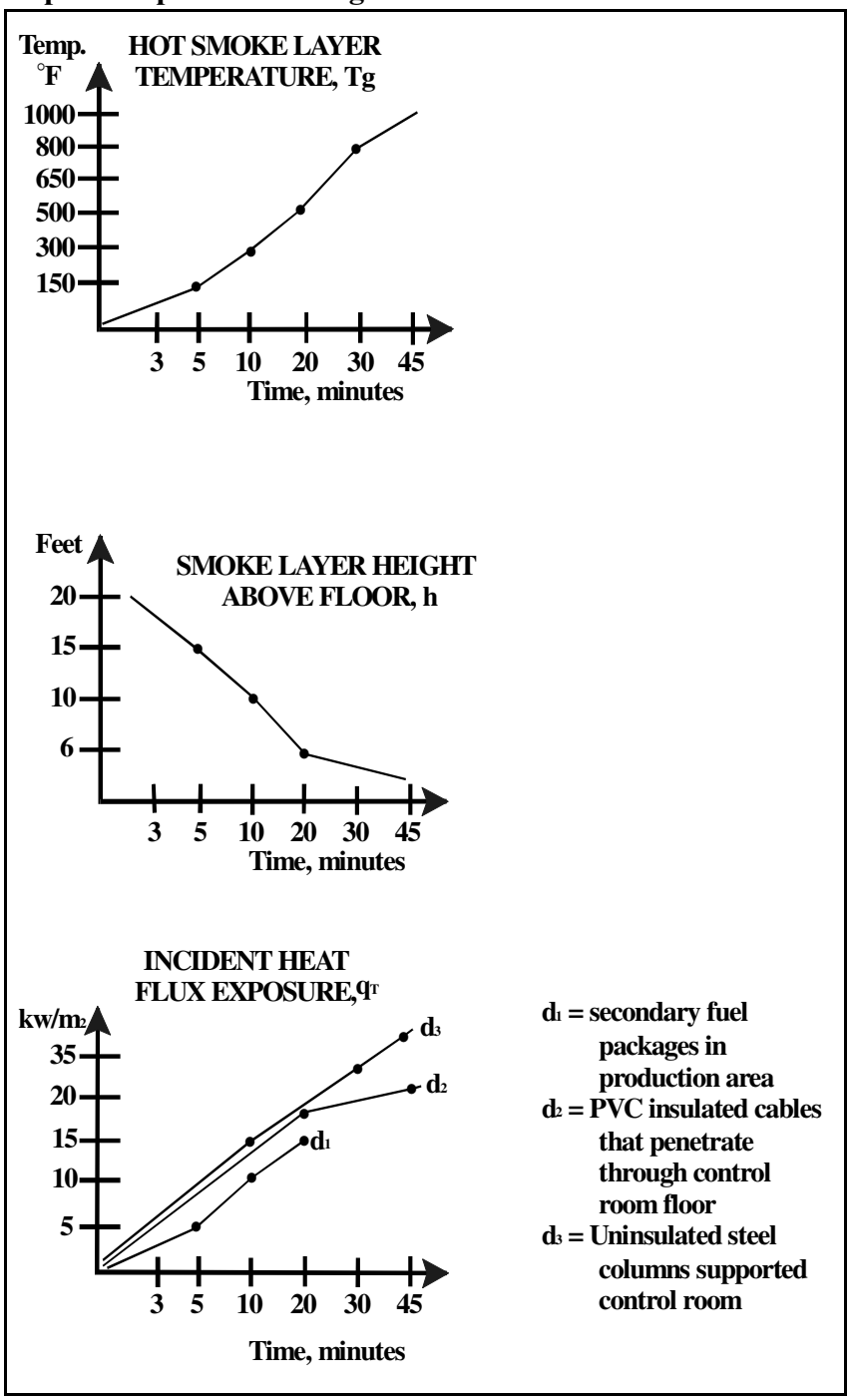


Figure 5.16 provides an example of computer modeling result, which we will use for this example. Results include:

- Hot smoke layer temperature, Tg
- Smoke layer height above floor, h
- Incident heat flux exposure from both radiative and connective components, q_T

Fig. 5.16: Example Computer Modeling Results



From the example computer modeling results in Fig. 5.16 and the established thermal limits for loss of functional performance in Table 5.22, some time-intensity-exposure relationships can be made in Table 5.23.

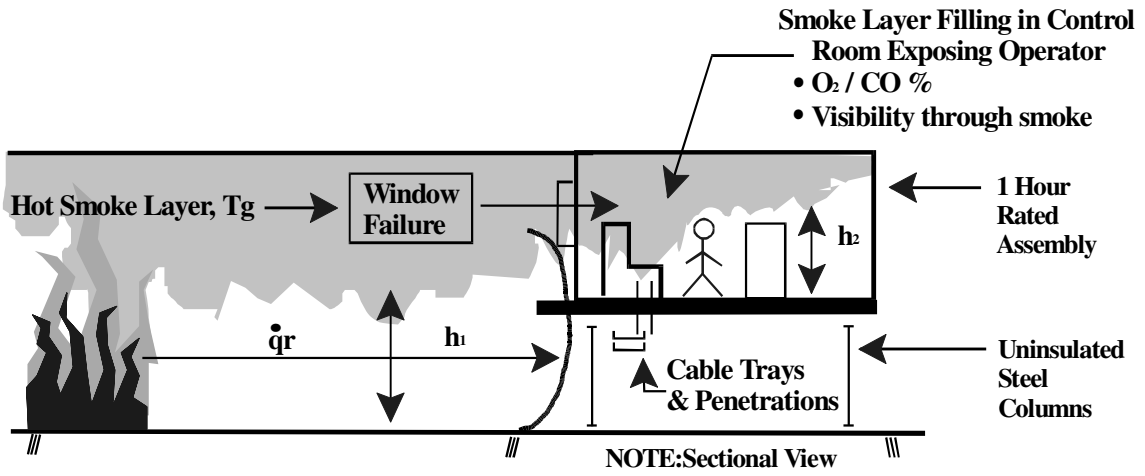
Table 5.23: Potential Time-Related Thermal Exposure to Control Room Subsystems

TIME, MINUTES	INTENSITY	POTENTIAL EXPOSURE	REMARKS
5	• 150°F Smoke layer • Smoke layer exposes control room window	Start of cracking of glass window in control room	Note: 150°F is average smoke layer temperature. It would take some period of time to heat glass up to 150°F
10	• 300°F Smoke layer • Smoke layer exposes control room wall	Beginning of heat exposure to operator and DCS equipment in control room	Assumes glass fails from 5 – 10 min exposure
20	• 500°F Smoke layer • Smoke layer to within 6 ft of production floor • q_T = for d_1 = 16 kw/m^2 • q_T = for d_2 = 19 kw/m^2	• Severe heat exposure to control room equipment • Ignition of secondary fuel package on production floor • Potential ignition of PVC insulated cables which enter through control room floor	Production floor secondary ignitions and flame spread comes into effect Would expect ignition and sustained burning of cables at 20 – 30 min, evolving corrosive HCl gases
30	• 800°F Smoke layer • Smoke layer to within 2 ft of production floor	• Severe heat exposure and minimum visibility for plant fire brigade in building	
45	• Smoke layer starts to exceed 1000°F • Smoke layer descends to floor • q_T = for d_3 = 36 kw/m^2	• Uninsulated steel columns supporting control room start to loose strength	• If fire is not suppressed, steel columns could buckle at 45 – 55 min

Exposure to Control Room Operator

Figure 5.17 provides a simple graphical depiction of potential exposure to the control room operator, who must remain in the control room to safely shut down the production equipment. Thermal exposure has already been discussed. Nonthermal exposures of interest in this example include the concentration of O_2 and CO (carbon monoxide) in the smoke filling the control room and tenability (i.e., visibility through smoke layer) for operator to perform functions and then escape.

Fig. 5.17: Thermal and Nonthermal Exposures to Control Room Operators



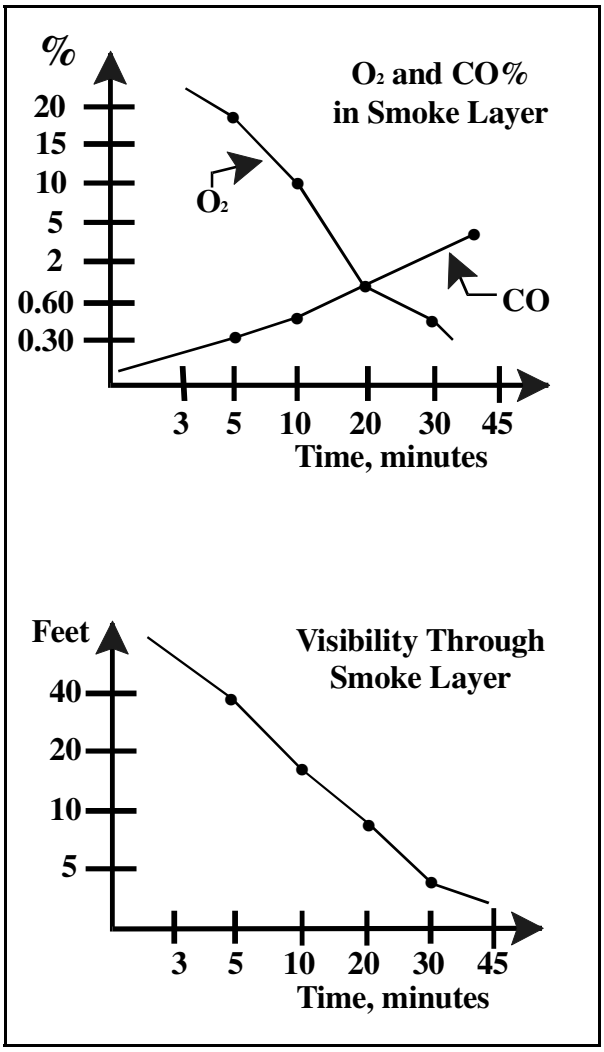
Tg = hot smoke layer temperature
$\dot{q}r$ = incident radiant heat flux
h_1 = smoke layer heights above floor in production equipment area
h_2 = smoke layer height above floor in Control Room

Figure 5.18 provides an example of computer modeling results used for this example. Results include:

- O_2 and CO% concentration in smoke layer
- Visibility through smoke layer

Another concern might be the level of potential irritants in the smoke that could affect operator functions and safe egress.

Fig. 5.18: Example Computer Modeling Results



From the modeling results in Fig. 5.18 and the established nonthermal exposure limits to control room operators in Table 5.22, the following time-intensity-exposure relationships, summarized in Table 5.24, can be made.

Table 5.24: Potential Time-Related Nonthermal Exposure to Control Room Operators

TIME, MINUTES	INTENSITY	POTENTIAL EXPOSURE TO CONTROL ROOM OPERATOR(S)	REMARKS
5	0.30 CO%* 18 O_2%* 3- ft visibility through smoke layer	CO – maximum safe exposure for 5 min	* Concentration in smoke layer at control room window
10	0.60 CO% 10 O_2% 18-ft visibility through smoke layer	CO – headache and dizziness in 1 – 2 min, danger of death in 10 – 15 min O_2 – (10 – 14%) – faulty judgement, rapid fatigue, insensitivity to pain	At 5 – 10 min smoke filling of control room occurs (assuming glass window failure)
20	1.5 CO% 1.5 O_2% 7-ft visibility through smoke layer	CO – unconscious after 2 – 3 breaths, danger of death in 1 – 3 min O_2 – (< 6%) death in 6 – 8 min	 Smoke layer to within 6 ft of production floor
30	2.0 CO% 0.50 O_2% 4-ft visibility through smoke layer		 Smoke layer to within 2 ft of production floor
NOTE: Other concerns might include irritant gases in the smoke layer that might affect operator functions and escape. For example, HC1 (200 ppm or 0.02%), HF (120 ppm or 0.012%), SO_2 (30 ppm or 0.003%).			

Exposure to Control Room Equipment

Figure 5.19 provides a simple graphical depiction of potential exposure to control room digital control system (DCS) equipment. In addition to the thermal exposure from the fire, smoke particulate and corrosive gases are of major concern.

Fig. 5.19: Thermal and Nonthermal Exposures to Control Room Equipment

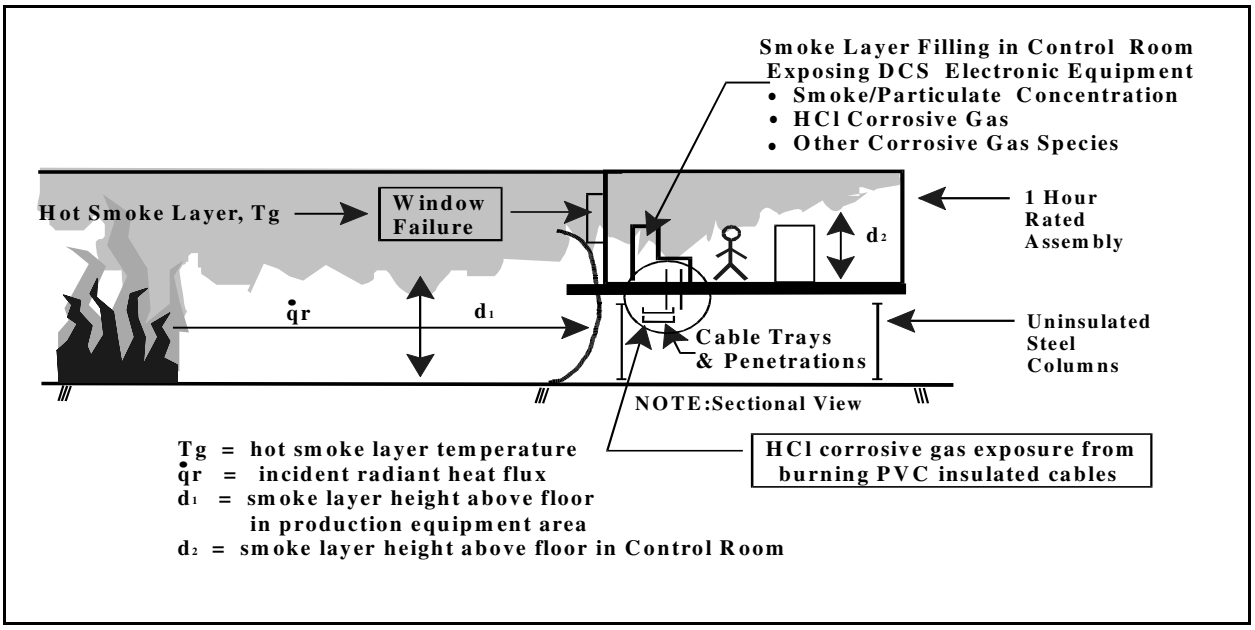
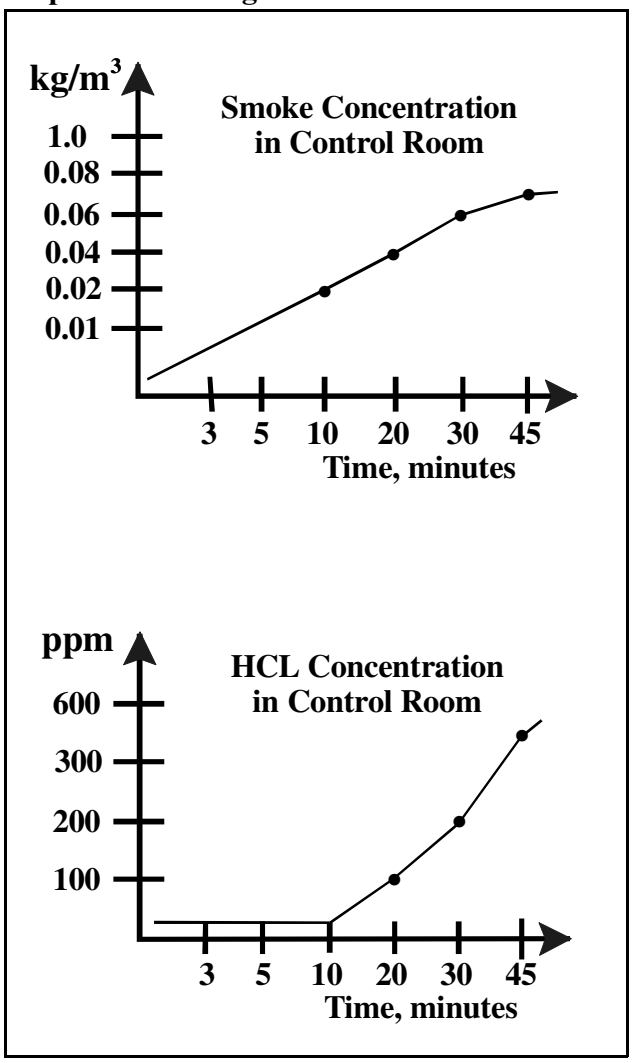


Figure 5.20 provides an example of computer modeling results used for this example. Results include:

- Smoke concentration (i.e., particulate, soot) in Control Room
- HCl concentration in Control Room (from burning PVC cables)

Fig. 5.20: Example Computer Modeling Results



From the modeling results in Fig. 5.20 and the established nonthermal exposure limits to Control Room DCS equipment, the following time-intensity exposure relationships, summarized in Table 5.25, can be made.

Table 5.25: Potential Time-Related Nonthermal Exposure to Control Room Equipment

TIME, MINUTES	INTENSITY	POTENTIAL EXPOSURE TO CONTROL ROOM DCS EQUIPMENT	REMARKS
10	0.02 kg/m^3 Smoke concentration[(a)] in control room	Potential for electrical shorting of some DCS components, depending on level of particulate (soot) in the smoke	At 5 – 10 min control room fills with smoke (assuming glass window fails)
20	0.04 kg/m^3 Smoke concentration in control room 100 ppm HCl concentration in control room	Moderate damage potential. At this level equipment can still be cleaned and repaired	At 20 min PVC insulated cables that enter through control room floor ignite
30	0.06 kg/m^3 Smoke concentration in control room 220 ppm HCl concentration in control room	Severe (possibly irreparable) damage potential to all control room equipment	

NOTE: [(a)] The level of potential particulate (soot) in the smoke in most cases has to be qualitatively judged dependent on the fuel source, combustion efficiency, and ventilation conditions. Other concerns might include other corrosive gas specifics in the smoke that might affect control room equipment

5.3.3 Damage Limiting Conditions and Time Line Parameters

Based on the information developed up to this point for the example control room, we can start to establish a target vulnerability time line. Table 5.26 provides an example of this.

There are various ways of setting up a time line table. Table 5.26 separates thermal exposure vs. nonthermal exposure for people, equipment, structures, and secondary effects. The time line, in minutes, is labeled across the top. A 45 min limit was selected, as past this point structural failures will start occurring if the fire is not controlled. The range of time denoted in Table 5.26 accounts for a degree of uncertainty.

Table 5.26: Example Loss of Functional Performance Versus Time for Thermal and Non-Thermal Exposures

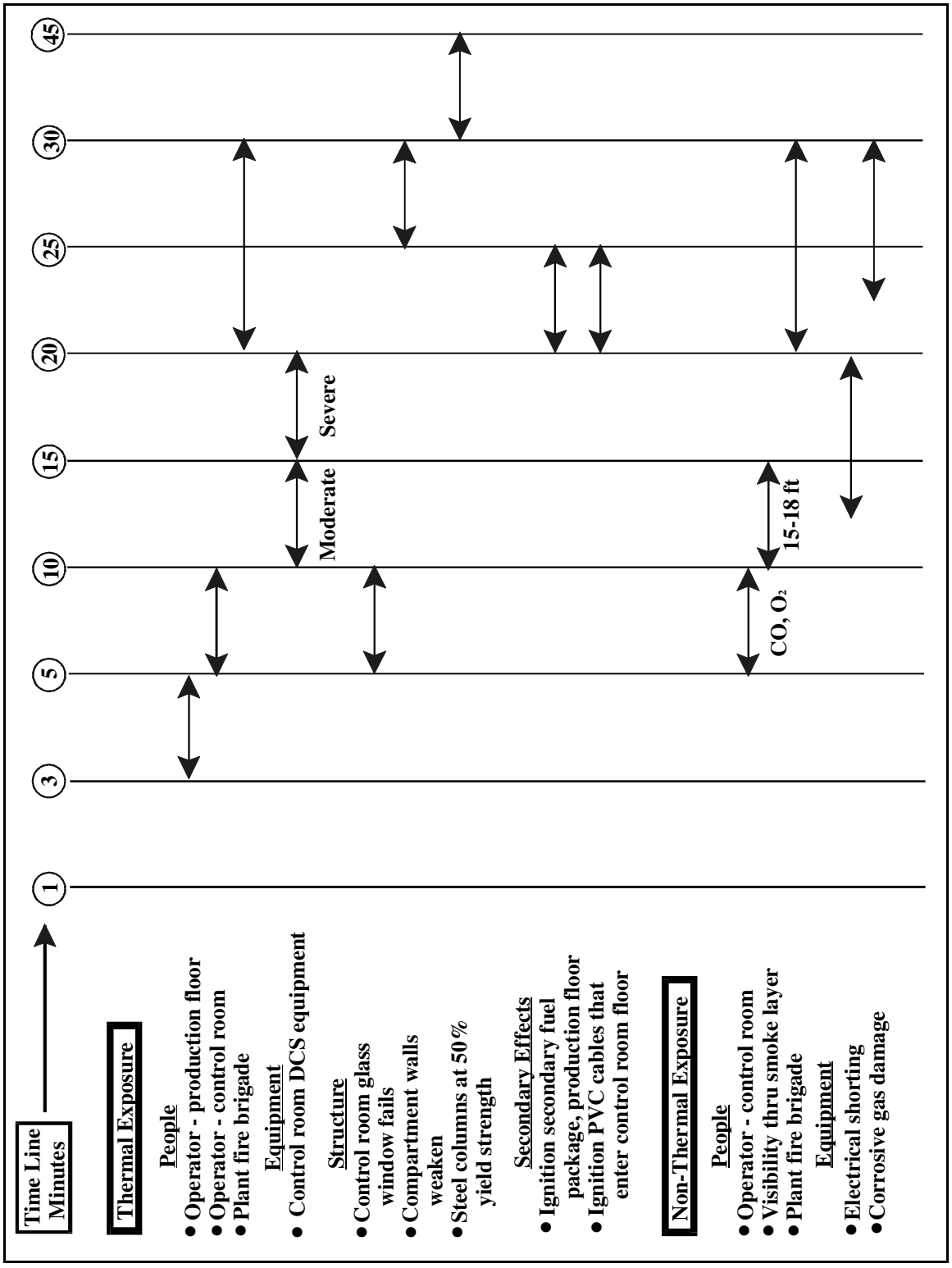
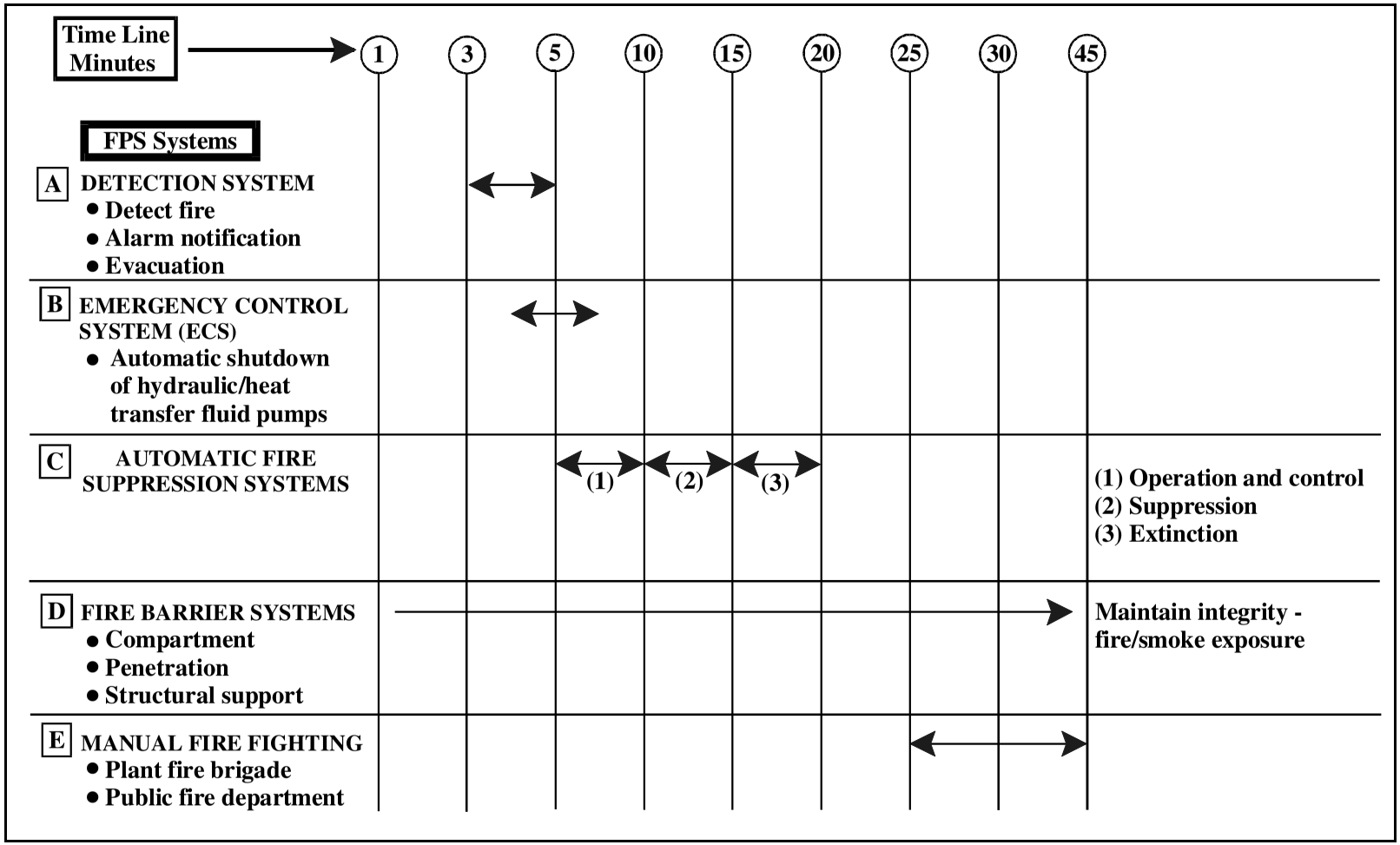


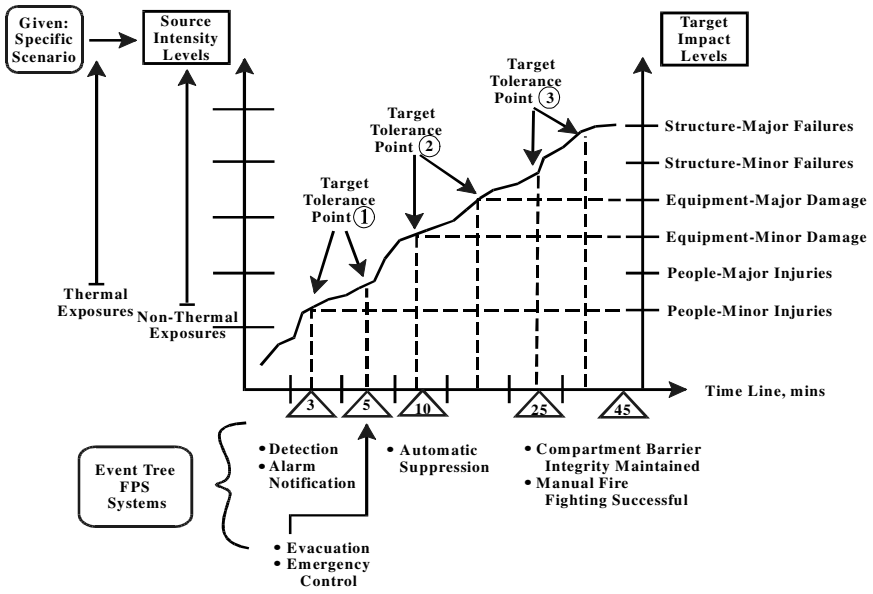
Table 5.27 provides an example of developing FPS response parameters based on the target vulnerability time established in Table 5.26.

Table 5.27: Example Fire Protection System (FPS) Response Parameters



Another way of looking at fire protection system (FPS) time line response parameters is shown in Fig. 5.21.

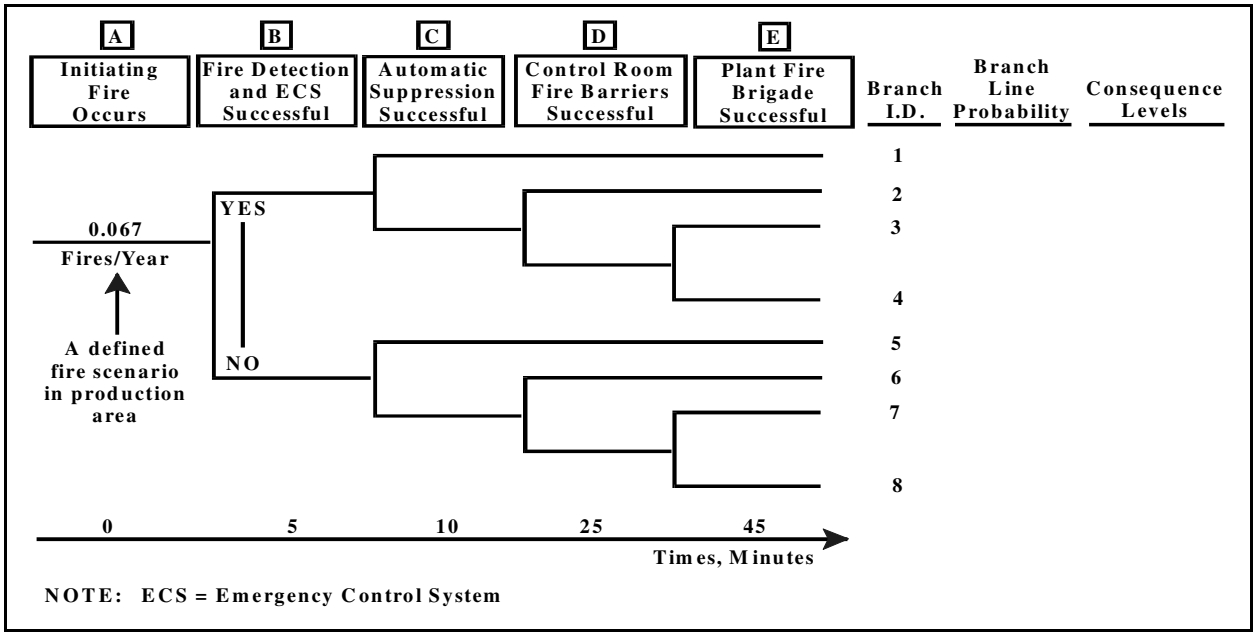
Fig. 5.21: Example Scenario-Based Exposure Profile Curve with Target Tolerance Points



TARGET TOLERANCE POINTS	ESTIMATED TIME LIMITS	TIME LINE FACTORS						
① People	3 – 5 min	Detection time	+	Alarm notification time	+	Evacuation time	≤	5 min
② Equipment	5 – 10 min	Detection time	+	ECS operation	+	Automatic suppression system operation	≤	10 min
③ Structure	25 – 45 min	Fire brigade notification time	+	Fire brigade response time	+	Manual suppression/ extinguishment	≤	45 min

Fig. 5.22 presents an example event tree time line based on Table 5.27 and Fig. 5.21.

Fig. 5.22: Example Event Tree



5.3.4 Categorizing Event Tree Consequence Levels

Event tree consequences of primary interest include:

- Life safety
- Property damage
  - — Equipment
  - — Stock
  - — Structure
- Business interruption
- Other
  - — Environmental
  - — Company image

Life Safety

Life safety exposure and consequences can be broken down into categories related to injury or fatality potential to operators, employees, contractors on-site, and off-site to the public. Table 5.28 presents a general example of establishing life safety exposure and consequence levels.

Table 5.28: General Example of Life Safety Exposure and Consequence Levels

HUMAN EXPOSURE LEVELS	GENERAL CONSEQUENCE DEFINITION	REMARKS
1 – Low	First aid (one person – primarily smoke-related exposure)	
2 – Moderate	Moderate burn injury potential may require hospital treatment (one person)	
3 – High	Severe burn potential requiring hospital treatment (1 – 2 people)	
4 – Very High	Potential for multiple injuries, single person death	
5 – Extremely High	Potential for 2 – 10 fatalities	
6 – Catastrophic	Potential for greater than 10 fatalities	

The event tree in Fig. 5.23 provides an example of associating life safety consequence levels with branch line scenarios: 1 (best case), 3 (probable case), and 8 (worst case).

Fig. 5.23: Example Event Tree With Life Safety Consequence Levels

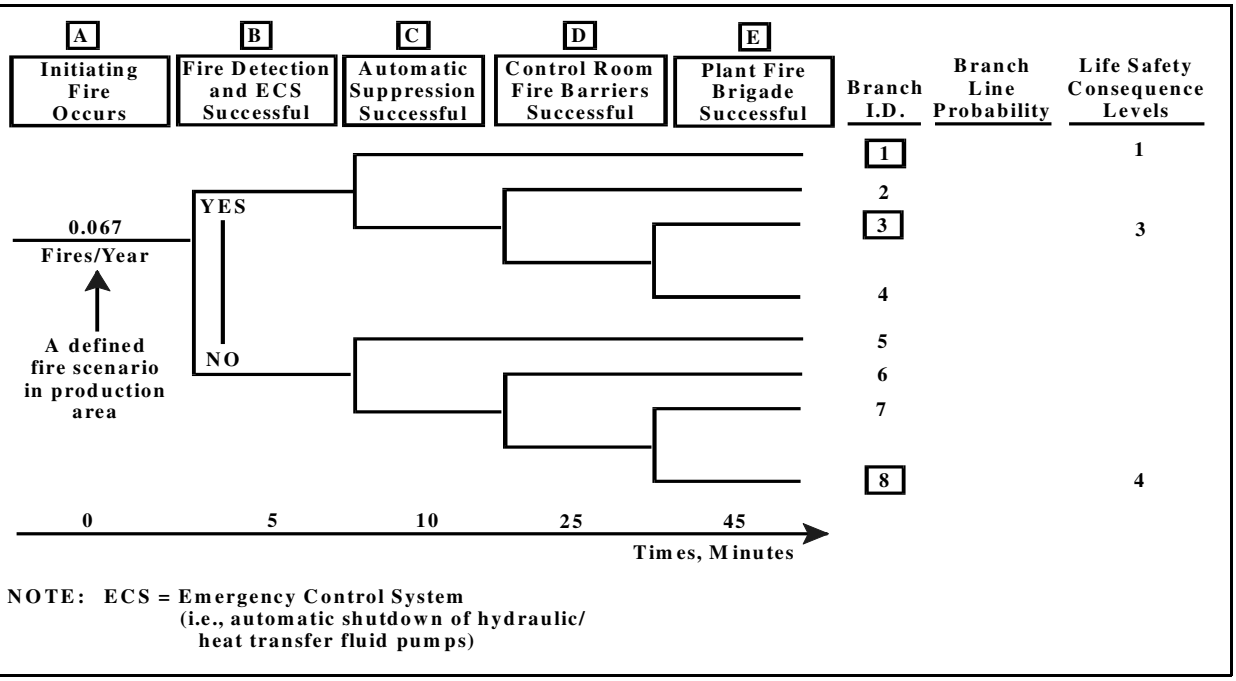


Table 5.29 presents an example worksheet for describing and documenting selected life safety exposure and consequence categories.

Table 5.29: Example Worksheet – Life Safety Exposure/Consequence Categories

BRANCH LINE	SCENARIO DESCRIPTION	LIFE SAFETY EXPOSURE	EXPOSURE/CONSEQUENCE CATEGORY
1	Following fire initiation – fire detection and alarm notification occurs within 5 min. Shutdown of production equipment occurs within 5 – 10 min. The automatic suppression system is successful in controlling fire temperatures below the failure point of the control room viewing glass window	• People in production floor evacuate within 5 min • The control room operator(s) is not exposed if the control room window does not fail	1 – Low exposure Potential first aid from smoke exposure on production floor
3	Fire detection and alarm notification occurs. Automatic suppression system performance is not successful within 10 min and the control room window fails. The plant fire brigade responds and prevents structural damage	• The control room operator(s) is exposed if the control room window fails and the operator must remain in the control room to manually shut down production equipment, which could take 5 – 10 min	3 – Moderate exposure Potential burn injuries, toxic smoke exposure to control room operator
8	Fire detection and alarm notification does not occur within 5 – 10 min. Automatic suppression is not successful. control room barrier components fail (glass window, cable penetration, etc.) and the plant fire brigade fails to prevent structural failures	• With a failure of fire detection and alarm notification within 5 min, people in the production floor could be exposed during a delayed evacuation • Without quick fire detection and notification, the control room operator would be delayed in shutting down production equipment	4 – High exposure Severe burn and toxic smoke exposure might require hospital treatment

Evasive Action

The objective of planned evasive action is to reduce the potential consequences to people from fire or explosion incidents. Evasive actions can include sheltering-in-place, escape to a designated safe shelter, or evacuation from a building, a process area, or from the plant area.

For assessing evacuation time effectiveness from a building, there are numerous factors to consider: the nature of the incident and its intensity level; the type of building, building construction, ventilation systems, fire or blast resistance integrity, type of occupants, populations, efficiency of egress routes, and frequency and quality of occupant training.

For an existing facility, based on specific initiating event scenarios, these factors can be evaluated and evacuation drills can be conducted and timed. For proposed facility design for new construction or renovation projects, evacuation time effectiveness may have to be modeled.

Building evacuation models are commonly termed egress models and are based upon studies of humans' movement within buildings. Egress modeling is usually conducted as part of the fire modeling effort.

Table 5.30 provides a listing of a few egress computer models.

Table 5.30: Some Egress Computer Models

EGRESS MODEL	DESCRIPTION AND AVAILABILITY
Evacnet 4	Interactive computer program that models building evacuations. Produces results that describe an optimal evacuation of the building Available from: University of Florida web site: www.ise.ufl.edu/kisko/files/evacnet/index.htm Demo is available
Simulex	Simulates escape movement of occupants from large, geometrically complex buildings Available from: Integrated Environmental Solutions web site: www.ies4d.com/products/4DPerformanceAssessmentTools/simulex/simulex.htm Email: sales@ies4d.com Demo is available
Building EXODUS	Evacuation and crowd simulation software. Allows realistic desktop simulations of people in both normal and emergency conditions. Can interface with the latest version of the NIST fire model, CFAST Available from: University of Greenwich Fire Safety Engineering Group web site: www.fseg.gre.ac.uk/exodus/ Email: exodus@gre.ac.uk Demo is available

Property Damage

Property damage (PD) values are usually broken down into building, equipment, and stock replacement costs. PD estimates are very plant, facility, and operation specific. To develop PD, it is advantageous to establish some general, property categories, or damage levels. A general example is presented in Table 5.31.

Table 5.31: Example of Property Damage Levels

PROPERTY DAMAGE LEVELS	DAMAGE FACTOR RANGE (%)	CENTRAL DAMAGE FACTOR (%)	GENERAL DEFINITION	REMARKS
1 – Slight	0 – 1	0.5	Limited localized minor damage not requiring repair	
2 – Light	1 – 10	5	Significant localized damage of some components generally not requiring major repair	
3 – Moderate	1 – 30	20	Significant localized damage of many components warranting repair	
4 – Heavy	30 – 60	45	Extensive damage requiring major repairs	
5 – Major	60 – 100	80	Major widespread damage that may result in the facility being razed, demolished, or repaired	
6 – Destroyed	100	100	Total destruction of the facility, equipment, stock	

Table 5.32 provides some additional information that could be used to establish classes or categories of property damage.

Table 5.32: Example – Classes of Damage After Fire, Characterization and Description

CLASS	CHARACTERIZATION	DESCRIPTION
1	Cosmetic damage, surface	Characterized by soot deposits and discoloration. In most cases, soot and discoloration can be washed off. Uneven distribution of soot deposits may occur. Permanent discoloration on high-quality surfaces may occur. Odor is included in the class; it may be difficult to remove, but chemicals are available for elimination
2	Technical damage, surface	Characterized by damage on surface treatments and coatings. Small extent only of concrete spalling or corrosion on uncovered metals. Painted surfaces can be repaired. Plastic-coated surfaces need replacement or covering. Minor spallings may remain or can be replastered
3	Structural damage, surface	Characterized by some concrete cracking and spalling, lightly charred wood surfaces, some deformation of metal surfaces or moderate corrosion damage. Type of damage includes class 2 damage, and can be repaired similarly
4	Structural damage, cross-section (interior)	Characterized by major concrete cracking and spallings in web of I-beams, deformed flanges and partly charred cross-sections of wood constructions, degraded plastics Damage can in many cases be repaired on the existing structure. Within the class are also deformations of structures so large that the load-bearing capacity is reduced, or dimensional alterations prevent proper fitting into building. This applies in particular to metal/steel constructions
5	Structural damage to members and components	Characterized by severely damaged structural members and components, impaired materials and large deformations. Concrete constructions are characterized by extensive spalling, exposed reinforcement and impaired compression zone. In steel structures extensive permanent deformations have arisen due to diminished load-bearing capacity caused by high-temperature conditions. Wood structures may have almost fully charred cross-sections

The event tree in Fig. 5.24 provides an example of PD consequence levels (equipment, stock, structure) related to branch line scenarios 1 (best case), 3 (probable case), and 8 (worst case).

Fig. 5.24: Example Event Tree Indicating Property Damage Levels

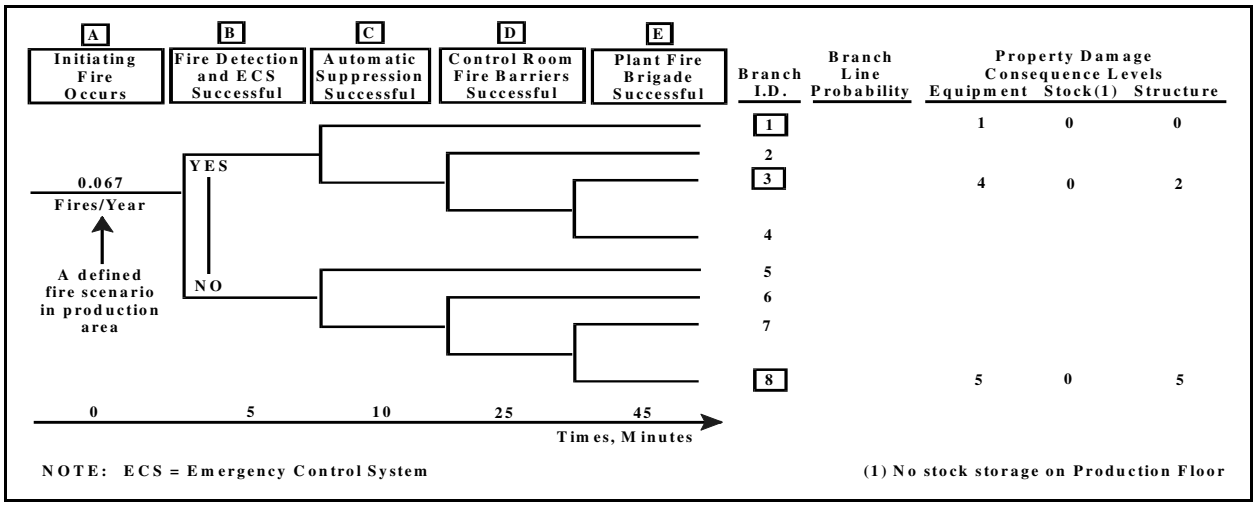


Table 5.33 presents an example worksheet for describing and documenting selected PD consequence categories or levels.

Table 5.33: Example Worksheet – Property Damage Exposure/Consequence Categories

BRANCH LINE	SCENARIO DESCRIPTION	PROPERTY DAMAGE EXPOSURES	EXPOSURE/CONSEQUENCE CATEGORY
1	Following fire initiation – fire detection and alarm notification occurs within 5 min. Shutdown of production equipment occurs 5 – 10 min. The automatic suppression system is successful in controlling fire temperatures below the failure point of the control room viewing glass window	• Equipment: limited exposure from fire and smoke particulate requiring cleanup	Equipment: 1 – Slight; cleanup of equipment, no significant damage requiring repairs
3	Fire detection and alarm notification occurs. Automatic suppression system performance is not successful within 10 min and the control room window fails. The plant fire brigade responds and prevent structural damage	• Equipment; Potential heavy damage from heat and corrosive smoke to control room DCS equipment • Structure; Light exposure to control room structure, requiring cleanup and minor repairs	Equipment: 4 – Heavy to control room equipment Structure: 2 – Light to Control Room structure
8	Fire detection and alarm notification does not occur within 5-10 min. Automatic suppression is not successful. Control Room barrier components fail (glass window, cable penetration, etc.) and the Plant Fire Brigade fails to prevent structural failures	• Equipment and structure; major damage to control room equipment and structure	Equipment and structure: 5 – Major damage potential requiring major repairs or replacement

Business Interruption

Business interruption (BI) estimates are usually broken down into days downtime, percent production loss, and dollars per day production loss. Estimating BI is very facility and operation specific.

Variables in the BI evaluation include the value of the product being produced, the market cycle of the product, the product profit margins, and BI interdependency if the product is used in others parts of the overall production process. The operations department should be able to provide good data support in these areas.

For BI evaluation, consequence levels or categories can be developed. A general example is presented in Table 5.34.

Table 5.34: Example of Business Interruption (BI) Categories

BI LEVELS	PRODUCTION DOWNTIME RANGE	AVERAGE PRODUCTION DOWNTIME, DAYS	GENERAL DEFINITION	REMARKS
1 – Slight	0 – 1 days	0.5	Limited localized minor equipment damage not requiring repair, but clean up	
2 – Light	1 – 10 days	5	Significant localized damage of some equipment components generally not requiring major repair	
3 – Moderate	10 – 30 days	20	Significant localized damage of many equipment components warranting repair	
4 – Heavy	30 – 90 days	60	Extensive damage requiring major equipment repair & replacement	
5 – Major	90 – 270 days	180	Major widespread damage that may result in extensive repairs and equipment replacement	
6 – Critical	270 – 360 days	315	Total downtime of the majority of the facility, close to one year	
7 – Total	1 – 2 Years	Use Maximum Expected	Extended downtime of facility exceeding 1 year	

The event tree in Fig. 5.25 provides an example of associating BI (i.e., production downtime) with branch line scenarios and property damage levels.

Fig. 5.25: Example Event Tree

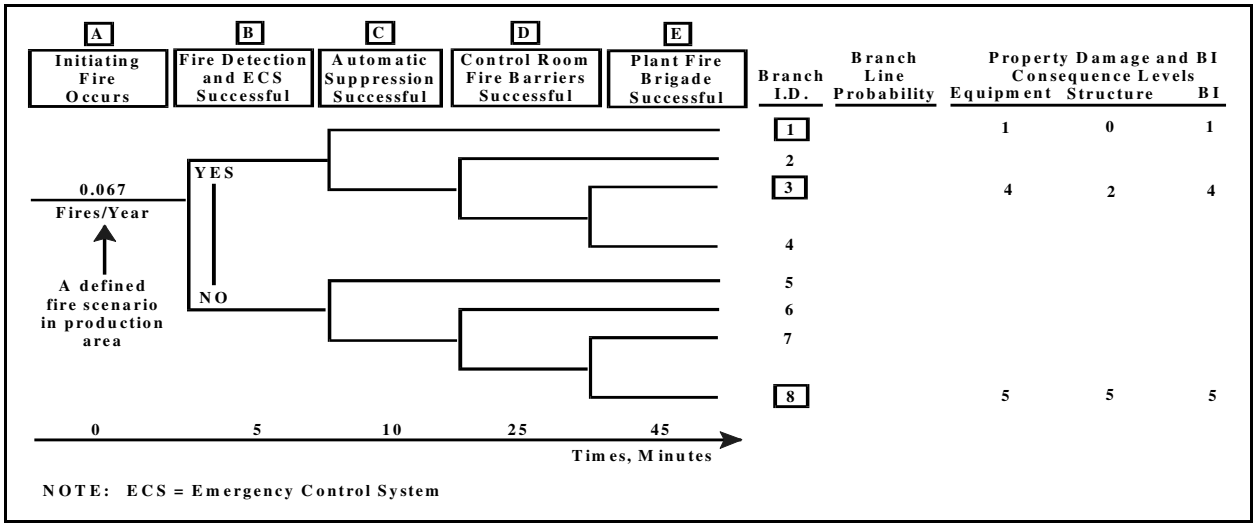


Table 5.35 presents an example worksheet for describing and documenting selected BI exposure and consequence categories or levels.

Table 5.35: Example Worksheet – Business Interruption Exposure/Consequence Categories

BRANCH LINE	SCENARIO DESCRIPTION	BUSINESS INTERRUPTION EXPOSURES	BI EXPOSURE/CONSEQUENCE CATEGORY
1	Following fire initiation – fire detection and alarm notification occurs within 5 min. Shutdown of production equipment occurs 5 – 10 min. The automatic suppression system is successful in controlling fire temperatures below the failure point of the control room viewing glass window	BI exposure is based on Equipment and structural property damage exposure = 1 — Slight	1 – Slight Limited damage, primarily cleanup 0 – 1 days production downtime
3	Fire detection and alarm notification occurs. Automatic suppression system performance is not successful within 10 min and the control room window fails. The plant fire brigade responds and prevents structural damage	BI Exposure is based on: Equipment property damage exposure = 4 — Heavy Structure property damage exposure = 2 — Light	4 – Heavy Extensive damage requiring major equipment repair and replacement 60 days average production downtime
8	Fire detection and alarm notification does not occur within 5 – 10 min. Automatic suppression is not successful. Control room barrier components fail (glass window, cable penetration, etc.) and the plant fire brigade fails to prevent structural failures	BI Exposure is based on equipment and structural damage = 5 — Major	5 – Major Extensive repairs and replacement of equipment and structures 180 days average production downtime

Environmental Damage

Potential environmental impacts related to fire and explosion (F&E) incidents are difficult consequences to estimate as environmental impacts following a fire can take several forms. There may be clean-up costs associated with toxic material spills, contamination, and the cost associated with treatment and disposal of waste streams. Though this is a real potential cost, it is often not considered in fire or explosion exposure and consequence analysis.

The costs for cleanup of environmental spills can be estimated along with potential regulatory fines that the company may incur. Other consequences, such as the effects of negative publicity surrounding F&E related environmental accidents, are more difficult to estimate.

Table 5.36 presents an example of some environmental impact ratings primarily associated with cleanup costs from the Department of Energy (DOE).

Table 5.36: Example DOE Environmental Impact Rating

ENVIRONMENTAL IMPACT: The following criteria pertain to the environmental damage that an accident might cause. Typical accidents include spills, accidental discharges, or breaches of material tanks.	
1. *Negligible*	1 – Less than or equal to $50,000 in clean up costs 2 – Small spills or spills that do not immediately enter into the soil. Contamination that is quickly and readily cleaned up with on site or locally available technology
2. *Marginal*	1 – Accidents resulting in greater than $50,000 and less than or equal to $1,000,000 in clean up costs 2 – Minor soil contamination with nearly no potential for contaminant migration
3. *Critical*	1 – Accidents resulting in greater than $1,000,000 and less than or equal to $10,000,000 in clean up costs 2 – Significant on site soil contamination 3 – Likely long term migration of contamination off site or to water source. However, does not pose any short term threat
4. *Catastrophic*	1 – Accidents resulting in greater than $10,000,000 in clean up 2 – Groundwater or surface water in immediate danger of contamination

Other F&E consequence considerations can include regulatory fines, media reaction, public perception, and company image.

Noncompliance costs result directly from fines and penalties that may be imposed should a regulatory agency find violations. In addition to the more common consequences, an often overlooked but critical risk faced by companies are those driven by public perception and community and customer goodwill. Perception and company image can have significant impacts on shareholder equity and, in the case of consumer product companies, loss of customers and direct impact on sales.

The relative importance of these types of risks varies depending on the nature of operations at a plant site and the types of business. The challenge is to estimate potential unplanned costs associated with these risks. Table 5.37 presents a general example of establishing company image consequence levels.

Table 5.37: Example Company Image Consequence Levels

COMPANY IMAGE EXPOSURE LEVELS	GENERAL CONSEQUENCE DEFINITION	REMARKS
1	• Local news coverage • Minor community and customer awareness/concerns	
2	• State news coverage • Moderate community and customer awareness/concerns	
3	• National news coverage • Major community and customer awareness/concerns	

Developing equivalent monetary values (EMVs) for various exposures and consequences to facilitate risk reduction cost/benefit analysis is addressed in Chap.7, Risk Estimation.

5.4 COMPARTMENT FIRE MODELS

Compartment fire models, whether single equations set up in a spreadsheet, zone computer models capable of quickly running on a standard PC, or more complex field models requiring major computing power, are all fundamentally based on the conservation equations for energy, mass species, and momentum. A description of conservation equations and the basis for commonly used fire modeling equations is beyond the scope of this section. The following box provides some references on these topics.

Some References On Fire Dynamics and Modeling

The SFPE Fire Protection Engineering Handbook, 2nd Edition: [1]

- Chap. 3-5, Compartment Fire Modeling
- Chap. 3-7, Zone Computer Fire Models
- Chap. 3-1, Burning Rates
- Chap. 2-1, 2-2, 2-4, Flame Height, Fire Plumes, Ceiling Jets

NFPA Fire Protection Handbook, 18th Edition: [8]

- Sect. I, Chap. 7, Dynamics of Compartment Fire Growth
- Sect. II, Chap. 4, Introduction to Fire Modeling
- Sect. II, Chap. 5, Deterministic Computer Fire Models

Karlsson, B., J. Quintiere, Enclosure Fire Dynamics [17]

Drysdale, Dougal, An Introduction to Fire Dynamics, 2nd Edition [18]

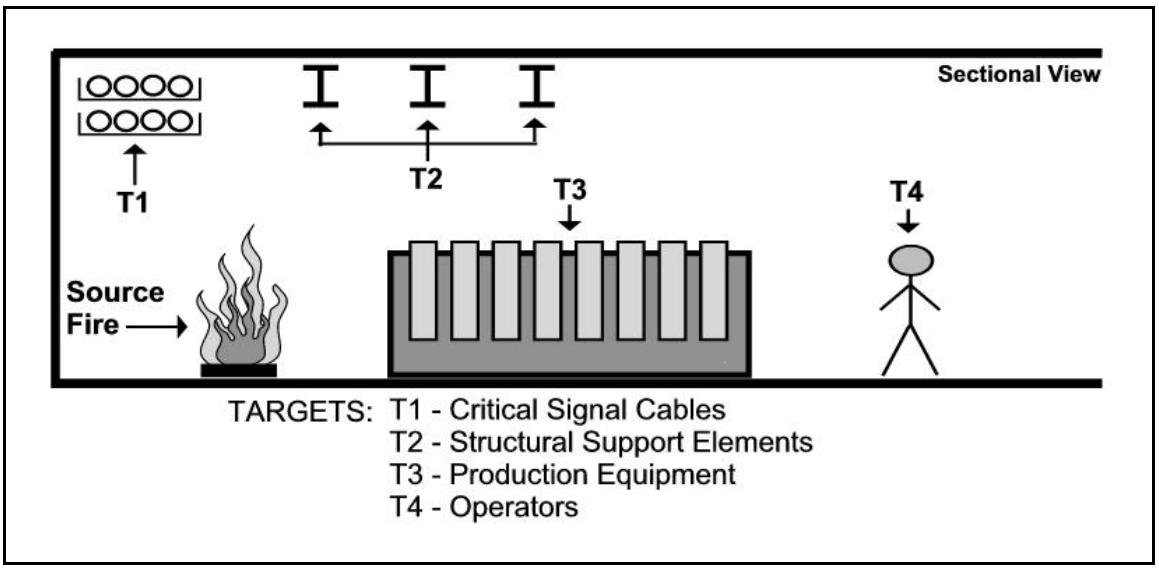
The selection and use of fire models will require that at least one member of the risk assessment team have a good understanding of fire dynamics, fire modeling methods, and specific fire model capabilities and limitations.

Fire models provide a tool to assist the risk assessment team in developing exposure profiles and must be used with engineering insight and judgement. This section overviews some basic features of zone and field fire models.

5.4.1 Source → Pathway → Target

The focus of exposure profile modeling is to evaluate the level of exposure at the target versus time. One of the first steps is to assess the vulnerability of the selected target(s), which was discussed in the previous section. As shown in Fig. 5.26, targets can include people, equipment, utilities, storage, and building structural elements.

Fig. 5.26: Example of Target Selection

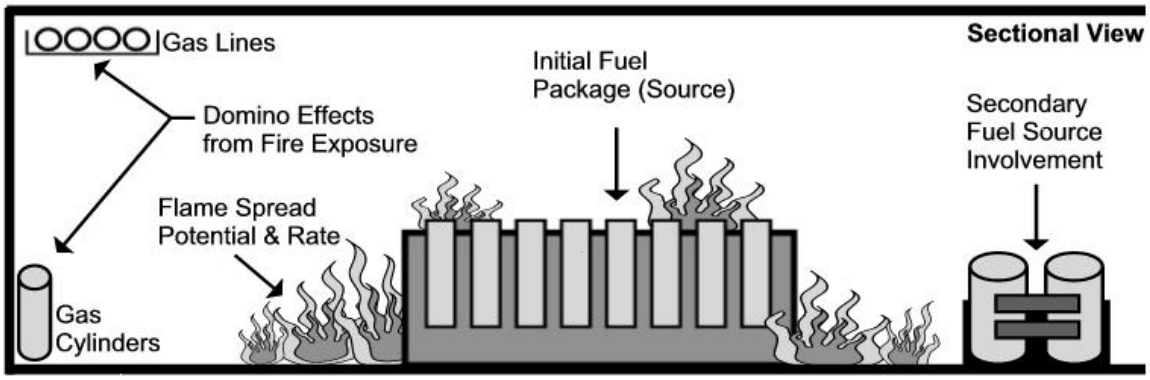


The majority of compartment fire models should be called fire effects models as the outputs these models estimate are based on an input fire scenario that is selected and quantified by the model user. Whether using hand calculations or a computerized zone or field model, the input fire scenario is generally the most uncertain and sensitive variable. As shown in Fig. 5.27, some of the issues of primary concern include:

- Definition of the initial fuel package (i.e., source fire) boundaries
- Estimation of the potential fire growth and HRR of the initial fuel package
- Flame spread potential and rate from the initial fuel package to adjacent objects and to the structure
- Ignition, fire growth, and additional HRR from secondary fuel sources or packages
- Domino effects of the fire such as exposure and involvement of flammable gas lines or cylinders in the area, structural failures, etc.

Because source fire quantification is such an important issue, Sect 5.5 provides additional discussion.

Fig. 5.27: Example of Some Fire Evaluation Concerns



The pathway is what the target "sees" of the source fire exposure intensity (i.e., temperature, radiant heat, smoke concentrations, toxic or corrosive gas species, etc.) over a time interval. This will be primarily related to:

- Compartment geometry and the location of the target(s) in relation to the source fire
- The fire size (flame height, HRR, plume strength, etc.) and potential duration
- Ventilation systems and interlocks
- Performance of fire suppression systems

The location of the target(s) can be initially evaluated in terms of near field, intermediate field, and far field exposure zones.

Figure 5.28 presents an example of a target and secondary ignition source located within the near field or flame zone. Within this zone, there is a high potential for having direct flame impingement on the target or secondary ignition sources. To assess this exposure potential, the flame geometry and the heat transfer from the flame to the target can be calculated.

Fig. 5.28: Example Secondary Ignition Sources(s), Target(s) Within Flame Zone or Near Field

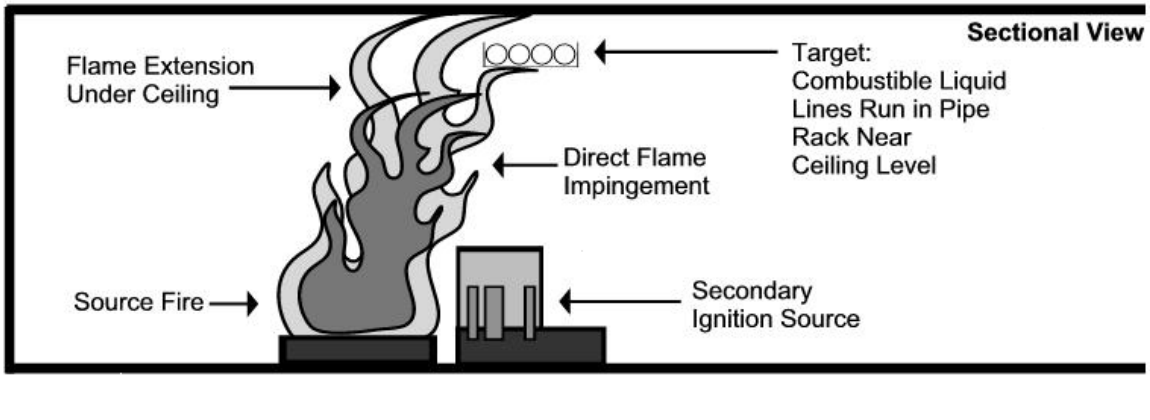
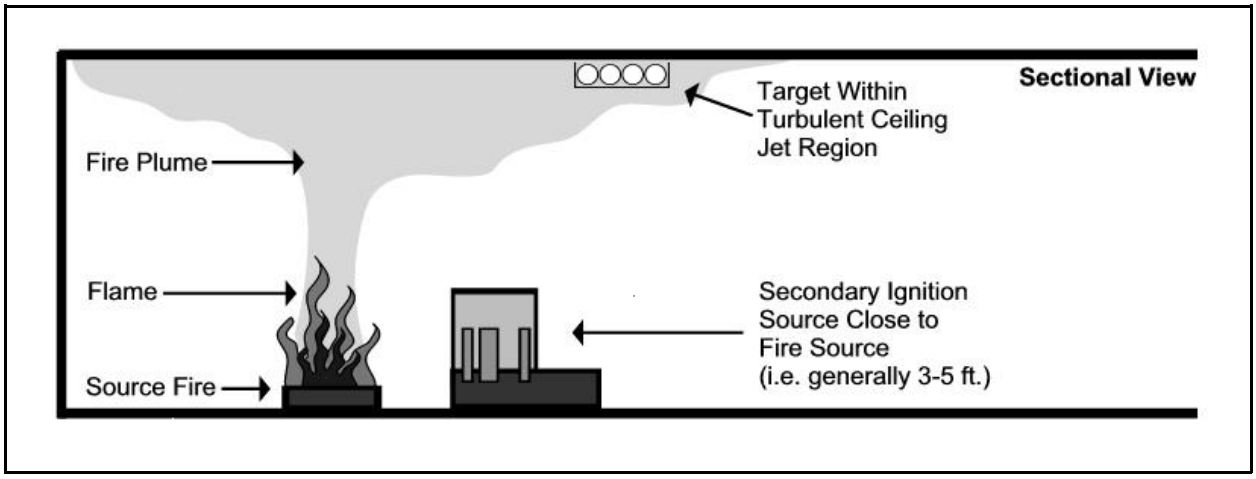


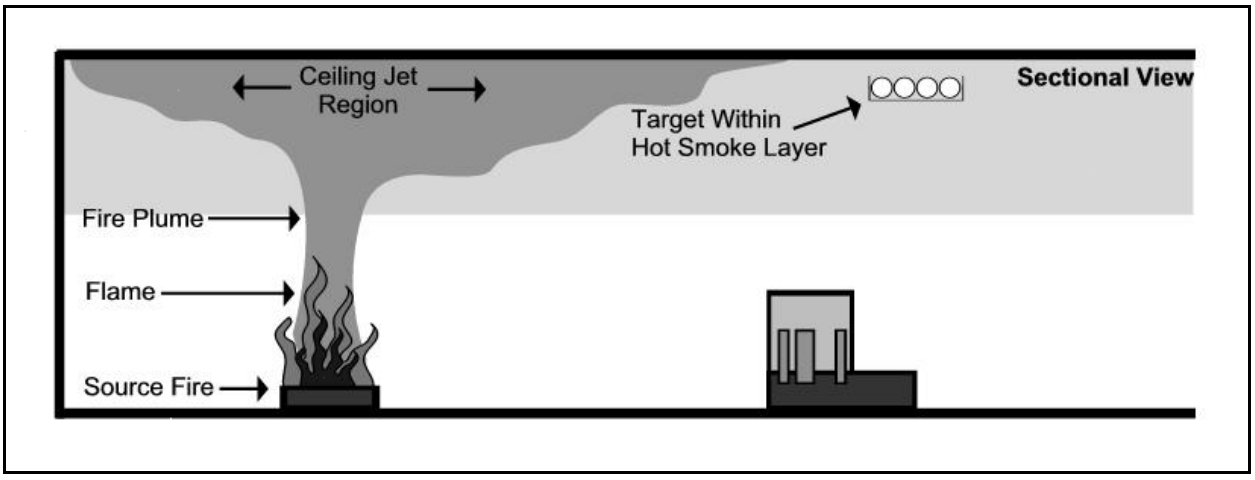
Figure 5.29 presents an example of a target and secondary ignition source within the intermediate zone. The general boundaries of the intermediate zone include targets or potential secondary ignition sources within the turbulent ceiling jet region of the fire plume (subject to high convective heat) or within a radiant heat exposure range where damage or ignition could occur within 10 min.

Fig. 5.29: Example Secondary Ignition Source Target Within Intermediate Field



Far field exposure as presented in Fig. 5.30 can extend to a wide area depending on the intensity and duration of the fire source. As a general definition, this would include targets within the hot gas or smoke layer or within a radiant heat exposure range where the potential for damage or ignition could occur within 20 – 45 min.

Fig. 5.30: Example, Target Within Far Field



The location of the target in the exposure field (near, intermediate, or far) will have a direct bearing on the potential time to damage versus the response time needed for successful fire detection and fire suppression response.

In risk-informed, performance-based evaluations, the primary focus is the near and intermediate field exposure during the first 20 to 45 min following ignition. This is where much effort is needed to realistically define source fire scenarios and intensity levels within the near and intermediate exposure zones. This information, when presented in an exposure time line, becomes the foundation for the ETA of layered fire risk controls, which include fire detection and protection systems.

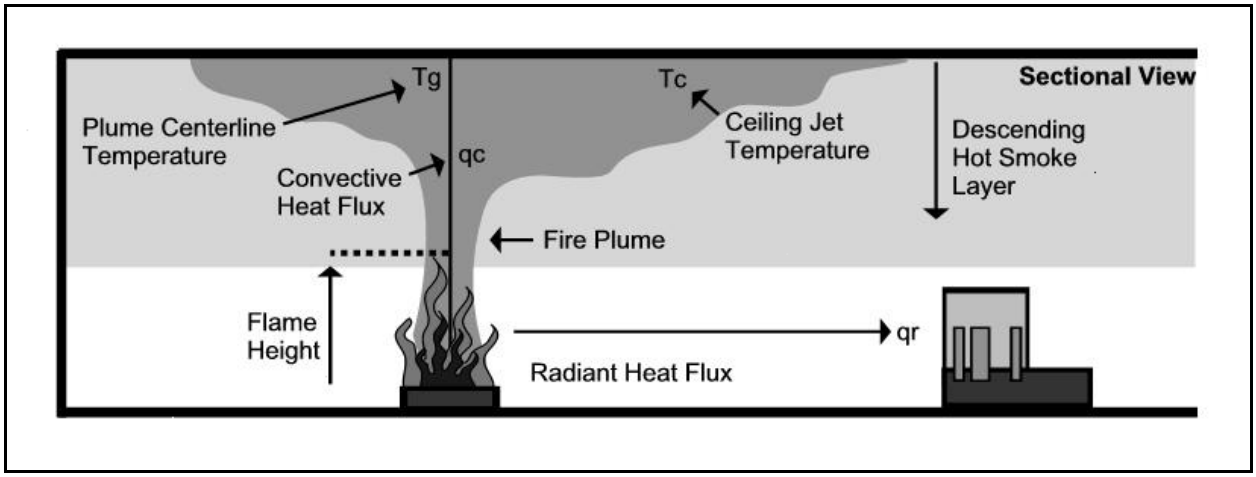
5.4.2 Some Fire Calculation Concepts

As depicted in Fig. 5.31, some primary fire calculations of interest for the initial stages of near and intermediate exposure include:

- Flame height
- Fire plume centerline temperature
- Ceiling jet temperatures
- Radiant heat exposure to secondary fuel sources

This section provides a brief overview of some calculation concepts. Estimating fire's HRR, which is the driving force in estimating fire exposure, is addressed in Sect.5.5, Initial HRR Evaluation.

Fig. 5.31: Some Primary Fire Calculation Measures



Flame Height

Knowledge of flame height is important for evaluating near field hazards to personnel, property, and fire spread potential. Flame heights must be known to estimate flame impingement boundaries and the effects of flame radiation when radiant heat solid flame, geometric view factors are applied. In addition, as fire plume relationships are only valid above the flame, it is necessary to be able to predict flame height.

The estimated flame height is the height where the luminous yellow flame is present at or slightly above that height 50% of the time. Available flame height correlations are all based on empirical observations (timed photographs, videotape analysis, recorded visual observations) from small and large scale fire tests.

There is general agreement in available flame height correlations that the flame height (L_f) is proportional to $\dot{Q}^{2/5}$ (HRR). For free burning fires in an open area (not against a wall or in a corner) the Heskestad correlation is: [1]

$$L_f = 0.230\,\dot{Q}^{2/5} - 1.02D$$

L_f = flame height, meters

$\dot{Q}$ = total heat release, kW, for the fuel package

D = diameter of the fire source, meters

For noncircular fire sources, the effective diameter can be calculated by the following equation:

$$D = \sqrt{\frac{4 x SurfaceArea}{\pi}}$$

This equation is valid when the length to width ratio of the rectangular fire source is less than 4.

The Heskestad flame height equation is generally valid over a wide range of free burning pool fires and solids where the peak HRR can be estimated. To evaluate flame height for a fuel package located inside a building against a wall or in a corner, the following equation can be used: [1]

$$L_f = .1743\left(K_{LF}\,\dot{Q}\right)^{2/5}$$

$\dot{Q}$ = total heat release, for the fuel package, *Kw*

K_{LF} = 1 when the fuel package is in the open

K_{LF} = 2 when the fuel package is against a wall

K_{LF} = 4 when the fuel package is in a corner

The flame height from a large, outside, freely burning fire (3 – 30 m) can be estimated using Thomas's equation: [1]

$$L_f = 42\left(\frac{\dot{m}''}{P_a\left(g \cdot D\right)^{1/2}}\right)^{0.61}$$

L_f = flame height (m)

D = fuel source diameter (m)

$\dot{m}''$ = fuel mass burning rate (kg/m^2-s)

g = gravitational constant (9.78 m/s^2)

P_a = density ambient air (1.206 kg/m^3)

Uncertainties in flame heights associated with different methods of measurement and associated calculation methods are typically on the order of plus or minus 10 to 20%.

Fire Plume/Ceiling Jet Correlations

Calculations discussed in this section provide estimates of fire temperatures directly above a strong, buoyant flame and radially outward from the fire centerline along an unconfined ceiling above the flame.

This output is useful in assessing:

- Thermal damage to targets
- Fire detector and sprinkler head response time
- Smoke filling rates and smoke venting
- Flashover potential

The engineering analysis of fire plume/ceiling jets was initially developed from numerous large-scale fire experiments conducted at Factory Mutual Research Center (FMRC). These experiments span a range of HRRs from 670kW to 98MW, a range of ceiling heights from 4.6 m (15 ft) to 15.5 m (50 ft), and a range of normalized radial distances (r) from the plume centerline to approximately r/H = 8, where H is the fire source to ceiling height. Empirical relationships were developed to describe plume and jet characteristics.

The heat generated by a fire is either convected or radiated away from the flame. In most cases at least 60 – 70% of the total heat released is carried away by convection. The convective heat flux is carried away by the fire plume above the flames, while the rest of the total heat is radiated away in all directions.

The temperature under a ceiling will be at a maximum directly above the centerline of the fire and with decay outward from this point. When hot gases are vented some distance from the fire, or if there is negligible accumulation of stagnant hot gases, the maximum gas temperature occurs at a distance below the ceiling of less than 1% of the total ceiling height above the burning fuel.

Within the continuous flame region, temperatures can range from 1600°F to 2400°F (i.e., for hydrocarbon fires). Centerline temperatures above the flame vary with the strength of the fire and

the height above the flame. Heskestad presents the following temperature rise relationship above the centerline of a steadily burning fire (i.e., plume region): [1]

$$\Delta T_{PL} = 25\left[\frac{\dot{Q}_c^{2/3}}{(z - z_o)^{5/3}}\right]$$

where

ΔT_{PL} = plume centerline temperature rise (°K)

$\dot{Q}_c$ = connective HRR (kW)

$z - z_o$ = height above fuel surface (m)

Plume gases impinge on the ceiling and turn to form a ceiling jet that spreads radially beneath the ceiling. The plume impingement region extends in an area that has a radius of approximately 0.2 times the height from the fire source to the ceiling. Within this radial distance, the gases are considered part of the fire plume. Beyond, the fire gases form a relatively thin ceiling jet that has a thickness of approximately 10% of the fire source to ceiling height. Alpert has developed a simplified correlation for unconfined ceiling jet temperatures: [1]

$$\frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.32}{(r / H)^{2/3}}$$

where

ΔT_{cj} = ceiling jet temperature rise

r = radial distance from fire axis

H = ceiling height

ΔT_{pl} = plume centerline temperature rise

Using the simple, empirical relationships given above, the temperatures above strong, steady-state fires that burn under unconfined ceilings can be estimated. With this information, one can evaluate the potential for thermal damage to targets in the near and intermediate exposure zones and the potential for ignition of secondary fuel sources that may be located near the ceiling level. Other researchers have developed slight variations of the above fire plume and ceiling jet correlations. [1]

To perform the iterative process of calculating the depth and temperature of a descending hot smoke layer versus time in a confined compartment and dynamic effects if the fire transitions from a fuel controlled fire to a ventilation controlled fire, zone computer fire models can be employed. The next section provides an overview of some available zone fire models with a discussion of issues and limitations.

Calculating radiant heat exposure is addressed in Sect. 5.6.

5.4.3 Zone Fire Models

Fire models have been applied in industrial plants to predict environmental conditions inside a compartment or room of interest. The models typically try to estimate parameters such as temperature, hot smoke gas layer height, mass flow rate, toxic species concentration, heat flux to a target, and the potential for fire propagation in the pre-flashover stage of a compartment fire. Current fire models do not accurately predict post-flashover. Therefore, fire modeling calculations should be limited to the pre-flashover period of the fire. [19]

Zone models can range from a single compartment zone models to multi-compartments, which are located and connected within the defined boundaries of a building or structure. A zone model is primarily one-dimensional and divides the compartment into several zones that may include:

- flame or combustion zone
- fire plume
- compartment hot gas zone or upper layer
- compartment lower layer
- compartment ambient zone
- target exposure zone

Each zone is assumed to have uniform temperature and gas concentrations. Zone models solve the conservation equations for mass, momentum, energy, and in some models, gas species. Zone models usually incorporate simplifying assumptions to the conservation equations to reduce the computational demand for solving these equations. Most zone models can be run quickly on a PC and can provide a good "first-order" target exposure prediction tool if properly applied within the framework of engineering insight and judgement.

Some typical outputs from compartment and multicompartment zone fire models may include:

- Layer temperature
- Layer height
- Concentration of O^2, CO^2, CO, etc.
- Vent flows (mass and energy)
- Heat release history
- Mass loss history
- Fire duration
- Temperature at detection devices and sprinkler heads
- Room lining temperature
- Ignition of other fuel packages
- Flame height
- Flashover
- Mass entrainment
- Energy entrainment
- Vision distance
- Egress time

Some of the more complex zone type models provide additional features such as:

- Radiation calculations from the flame and upper layer to room objects (to determine secondary ignition potential)
- Multiple compartment analysis, with mass exchange between each compartment
- Transport of toxic or corrosive gas species (HCN, HCl, etc.)

Table 5.38 provides a listing of some of the fire models developed by the National Institute of Standards and Technology (NIST). You can access a description of these models and also download many of these models at the NIST web site, http://www.bfrl.nist.gov/866/fmabbs.html.

Table 5.38: Some NIST Fire Modeling Programs

ALOFT-FT	A Large Outdoor Fire Plume Trajectory model – Flat Terrain
ASCOS	Analysis of Smoke Control Systems
ASET-B	Available Safe Egress Time – BASIC
ASMET	Atria Smoke Management Engineering Tools
BREAK1	Berkely Algorithm for Breaking Window Glass in a Compartment Fire
CCFM	Consolidated Compartment Fire Model version VENTS
CFAST	Consolidated Fire and Smoke Transport Model
DETACT-QS	Detector Actuation – Quasi Steady
DETACT-T2	Detector Actuation – Time squared
ELVAC	Elevator Evacuation
FASTLite	A collection of procedures that builds on the core routines of FIREFORM and the computer model CFAST to provide engineering calculations of various fire phenomena
FIRDEMIND	Handheld hosestream suppression model
FIRST	Fire Simulation Technique
FPETool	Fire Protection Engineering Tools (equations and fire simulation scenarios)
Jet	A model for the prediction of detector activation and gas temperature in the presence of a smoke layer
LAVENT	Response of sprinkler links in compartment fires with curtains and ceiling vents
NIST Fire Dynamics Simulator and Smokeview	The NIST Fire Dynamics Simulator predicts smoke and/or air flow movement caused by fire, wind, ventilation systems, etc. Smokeview visualizes the predictions generated by NIST FDS. This is a field model, not a zone model

The CFAST (Consolidated model of Fire growth And Smoke Transport) program listed in Table 5.38 is an upgrade of the FAST (Fire And Smoke Transport) program. CFAST is a multiroom fire model that predicts the conditions within a structure resulting from a user-specific fire. CFAST version 2.0.1 can accommodate up to 15 compartments with multiple openings between the rooms and to the outside. The required program inputs are the geometrical data describing the rooms and connections; the thermophysical properties of the ceiling, walls, and

floors; the fire as a rate of mass loss; and the generation rates of the products of combustion. The program outputs are the temperature and thickness of, and species concentrations in, the hot upper layer and the cooler lower layer in each compartment. Also given are surface temperatures and heat transfer and mass flow rates. CFAST also includes mechanical ventilation (up to 30 ducts and 5 fans), a ceiling jet algorithm, and capability of multiple source fires (up to 16).

The transport of products of combustion can be roughly estimated using a wide range of existing smoke transport models such as FAST, CFAST, and CFAST/FIRAC. FIRAC is an HVAC code that can be used alone or in conjunction with a zone model such as CFAST.

5.4.4 Issues and Limitations of Zone Fire Models

Zone models are limited by the need to specify a fire source scenario HRR history. The importance of the initial HRR evaluation is discussed in Sect. 5.5.

Another limitation is flame spread and secondary fuel source involvement. Babrauskas states: [20]

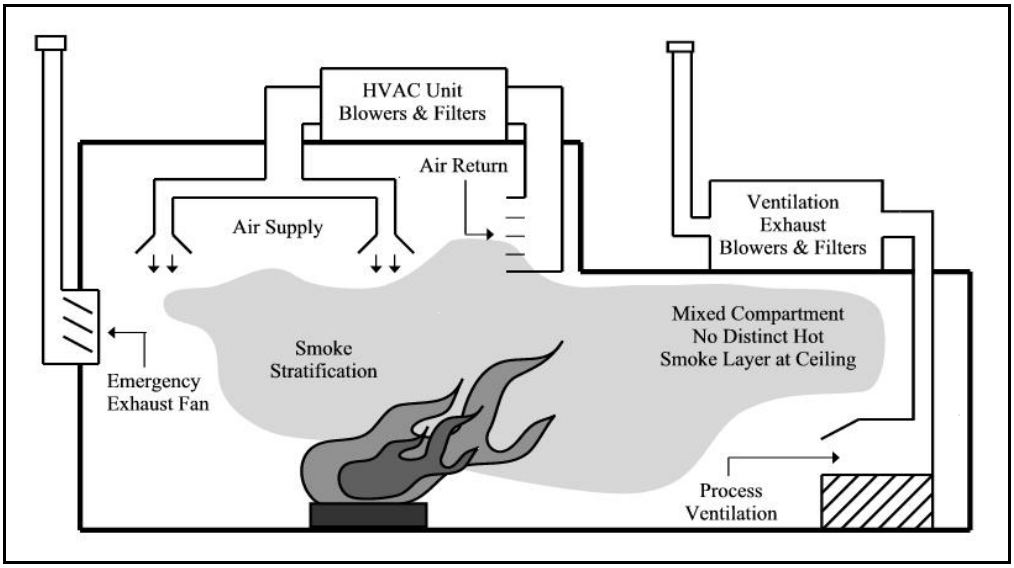
> "Not a single available room fire model today offers flame spread calculations. Flame spread needs to be considered in any fire where combustible solids are present and can ignite and spread flame. Theories of flame spread, of course, do exist, and a number of them have been published in the literature. None of them, however, are incorporated in the available fire models. This, perhaps, is the single most serious limitation of today's models."

If there is flame impingement at the ceiling, flame extension into the upper hot gas layer, or secondary fuel combustion in the hot gas layer, two-zone fire modeling correlations become invalid in most cases.

Sloped ceilings, irregular ceiling levels, very tall ceilings (i.e., typically greater than 35 ft), or obstructions at the ceiling level (such as ventilation ducting, cable trays, etc.) may limit or invalidate the application of a zone model.

In buildings containing process equipment or electronic equipment, the area ventilation air-exchange rates are usually very high. As presented in Fig. 5.32, there may be various modes of ventilation — process ventilation, recirculated air via unit-area HVAC system, emergency exhaust ventilation systems, etc. The question becomes, is a two-zone model valid for the ventilation conditions or is there a "mixed" compartment situation that may invalidate the two-zone concept? Engineering evaluation of ventilation shutdown or startup interlocks (i.e., from a detection system, suppression system, manual controls, etc.) coupled with performing smoke simulation tests to assist in determining smoke movement or stratification may be needed to answer this question.

Fig. 5.32: Example of Possible Industrial Ventilation Systems



Industrial process buildings and storage facilities are generally large, mostly open buildings, with high ceilings, and varied construction and ventilation systems, and contain many diversified fire sources. Zone fire models used for first-order assessment of fire exposure in industrial facilities may be suitable, provided the user understands the conditions under which the model will yield acceptable predictions or estimates. Acceptability or accuracy will depend on the particular fire exposure information needed to support development of event tree time lines and consequence levels.

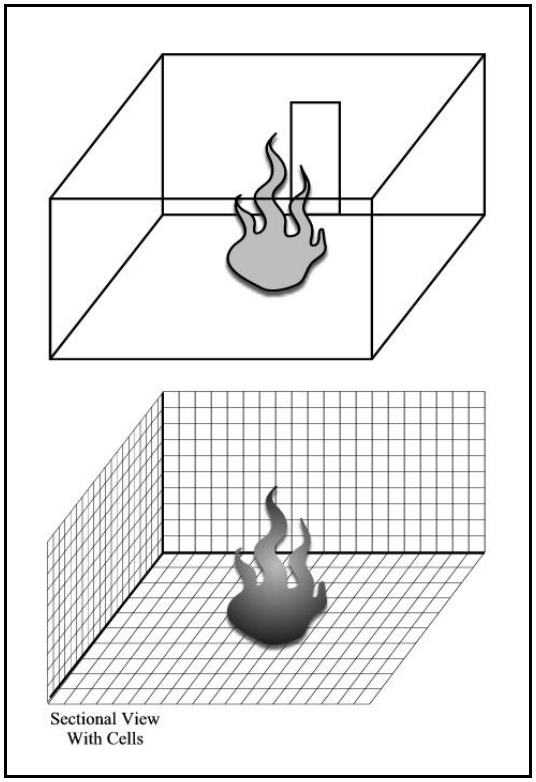
With all fire models, sound engineering judgement is needed in the interpretation of the results. Understanding the validity of a zone model to provide reasonably accurate predictions for the fire exposure problem under risk review may require research into the model's validation tests and discussion with the model's developers. For irregular or complex building geometries, complex ventilation systems, or where more detail is required on convective or radiant heat exposure levels at specific points, the use of a field fire model may be required.

5.4.5 Field Fire Models

Field fire models employ computational fluid dynamics (CFD) software, which can predict three-dimensional fluid flow (i.e., the flow of hot turbulent fire gases) with heat and mass transfer across a whole field of points or cells within a compartment.

In general, CFD-based field modeling equations consist of three dimensional, time dependent, nonlinear partial differential equations — the Navier-Stokes equations. CFD software solves the fundamental equation of fluid flow and mass, energy, and momentum conservation for the fire exposure at discrete points in time and space. To accomplish this, the compartment is divided into a large number of three dimensional cells or control volumes as illustrated in Fig. 5.33.

Fig. 5.33: Example of Dividing an Enclosure Into Cells for Field Modeling



The approximate number of computational cells appropriate for the field modeling effort will depend on the compartment geometry, the accuracy required, and from a practical standpoint, the computer speed and memory. As a general example, a small control room may require around 6,000 cells, while an industrial process area may require in excess of 60,000 cells.

To accommodate fire field modeling, CFD models generally require the incorporation of submodels such as combustion, convection, conduction, and radiant heat models. The modeling equations are simultaneously solved in each cell to obtain parameters of interest such as fire gas velocity, pressure, temperature, radiation, species concentration, etc. The model can then graphically display quantitative differences in these parameters throughout the computational grid and at selected target locations.

Table 5.39 provides a listing of some field fire models, which was provided by Combustion Science and Engineering, Inc., Columbia, Maryland.[21] In the listings, the developers' Internet web site address is provided as many of these web sites provide graphics and video clips of field modeling simulations. CFD-based field models have been successfully used for various fire exposure evaluations including airport terminals, aircraft cabins, transportation tunnels, high rise office buildings and hospitals, response of smoke control systems, water spray systems, etc. The selected model validation references in Table 5.39, which provide application examples, are listed in Sect. 5.9, References.

Table 5.39: A Listing of Some Field Fire Models

MODEL NAME	BRIEF DESCRIPTION	COMPANY / ORGANIZATION WEB SITE ADDRESS	SOME VALIDATION REFERENCES	COMMENTS
CFX CFX-4 and CFX-5	General-purpose fluid dynamics software, applicable to dispersion, fire, and explosion within internal and/or external environments The software can be used for assessing fire dynamics, smoke movement, fire-structure issues, and fire suppression	AEA Technology PLC. http://www.software.aeat.com /cfx.	IA to IH	Commercially available software Supports Windows NT and UNIX platforms
Fire Dynamics Simulator (FDS)	General purpose low Mach number CFD code specific to fire-related flows Large eddy simulation based fire model. Solution of the low Mach number approximation to the Navier-Stokes equations Rectilinear, single block grids, mixture fraction based combustion model Sprinklers included. Rudimentary suppression algorithms Visualization via the software package Smokeview	National Institute of Standards and Technology (NIST) Model developers: Kevin McGrattan, Glenn Forney, NIST www.fire.nist.gov	See NIST web site	Hardware: UNIX or PC
FIRE Version 1.8	CFD model with water sprays and coupled to solid/liquid phase fuel to predict burning rate and extinguishment FIRE is a computational fluid dynamics code for two-dimensional or three-dimensional combustion situations. It can be applied to solid, liquid, or gas fueled fires. FIRE predicts flow patterns and velocities, gas species concentrations and smoke dispersal, temperatures, combustion, particle trajectories, convective heat transfer, radiative heat fluxes. Solutions can be steady state or time dependent	J. H. Kent; Department of Mechanical Engineering, University of Sydney Australia e-mail: jolnk@aeromech.usyd.edu.au	2A to 2F	Research software, not commercially available Contact developer for information.

Table 5.39: A Listing of Some Field Fire Models (Cont'd)

MODEL NAME	BRIEF DESCRIPTION	COMPANY / ORGANIZATION WEB SITE ADDRESS	SOME VALIDATION REFERENCES	COMMENTS
PHOENICS Version 3.3.1	PHOENICS is a general-purpose computational fluid dynamics (CFD) code for use by academia and industry as a design and analysis tool for any process involving fluid flow, combustion, and heat and mass transfer. The code employs the finite-volume technique, and it has been applied across a wide range of industries, including aerospace, chemical process, power generation, biomedical, HVAC, health and safety, automobile, defense, environmental and electronics Demo is available at http://www.simuserve.com/adelfi/prompt.htm	Professor D. B. Spalding, CHAM Ltd, 40 High Street, Wimbledon, London SW19 5AU,UK. PHOENICS can be obtained directly from CHAM, see http://www.cham.co.uk/phoenics/d_polis/d_info/phover.htm . For further information, see also http://www.cham.co.uk/website/new/mes2sals.htm.	For publications list see http://www.cham.co.uk/website/new / support/publish.htm and also http://www.simuserve.com/cfd-shop/journal.htm. For on-line application examples which includes validation examples, see http://www.cham.co.uk/phoenics/d_polis/d_applic/applic.htm	Academic, commercial and R&D licenses are available whose price depends on computer platform and duration of license. Shareware versions are available by downloading them from the Internet (see http://www.simuserv.com/cfd-shop/shwrtop.htm). DOS; Windows 95, or 98; NT, LINUX; and UNIX platforms. Parallel versions use standard message-passing protocols (PVM or MPI) as used all major paralled platforms, and so the code can run on any parallel machine that supports PVM or MPI (see http://www.cham.co.uk/phoenics/dis/dinfo/ phover.htm#paral2)
SMARTFIRE	A PC based fire field model with auto mesh generation and interactive graphical interface providing dynamic control of the CFD software. Capable of simulating fires within multiple compartment geometries. SMARTFIRE is an open architecture CFD environment with an integrated knowledge based system that attempts to make fire field modeling accessible to non-experts in CFD. There are three major components to the software: CFD code, User Interfaces, and Expert System. By embedding expert knowledge into the CFD software, it is hoped that fire field modeling is made more accessible to the fire engineer with limited CFD expertise. The expertise currently embedded within the code is used to support the critical task of mesh specification of fire field simulation scenarios. More information about SMARTFIRE can be found at http://fseg.gre.ac.uk/smartfire/	SMARTFIRE development Team, FSEG, The University of Greenwich, key members consist of Dr. John Ewer, Prof. Ed Galea, Dr. Mayur Patel, Dr. Fuchen Jia, Mr. Angus Grandison Contact Professor E. Galea, FSEG, The University of Greenwich, 35 Park Row, Greenwich, UK SE10 9LS, smartfire@gre.ac.uk, http://fseg.gre.ac.uk/smartfire/	6A to 6G	Annual commercial license, discounts available for education, fire brigades, local authorities, etc. Intel architecture running Windows 95 or 98 or NT 4.0. Not yet validated under Windows 2000. Workstations using Motif supported by request
SOFIE	SOFIE (Simulation of Fireslin Enclosures) Description and examples can be viewed at www.cranfield.ac.uk/sme/sofie/	Contact Information: Dr. P. Rubini, School of Mechanical Engineering, Cranfield University, Cranfield, Bedfordshire, MK43 OAL, UK, (p.a.rubini@cranfield.ac.uk).	7A to 7G	License agreement, see http://www.cranfield.ac.uk/sme/sofie Site license for research use only. Commercial licenses available. Win9x/NT/2000, Unix (sun Solaris, Compaq Alpha), Linux (Intel)

Table 5.39: A Listing of Some Field Fire Models (Cont'd)

MODEL NAME	BRIEF DESCRIPTION	COMPANY / ORGANIZATION WEB SITE ADDRESS	SOME VALIDATION REFERENCES	COMMENTS
JASMINE Version 3.1	A CFD or field model for predicting consequences of fire to evaluate design issues such as the assessment of smoke ventilation design and/or interactions with HVAC and other fire protection measures The FRS model JASMINE (Analysis of Smoke Movement In Enclosures) uses CFD to describe the heat and mass transfer processes associated with the dispersion of combustion products from a fire. The processes of convection, diffusion, and entrainment are simulated by the Navier-Strokes equations. JASMINE has been developed, validated, and improved over a 20-year period and includes the key processes of buoyance, convection, entrainment, turbulence, combustion, thermal radiation, and boundary heat transfer relevant to the movement of smoke	Suresh Kumar (Dr.), Stewart Miles, Richard Chitty, Building Research Establishment, V.K. Available from Building Research Establishment. Watford WD2 7JR, UK Tel: +44 (0) 1923 66 4921 Fax: +44 (0) 1923 66 4910 Email: kumars@bre.co.uk Email: frsenquiries@bre.co.uk	3A to 3G	Currently supported on PC, and runs under Windows 95 and NT. Requires a minimum of 64MB RAM, 150 MHz processor and 1 Gb disc space in excess of system requirements. Can be adapted to workstations (e.g., COMPAC). A 300MHz, 64MB RAM PC can churn out a calculation overnight with a modest number of cells.
Kameleon FireEx Kameleon FireEx 99	Kameleon FireEx is a CFD code that solves the temperature, gas concentration, soot concentration, and radiation field in congested and open 3-dimensional geometry. Thermal response on solid surfaces and cooling and extinction by water sprays can also be calculated. Kameleon FireEx is also linked to the finite element code USFOS for complete structural response analysis of structures exposed to fires	Originally developed at SINTEF Energy Research AS. All commercial rights transferred to Computational Industry Technologies AS Bjørn Erling Vembe, Computational Industry Technologies AS, P.O. Box 1275, Pirsenteret, N-7462 Trondheim Norway. Phone +47 73 54 50 50. Email: bjorn.e.vembe@computit.no	4A to 4C	Hardware: Any main stream Unix work station, including Intel PC running Linux. Recommended RAM 512 Mb Will be commercialized by Computational Industry Technologies AS (ComputIT)
KOBRA-3D WINKOBRA 4.6	Three-dimensional CFD model for complex geometries to be used for smoke spread and heat transfer analyses The development of KOBRA-3D was initialized within a joint German-Norwegian research project to study enclosed hydrocarbon pool fires offshore. Since then, KOBRA-3D has been extended to describe fire and smoke spread in complex geometries. The CFD and fire modeling software of KOBRA-3D is embedded into a Windows 98 / 2000 / NT user surface (WinKobra) with 2D and 3D visualization tools, material data base and help functions assisting the user in generating the mesh and defining additional required computational parameters	Dr. Volker Schneider, I.S.T. Integrierte Sicherheits-Technik GmbH, Frankfurt / M., Germany Information available from: I.S.T. Integrierte Sicherheits-Technik GmbH, Feuerbachstr. 19, 60325 Frankfurt / M., Germany, Phone (069) 72 11 68, Fax (069) 72 11 94, Email IST-HSK@t-online.de	5A to 5E	Commercially available software Hardware: Pentium III, Windows 98 / 2000 / NT User guide available in German and English

Two field modeling programs listed in Table 5.39 of special interest are the SMARTFIRE field modeling software and the NIST developed Fire Dynamics Simulator (FDS).

An interesting innovation for CFD based field modeling applied to multi-compartment fire simulations is the SMARTFIRE software, developed by the Fire Safety Engineering Group, University of Greenwich, Greenwich, London. The SMARTFIRE software development project aims to make fire field modeling accessible to non-CFD experts such as fire protection engineers, architects, and building regulators by incorporating an expert system interface. A further project aim is the use of the interactive SMARTFIRE environment as a learning tool that will educate the novice user in good CFD practice. This is intended to make the skills learned using the SMARTFIRE software transferable to other CFD based fire models. Further information is available from the web site http://fseg.gre.ac.uk/smartfire.

Most CFD field models use empirical models of turbulence. An alternate approach, known as large eddy simulation models, is being developed and applied. Large-scale turbulence is directly modeled, and very small-scale turbulence is left unmodeled. Many present commercial CFD codes depend upon empirical turbulence models for their output, inherently limiting their predictive capability. This restriction leads to an ongoing burden of detailed experimental verification of the computations for each new fire scenario or building geometry.

A large eddy simulation (LES) model of smoke movement in enclosed spaces has been under development for several years at NIST. The focus of the work has been to simplify the Navier-Stokes equations that govern the fluid flow to yield high resolution solutions, which resolve the flow on length scales from centimeters to tens of meters. This enhanced resolution will greatly reduce the dependence on empirical turbulence models that are characteristic of present day field models. NIST's FDS consists of two programs, FDS and Smokeview. FDS predicts smoke and/or air flow movement caused by fire, wind, and ventilation systems. Smokeview visualizes the predictions generated by FDS.

FDS and Smokeview, along with example data files, can be downloaded from http://fire.nist.gov/fds. Documentation may be accessed directly or downloaded from the download page.

Summary

Use of field models for exposure profile modeling would be considered a second-order (i.e., highly detailed) assessment within the risk-informed, performance-based fire protection evaluation framework due to the time and costs involved. Application of field modeling requires specific CFD modeling skills, application experience, and substantial computer run-times. While very simple field models can be run on a high-end PC, usually super-mini computers or mainframes are needed to accomplish field calculations within a practical time frame. Therefore, the level and complexity of the risks under evaluation, the level of detail needed, and the project budget and constraints should dictate the feasibility of using computerized field models.

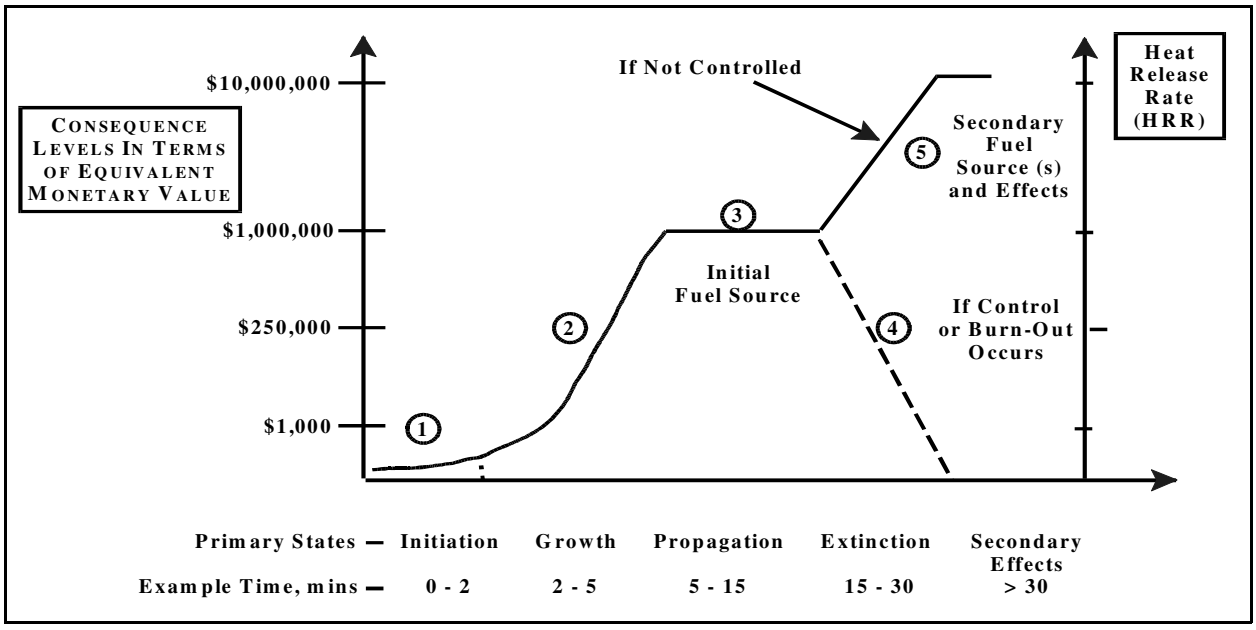
I do believe that the application versatility, calculation sophistication, and reduced use of empiricism inherent in field models make them more of a useful and valid tool than present zone models. Future developments and applications of field models will be a very valuable part of improving the accuracy and quality of risk and performance-based projects.

5.5 INITIAL HEAT RELEASE RATE EVALUATION

One of the key fire modeling inputs where uncertainty may pose a major issue is in the characterization of the fire source heat release rate (HRR). Computerized fire models (both zone and field) generally ask the user to input the HRR for the initiating fire source. This is the main reason a lot of people label currently available models as fire effects models, because these models calculate resulting effects such as temperature, smoke, gas species, etc., based on the user's fire source input. This section provides an overview on HRR characterization factors.

From a risk-informed perspective, we can analyze the fire and explosion consequences [life safety exposure, property damage (PD), business interruption (BI), company image, etc.] in terms of equivalent monetary value (EMV). Figure 5.34 was structured to reinforce the fact that the HRR-time profile (fire initiation, growth, propagation, secondary effects) is directly related to consequence severity and monetary loss.

Fig. 5.34: Example of Idealized HRR Profile Versus Potential Consequence Levels



Development of an HRR profile involves evaluation of fire propagation phases, which are depicted in Fig. 5.34 and include:

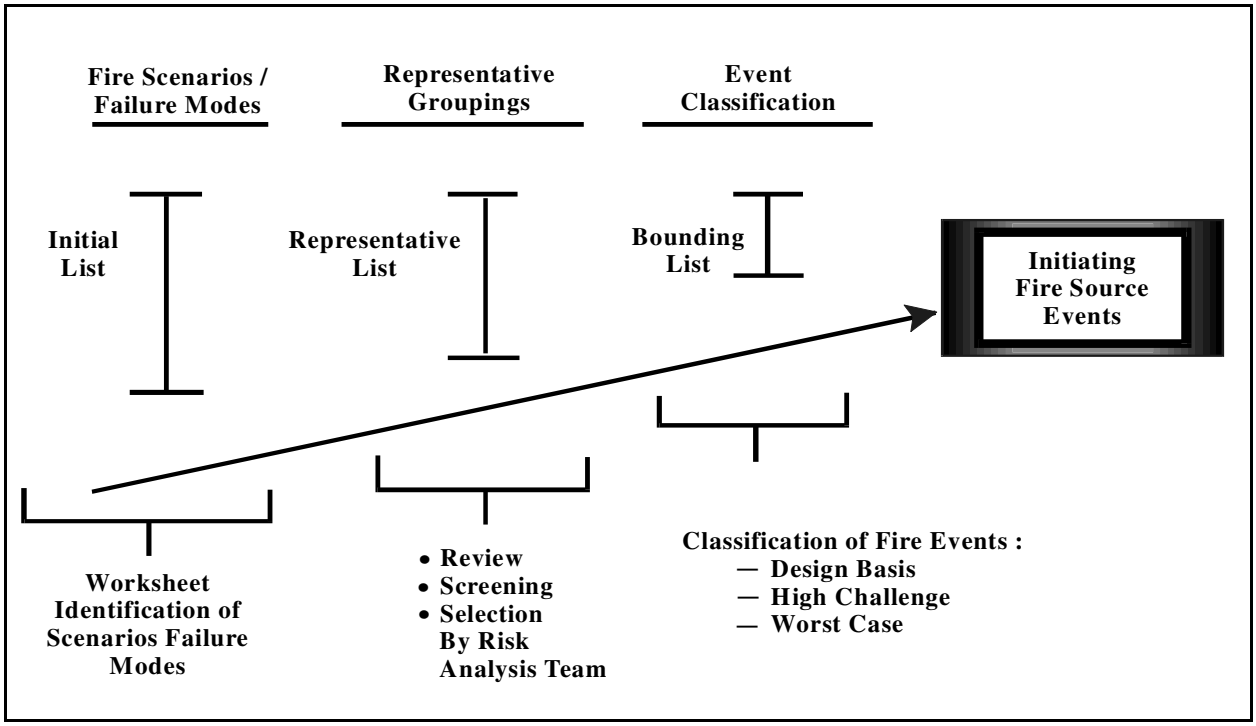
1. Ignition – initial fuel source
2. Fire growth – initial fuel source
3. Peak HRR – initial fuel source
4. Decay and extinction – initial fuel source
5. Ignition and flame spread – secondary fuel source(s)

5.5.1 Initial Fuel Source

The identification, grouping, screening, and classification of initiating events is done in Step 3, Loss Scenario Development. As presented in Fig. 5.35, the results of the scenario analysis provide a list of initiating fire events and establish representative fire event cases (i.e., fast flame spread, flammable liquid fires, high heat release plastics fires, smoldering electrical fires, etc.). Initiating fires can be further classified and bounded using the following categories:

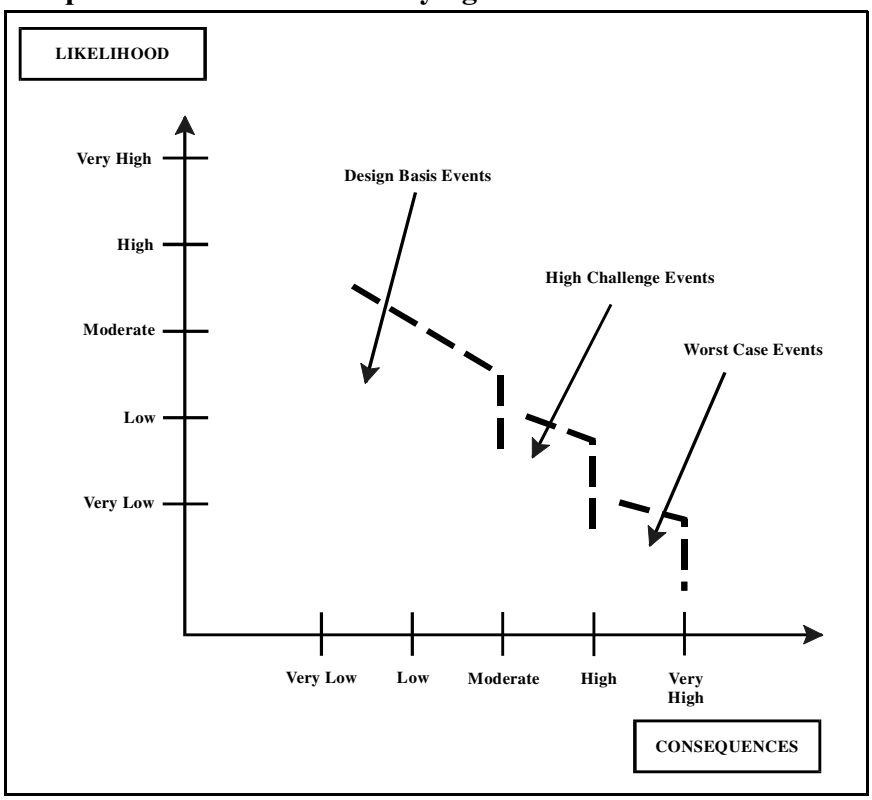
- Design-basis
- High challenge
- Worst case

Fig. 5.35: Example of Initiating Fire Event Selection Process



Step 4, Initiating Event Likelihood (Chap. 4) describes methods to quantify the likelihood (events/year) of initiating fire events. As depicted in Fig. 5.36, the initiating design-basis event, in most cases, is the event for which we perform exposure modeling and design fire protection systems. Design-basis fire events are fire source events that represent a credible risk to the target(s). In some cases due to likelihood uncertainties, exposure modeling and FPS evaluation may be performed for high challenge fire scenarios and worst case initiating events.

Fig. 5.36: Example Risk Profile for Classifying Fire Events



From my experience, the number of initiating source fire events modeled within an area of fire origin generally ranges between three and five. This is an important consideration, because it points out that there is usually more than one design-basis fire to model, as these fires may present a different type of exposure to the target and a different type of challenge to FPSs.

For example, in Fig. 5.37, there are three initiating fire sources that may need to be evaluated:

- Source 1 – Hydraulic system oil fire
- Source 2 – Production equipment fire (i.e., hazards include organic heat transfer medium and high pressure plastics extrusion)
- Source 3 – Cable tray fire (i.e., PVC insulated electrical cables, smoldering combustion fire exposure)

Fig. 5.37: Example: Multiple Source Design-Basis Fires

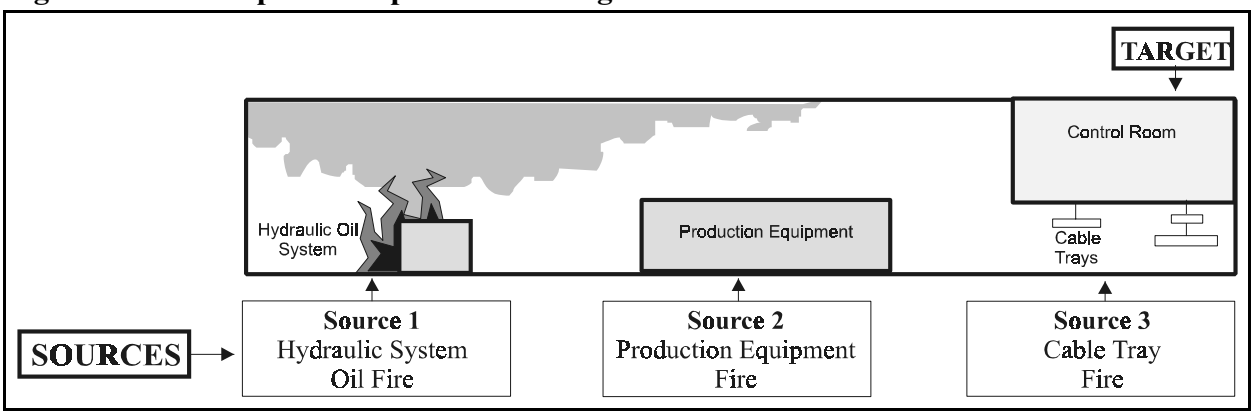


Table 5.40 provides an example of evaluating initiating source events in terms of design-basis (most likely), high challenge (less likely), worst case (remote likelihood).

Table 5.40: Initiating Fire Source Events for Fig. 5.37

INITIATING SOURCE	DESIGN-BASIS EVENT	HIGH CHALLENGE EVENT	WORST CASE EVENT
Source 1 Hydraulic system oil fire	Hydraulic oil pool fire	Hydraulic oil torch fire from failure of pump shutdown	
Source 2 Production equipment fire	Organic heat-transfer fluid pool fire	Heat transfer fluid torch fire from failure of pump shutdown	Release of flammable mist creating a vapor explosion potential from failures leading to undetected heating and release of fluid well above its boiling point
Source 3 Cable tray fire	Smoldering electrical cable fire		

For exposure modeling input, the initial fuel source must be defined in terms of the initial fuel package boundaries, which include objects close enough in physical proximity so that continuous flame spread from item to item is possible and the ignition delays between items are small.

An example of this (in Fig. 5.37) may be the production equipment (Source 2) where the organic heat transfer system, plastics components, and electrical components of the production equipment may be considered a single fuel package. The HRR profile would be dominated by organic heat transfer fluid combustion.

For flammable and combustible liquids, the release type and release quantity must be defined. In Table 5.40, the design bases events for both the hydraulic oil (Source 1) and organic heat transfer fluid (Source 2) are pool fires. The high challenge events could include a flowing three-dimensional fire or a torch fire scenario.

5.5.2 Fire Growth of Initial Fuel Package

Following source fire ignition, the fire growth rate of the initial fuel package must be evaluated. The rate of fire growth can be estimated using fire test data if available or empirically developed correlations.

Exponential and t-squared characterizations derived from fire test data and curve fitting are the most commonly used representations of fire growth rates. Conceptually, exponential representations have the advantage of yielding a "doubling" time, a useful characterization parameter, while t-squared representations have become somewhat standardized in terms of "slow," medium," "fast," and "ultrafast" fire growth curves, as shown in Fig. 5.38. [1]

During the growth period, HRR histories are characterized for t-squared representations as:

$$\dot{Q} = \propto t^2$$

where

$\dot{Q}$ = rate of heat release (kW)
$\propto$ = constant fire growth factor
t = time (seconds)

$\dot{Q}$ is assumed to continually grow until the HRR has reached a peak value or limiting value due to fuel consumption or intervention of fire control systems.

Fig. 5.38: Plot of t^2 Standardized Fire Growth Curves

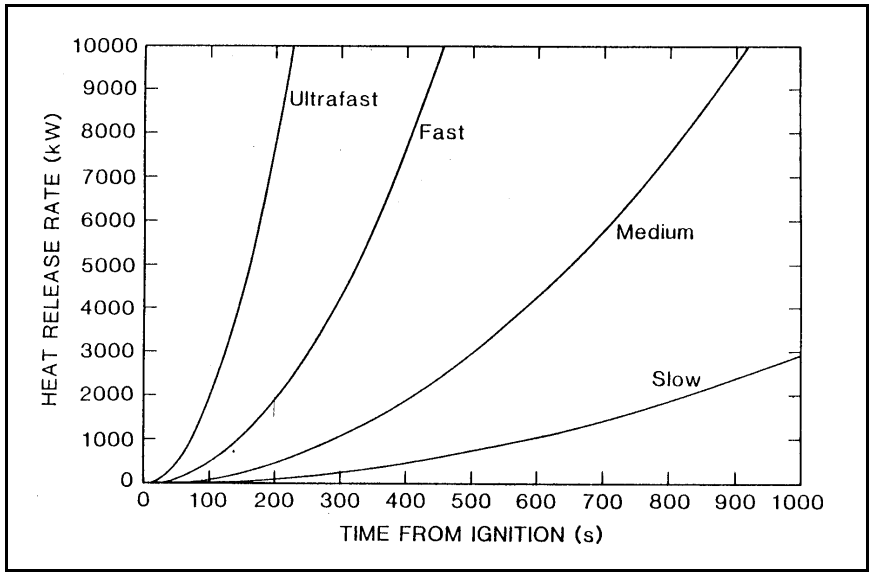


Table 5.41 provides a listing of the associated fire growth constant, $\propto$, for the fire growth curves in Fig. 5.38.

Table 5.41: Fire Growth Constants for t^2 Fires

RATE OF FIRE GROWTH	FIRE GROWTH CONSTANT, $\propto$
Ultrafast	0.178
Fast	0.0445
Medium	0.0111
Slow	0.000278

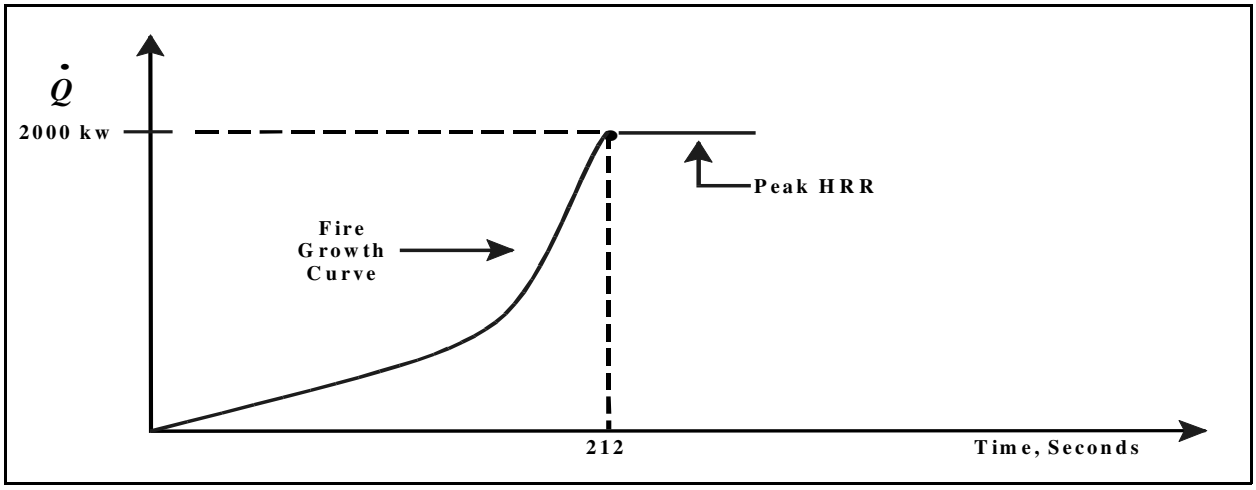
If we wanted to estimate the time for a "fast" growth fire to reach a peak HRR of 2,000 kw, assuming a representative t^2 fire scenario:

$$\dot{Q} = 2{,}000 \text{ kw}$$
$$\propto = 0.0445 \text{ (fast fire growth)}$$

$$\dot{Q} = \propto t^2$$
$$t = \left(\dot{Q} / \propto \right)^{1/2}$$
$$t = 212 \text{ seconds}$$

Figure 5.39 represents this in a graph.

Fig. 5.39: Example Fire Growth Curve



For flammable liquid fires you can generally use a fire growth time to reach peak HRR of 30 or less. For combustible liquids, or fast burning plastics, the "ultrafast" t^2 fire curve can usually be applied. For items such as wood pallets or combustible contents in cardboard cartons with plastic packaging material, stored at a height of over 5 ft, a "fast" t^2 fire curve can be applied.

t^2 Fire Uncertainty Issues

Use of t^2 fire curves to represent actual fire growth provides a simplified first-order estimation approach. Fire grows at various rates depending on a fuel type, location, fuel geometry, storage configuration, enclosure radiation effects, ventilation, etc. Use of t^2 fire curves should be applied with caution with fire test experience and engineering judgement backing up the selection.

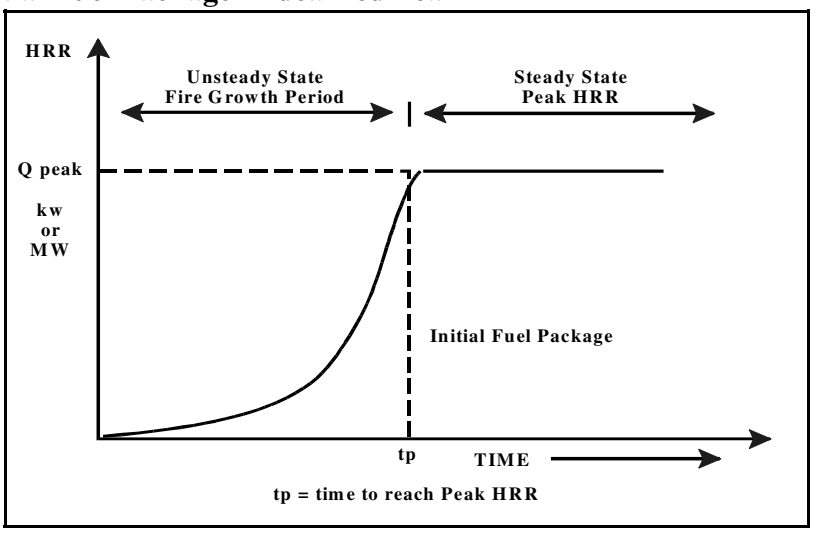
When performing fire exposure modeling, it is important to remember that the peak HRR of the initial fuel package is the most significant fire hazard characterization. Applying t^2 fire growth calculation should be used only to estimate the time to reach peak HRR.

Some fire models and performance-based building codes allow the user or designer to select a standardized fire curve to estimate fire hazard exposure versus time. Theoretically, these t^2 curves go to infinity and without a defined peak HRR (or cutoff point) level, these curves can be extrapolated beyond a reasonable level as related to real world fires.

5.5.3 Peak HRR of the Initial Fuel Package

As shown in Fig. 5.40, following an uncontrolled fire growth period (i.e., fire does not self extinguish, burnout, or is not suppressed or extinguished), the fire reaches a peak HRR condition where the exposed surface areas of the initial fuel package are burning with a somewhat steady mass burning rate.

Fig. 5.40: Initial Fuel Package – Idealized Peak HRR



The unit HRR $\dot{q}''$ of the fuel is dependent upon the maximum mass burning rate, m, expressed as weight per unit time; and the heat of combustion, H_c, expressed as heat produced per unit weight. The general form of the equation is:

$$\dot{q}'' = \dot{m}'' \times H_c$$

The heat of combustion, H_c, used in quantifying the rate of heat release in fire situations is referred to as the effective heat of combustion. This is the net heat of combustion of the fuel multiplied by a combustion efficiency factor. Thus, the combustion efficiency factor can be thought of in terms of the ratio of the total HRR to the theoretical HRR. Combustion efficiency can be close to unity for some fire sources (e.g., flammable and combustible pools) and can range between 0.6 and 0.8 for fully involved solid fuel configurations.

To explicitly include the combustion efficiency factor, which can include a number of variables such as fuel geometry and ventilation conditions, the following equation can be used:

$$\dot{q}'' = \dot{m}'' \times H_c \times x_e$$

where $\dot{m}$ = mass burning rate (Kg/m^2 - s)
H_c = net heat of combustion (KJ/kg)
x_e = combustion efficiency

and $\dot{q}''$ = unit HRR associated with fully involved burning conditions (kw/m^2)

The peak HRR, $\dot{Q}$ peak, is the estimated by:

$$\dot{Q} = \dot{q}'' \times A_S$$

where A_s = total exposed burning surface area of the fuel

Methods to obtain mass burning rate and HRR estimates include:

- Actual tests of the fuel, product, or storage configurations involved
- Actual tests of similar fuels, products, or storage configurations
- Algorithms derived from tests having similar fuels and dimensional characteristics
- Calculations based on tested properties and materials and expected radiant heat flux
- A combination of the above used with engineering insight and knowledge

The following box lists some HRR data sources.

Some HRR Data Sources

- Babrauskas, V., Burning Rates, *The SFPE Handbook of Fire Protection Engineering*, Chap. 3-1, 2nd ed., DiNenno, P. J., editor, National Fire Protection Association, Quincy, MA 1995[22]
- NFPA 92B, Smoke Management Systems in Malls, Atria, and Large Areas. Appendix B, Predicting the Rate of Heat Release in Fires.[23]
- National Institute of Standards and Technology (NIST) web sites:
  http://www.fire.nist.gov/fire/fires/fires.html
  http://www.fire.nist.gov/fastdata/ (CD-ROM)
- Babrauskas V. and S. J. Grayson, eds., *Heat Release in Fires*, Elsevier Applied Science, New York, 1992[24]
- Lund University, Report on initial fires; available on web site:
  http://www.brand.lth.se/bibl/3070.pdf

Table 5.4.2 from reference [25] lists some unit heat release data for liquid fuels:

Table 5.42: Some Unit Heat Release Data for Liquid Fuels

FUELS	NET HEAT OF COMBUSTION	IDEAL UNIT MASS LOSS RATE	ESTIMATED COMBUSTION EFFICIENCY	APPROXIMATE UNIT HEAT RELEASE RATE
	MJ/kg	kg/s-m^2		kW/m^2
LIQUID FUELS				
ACETONE	28.6	0.041	0.97	1137
BENZENE	40.1	0.085	0.69	2352
ETHANOL	26.8	0.015	0.97	390
FUEL OIL, HEAVY	39.7	0.035	0.90	1251
GASOLINE	43.7	0.055	0.92	2211
HEPTANE	44.6	0.101	0.92	4144
HEXANE	44.7	0.074	0.92	3043
JP-4	43.5	0.051	0.95	2108
KEROSENE	43.2	0.039	0.90	1516
METHANOL	20.0	0.017	0.95	323
TRANSFORMER OIL	46.4	0.039	0.85	1538
XYLENES	40.8	0.090	0.67	2460

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Using data from Table 5.42, for a 2-m^2 pool fire of acetone the peak heat release, $\dot{Q}$, would be estimated as follows:

$$\dot{Q} = \dot{q}'' \times A_S$$

$$\dot{Q} = 1137 kw/m2 \times 2m2 = 2{,}274 kw$$

As seen in this equation, the area of the pool will greatly affect the peak HRR and will also affect the burning duration.

Estimating Pool Fire Diameters for Unconfined Spills

When the spilled liquid is ignited, a pool fire develops. The diameter of the pool fire will depend upon the release mode, release quantity (or rate), and the burning rate. In the case of continuous spills, the liquid will spread and increase the burning area until the total burning rate is equal to the spill rate. This condition is given by the following equation:[26]

$$D_{eq} = 2\left[\dot{V}_L / \pi \dot{y}\right]^{1/2}$$

where:

D_{eq} = steady-state (equilibrium) diameter of the pool, m

$\dot{V}_L$ = liquid spill rate, m^3/s

$\dot{y}$ = linear liquid burning rate, m/s

For quick estimation of a liquid release of specific volume, the surface area of the liquid spill is a function of the quantity, viscosity, and surface tension of the spilled liquid and of the cohesion, contour, and absorptivity of the floor finish. In general, the area of a liquid spill on a smooth nonabsorbing floor surface will simply equal the volume (V) of liquid spilled divided by the thickness (W) of the spill once it stops spreading: [25]

$$A_s = \frac{V}{W}$$

For this situation, the problem reduces to determination of the spill thickness as a function of the variables mentioned above. Some experiments to evaluate the thickness of spills on concrete for some fuels that might be found in industrial plants are tabulated in Table 5.43.[25]

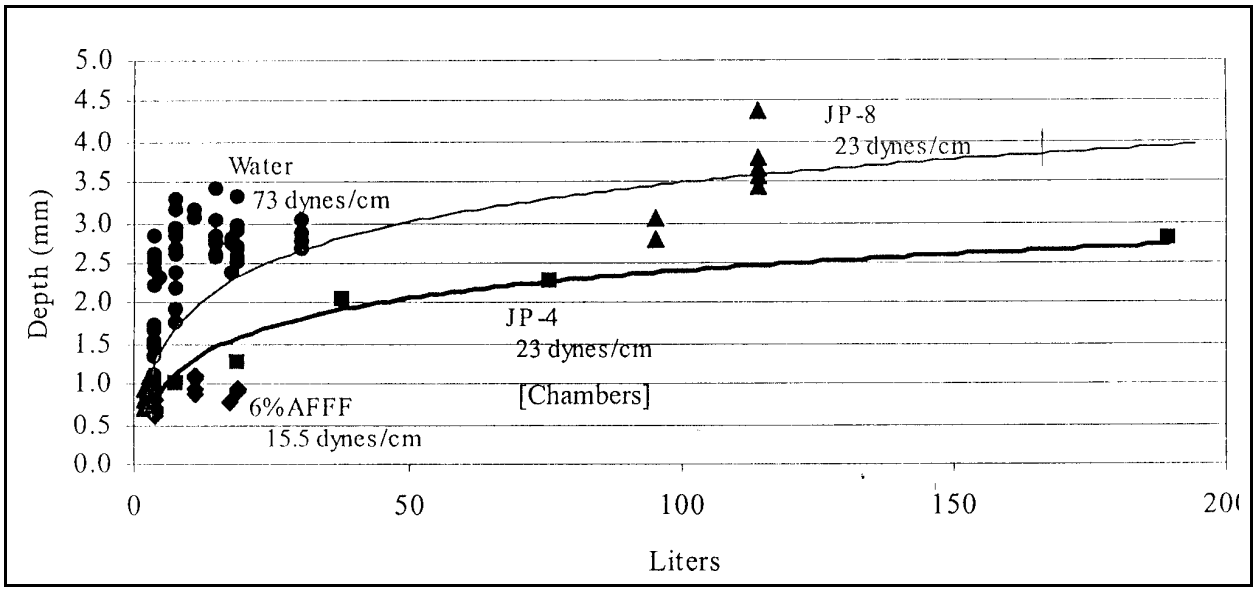
Table 5.43: Unconfined Liquid Spill Depths

LIQUID	UNCONFINED SPILL THICKNESS		SPILL AREA	
	inches	mm	ft^2/gal	$m^2/1$
#2 Fuel oil	0.009	0.22	185	4.55
Mobil DTE 797	0.013	0.34	120	2.94
Pennzoil 30-HD	0.030	0.75	54	1.33
Fyrquel 220	0.033	0.84	49	1.19

Figure 5.41 provides some test data from reference [27] for liquid spills of JP-4 and JP-8 fuels on concrete. Using the data in Fig. 5.41 for 50 L (approximately 13.2 gal) of JP-8, the unconfined spill depth is approximately 3.0 mm (0.118 in.). Using $A_S = V/W = 1.76\ ft^3/.0098\ ft = 180\ ft^2$ unconfined spill area.

Using the data in Table 5.43 for #2 fuel oil indicates an unconfined spill area of 185 ft^2/gal; for 13.2 gal = 2,442 ft^2. This is a big difference between two fuels with similar properties and both spilled on concrete. The pressure behind the release and the smoothness of the concrete finish certainly contribute to differences in spill test data.

Fig. 5.41: Liquid Spill Depths on Concrete



The uncertainty in estimating unconfined liquid spill areas leads to the practicality that measures such as containment sills, curbs, dikes, sloping of floors, or channeling of spills to a containment area, trench drains, drainage facilities should be provided. And remember, the smaller the surface area of the liquid pool, the smaller the HRR and radiant heat exposure.

Fire Burning Time

The uncontrolled pool fire burning duration is equal to the mass of the fuel spilled divided by the mass burning rate and pool area:

$$t_{fb} = \frac{f_{mass}}{\left(\dot{m}''\right)\left(A_S\right)\left(60_{\text{sec/min}}\right)}$$

f_{mass} = mass of fuel (kg)
A_s = surface area of pool $\left(m^2\right)$
$\dot{m}''$ = mass burning rate $\left(kg/m^2 - s\right)$
t_{fb} = time to fuel burnout (min)

Torch Fires

Escape of a combustible liquid from a fracture or leak containing liquid under pressure can produce a spray discharge and torch fire exposure. Only small sources of ignition are required to ignite suspensions at temperatures substantially below the flash point of the liquid. Two examples would be liquid release of a combustible hydraulic fluid under high pressure where the fluid is atomized into small droplets (droplet spray combustion), or a hot-oil heat exchange fluid where the fluid is heated above its flash point, close to its boiling point, and when released under pressure creates a torch fire exposure (mist or vapor jet fire). [28]

The mist or vapor jet release can be generally modeled as a gas jet fire, which is discussed in Sect. 5.7.

Khan and Tewarson, Factory Mutual Research Corporation (FMRC), conducted experiments on a number of commercially available hydraulic fluids — 15 esters (organic and phosphate), 2 water-in-oil emulsions, and 8 polyglycol-in-water fluids were examined. Pharmaceutical grade mineral oil methanol, ethanol, and heptane were also included in the study. [28]

Tests involving the hydraulic fluid spray combustion established relationships between the HRR, fluid exit velocity from the point of release, and the fluid's heat of combustion. The rate of (HRR) can be expressed as:

$$\dot{Q} = \dot{m}_f \times H_c \times x_e$$

where H_c is the heat of the combustion *(kJ/kg)*, m_f is the mass flow rate (*kg/s*), x_e is the combustion efficiency, $\dot{Q}$ is the HRR in *kw*.

The fluid exit velocity, u_o (m/s), can be related to the steady mass flow rate of fluid, $\dot{m}_f$, (*kg/s*), through the orifice with diameter, d_o (m), at constant pressure,

$$u_o = 4\dot{m}_f \Big/ \pi P_f do^2$$

where P_f is the fluid density (kg/m^3). Degree of atomization depends on u_o, physical nature of the fluid (such as surface tension and viscosity), and type of nozzle used. At high u_o, when spray is stabilized by an ignition source, a spray flame is established.

Evaluating secondary ignition effects from a torch fire exposure involve assessment of the potential flame length (L_f), which could impinge on adjacent fuel sources and the radiant heat flux exposure from the flame.

The correlations from a regression analysis of the FMRC hydraulic oil tests indicate that for hollow cone nozzles, $L_f = 0.075 \dot{Q}^{0.6}$ to $L_f = 0.0175 \dot{Q}^{0.6}$

These equations indicate that flame length varies with the total HRR to the power of 0.6. The difference in coefficients in these equations seems to indicate the effect of geometry and type of nozzle used.[28]

Concerning radiant heat flux potential, the radiative fraction of the efficiency of combustion for phosphate esters was the highest (0.38 – 0.40), followed by mineral oil (0.36), organic esters (0.28 – 0.35), water-in-oil emulsion (0.27 – 0.28), and polyglycol in water (0.12 – 0.25).

5.5.4 Solid Material HRR

HRR profiles for solid materials are affected by many variables, which include material density, geometry, mass to surface area ratio, ignition source strength, and ventilation factors. In addition many products consist of composite materials, with various packaging, stored in numerous configurations.

The peak HRR for solids is quantified using the same equation as for liquid fuels:

$$\dot{Q} = \left(\dot{m} \times H_C \times x_e\right) A_S$$

where: $\dot{Q}$ = peak HRR, kw

$\dot{m}$ = mass loss rate or mass burning rate, $kg/m^2\text{-}s$

H_C = heat of combustion, kJ/kg

x_e = combustion efficiency

A_s = surface area of the fuel, m^2

Because of the many variables, HRR for a specific material product or storage configuration is usually estimated by measuring the mass loss versus time in a combustion calorimeter. Testing laboratories such as Factory Mutual (FM) and Underwriters Laboratories (UL) have large scale calorimeters for HRR testing.

Table 5.44 provides some example unit heat release data for solid fuel and commodities.[25]

Table 5.44: Some Unit Heat Release Data for Solid Fuels

FUELS	NET HEAT OF COMBUSTION	IDEAL UNIT MASS LOSS RATE	ESTIMATED COMBUSTION EFFICIENCY	APPROXIMATE UNIT HRR
	MJ/kg	kg/s-m^2		kW/m^2
SOLID FUELS				
CARDBOARD BOXES	18.0	0.014	0.70	176
POLYETHYLENE (PE)	43.4	0.026	0.88	993
PMMA	24.9	0.030	0.96	717
POLYPROPYLENE (PP)	43.2	0.024	0.89	923
POLYSTYRENE (PS)	39.8	0.034	0.69	934
POLYURETHANE (PU)	23-28	0.025	0.65	455
POLYVINYL CHLORIDE (PVC)	16.4	0.016	0.35	92
WOOD (TYPICAL VALUES)	18.0	0.011	0.70	139
STORED COMMODITIES				
WOOD PALLETS	per m of height			2250
WOOD OR PMMA				
VERTICAL SURFACE	per m^2 of surface			250
HORIZONTAL SURFACE	per m^2 of surface			750
POLYSTYRENE (SOLID)				
VERTICAL SURFACE	per m^2 of surface			650
HORIZONTAL SURFACE	per m^2 of surface			1350
POLYPROPYLENE				
VERTICAL SURFACE	per m^2 of surface			450
HORIZONTAL SURFACE	per m^2 of surface			800
CARDBOARD CARTONS	stacked 4.6 m high			
COMPARTMENTED	stacked 4.6 m high			1700-4200
W/PE BOTTLES	stacked 4.6 m high			6200-7600
W/PS JARS	stacked 4.6 m high			14000-20900
W/PVC BOTTLES	stacked 4.6 m high			3400-7000
METAL LINED	stacked 4.9 m high			2800
POLYURETHANE BOARD	stacked 4.6 m high			1900-3200

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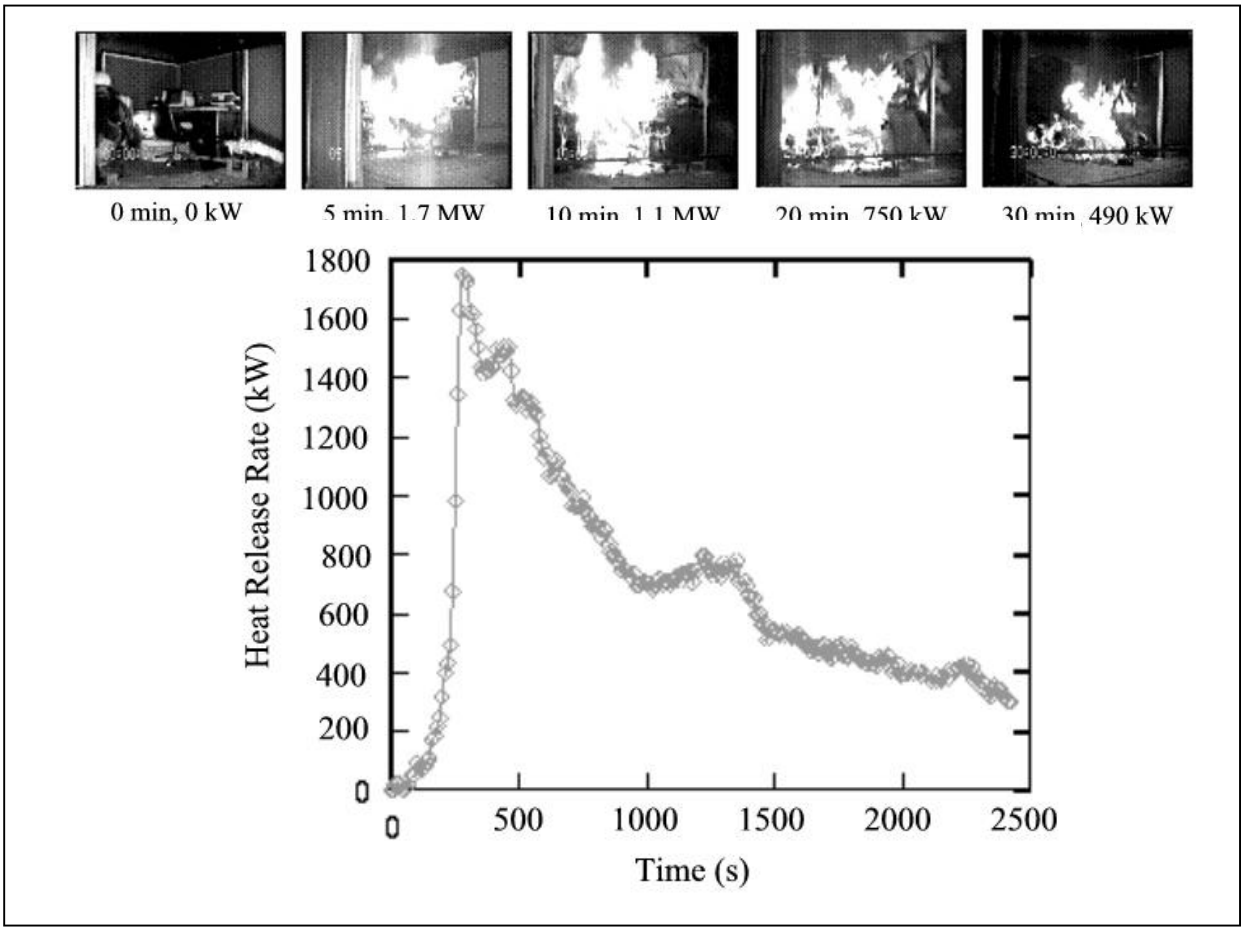
In many cases when dealing with a similar fuel or commodity, the data in Table 5.44 can be used. However, these data are for the peak unit HRR, and therefore, the fire growth rate (see

Sect. 5.5.2), and the surface area propagation needs to be addressed when constructing a HRR profile.

Figure 5.42 provides an example of a HRR profile for a computer workstation enclosed on two sides with partition panels (see NIST web site http://www.fire.nist.gov/fire/fires/work2/work2.html). At approximately 5 min, the HRR spikes to 1,700 kw and then starts a steady decline. This is a test run under very specific test conditions. If the type, size, or number of panels change, the HRR profile will change. If the ignition source strength or area ventilation changes, the HRR profile will change. The point is that when you assume fire test data is applicable to your fire scenario due to similarities, you should also be aware of the many variables that can affect HRR profile differences.

Fig. 5.42: Example Computer Workstation Fire Test HRR Profile



Many factors influence the fire hazard and HRR profile of combustible material storage arrangements. Some primary factors affecting fire growth, HRR, and fire suppression include:

- Material composition (e.g., extent of plastics)
- Packaging materials
- Exposed surface area

- Storage height
- Separation between storage
- Location of storage
- Storage stability
- Ventilation influences
- Fire suppression system response time and penetration capability

One of the major fire hazard and HRR prediction concerns with solids is plastic materials. Most products today have plastic components, plastic composites, plastic packaging, etc. The references in the following box provide information on plastic material types, burning characteristics, and HRRs.

References On Plastics

Tewarson, Archibald, Generation of Heat and Chemical Compounds in Fires, *The SFPE Handbook of Fire Protection Engineering*, 2nd ed., DiNenno, P. J. editor, National Fire Protection Association, Quincy, MA, 1995. [29]

Beyler, C. L., and Hirschler, M. M., "Thermal Decomposition of Polymers," *The SFPE Handbook of Fire Protection Engineering*, 2nd ed., DiNenno, P. J. editor, National Fire Protection Association, Quincy, MA, 1995. [30]

Hirschler, M. M., *Heat Release From Plastic Materials*," Chap. 12, Heat Release in Fires, Editors; V. Babrauskas and S. J. Grayson, Elsevier Applied Science, New York, 1992, pp. 375-422. [31]

5.5.5 Peak HRR Importance

From an exposure modeling and fire protection response design standpoint, the most important parameter to quantify is the peak HRR of the "initial" fuel package and the estimated time to reach peak HRR.

As stated by Dr. Vytenis Babrauskas, Fire Science and Technology, Inc. in the article "Heat Release Rate: a Brief Primer," on his website (http://www.aone.com/~vyto/hrr_prmr.html):

> "HRR is not just 'one of many' variables used to describe a fire. It is, in fact, the single most important variable in describing fire hazard. (The only notable exception is for explosions). There are three main reasons for this.
>
> 1. HRR is the driving force for fire.
>
>   The HRR can be viewed as the engine driving the fire. This tends to occur in a positive-feedback way: heat makes more heat. This does not occur, for instance, with carbon monoxide. Carbon monoxide does not make more carbon monoxide.
>
> 2. Most other variables are correlated to HRR.

The generation of most other undesirable fire products tends to increase with increasing HRR. Smoke, toxic gases, room temperatures and other fire hazard variables generally march step-in-step with HRR as HRR increases.

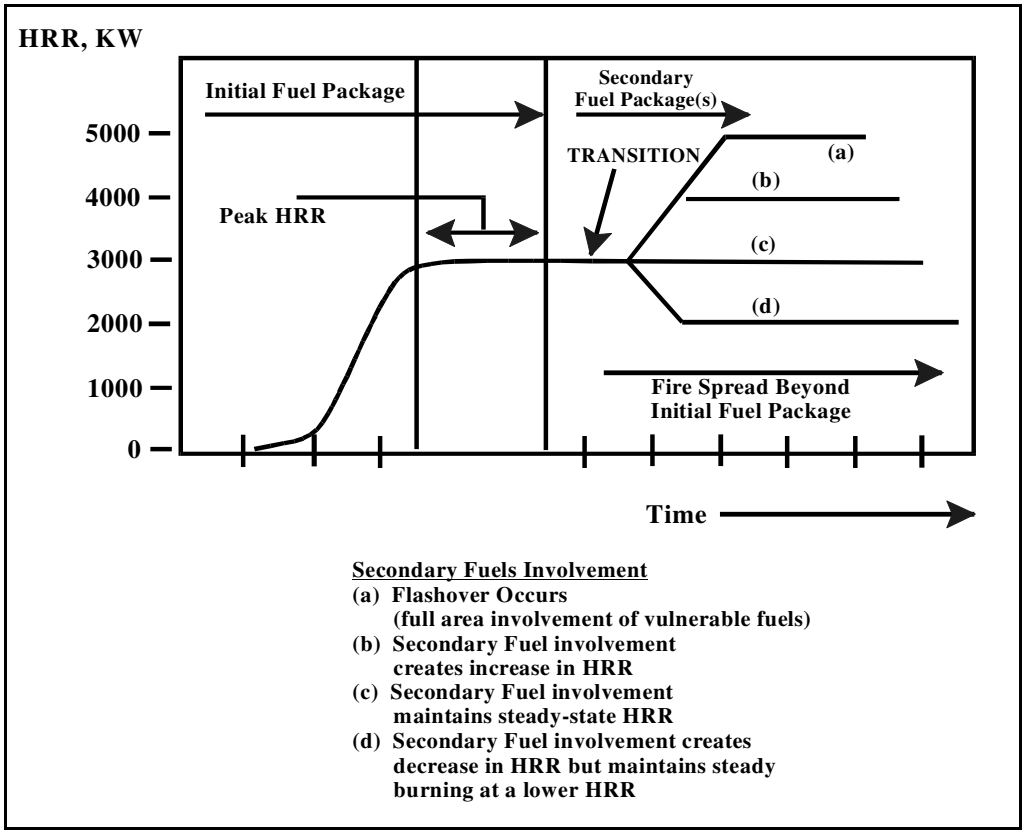
3. High HRR indicates high threat to life.

5.6 SECONDARY FUEL SOURCES

Secondary fuel sources are fuels that, when exposed to the thermal effects (i.e., temperature, heat flux – conduction, convection, radiation) of the initiating fuel source, are capable of ignition and flame propagation at some point.

Figure 5.43 presents an idealized graphical depiction of HRR following the transition from the initial fuel package to involvement of secondary fuel packages. Transition can range from slow continuous flame spread potential to area flashover. Evaluating HRR profiles following the initial fuel package presents many uncertainties, one of the main reasons that fire detection and fire protection performance success probability should be focused on response during the initial fire growth and initial fuel package involvement.

Fig. 5.43: Idealized HRR – Secondary Fuel Package Involvement



Flashover is defined as a stage in the development of a contained fire in which all exposed surfaces reach ignition temperatures more or less simultaneously and fire spreads rapidly throughout the space. Flashover occurs when the surface temperatures of combustible contents rise, producing combustible gases, and the room heat flux becomes sufficient to heat all such gases to their ignition temperatures. NFPA 555, Guide on Methods for Evaluating Potential for Room Flashover, provides a detailed discussion of flashover. [32]

If the initiating source fire continues to grow, the temperature in the compartment of fire origin increases, and every part of that compartment is exposed to flame radiation, which can lead to flashover. Flashover is characterized by the rapid transition from a localized fire to combustion of all exposed fuel surfaces within a compartment. The undesirability of the flashover event makes it important to know its likelihood and timing. The two criteria that can be used to determine the occurrence of flashover are that the temperature of the upper hot gas layer has reached 600°C or the radiation heat flux at the floor has reached 20 kW/m^2. Fires continuing beyond flashover are referred to as fully developed fires and are characterized by very high temperatures and HRRs.

The likelihood of flashover depends on a number of parameters, which include:

- Size of the enclosure
- Surface area of the enclosure
- Area of enclosure openings
- HRR of the initiating fire
- Amount of exposed materials
- Ventilation
- Thermal properties of compartment boundaries

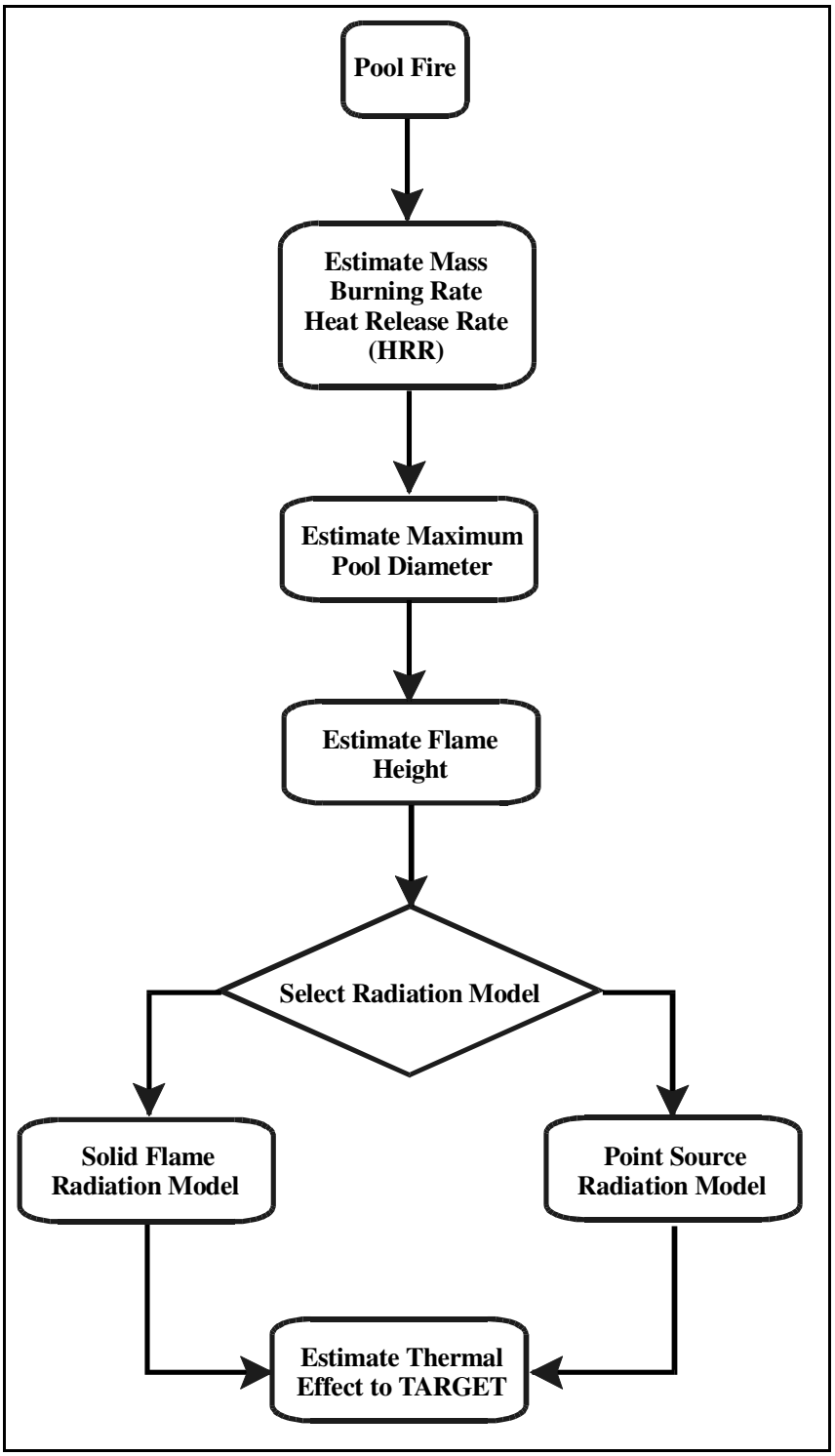
In large industrial compartments, the likelihood of flashover is much lower than it is in small compartments; however, in some cases, a backdraft fire potential exits. Backdraft fire potential is when limited ventilation during an enclosure fire can lead to the production of combustible unburnt gases. When air is introduced from an opening, the inflowing air mixes with the gases that have accumulated, usually within pockets inside the enclosure. Ignition creates a flashing fire situation and/or a fireball extension outside the enclosure opening, creating a very high heat exposure.

5.6.1 Radiant Heat Exposure

The dominant mechanism for secondary fuel ignitions and target damage within the immediate area around the initial fuel package fire is radiant heat exposure from the resulting source fire's flame envelope. Estimating the radiant heat flux emitted from the flame to objects (i.e., secondary fuel packages, specific targets) outside the flame envelope is needed to determine secondary ignition potentials.

Figure 5.44 depicts the general logic diagram for calculating pool fire radiant heat exposure.

Fig. 5.44: General Logic Diagram for Calculating Pool Fire Radiant Heat Exposure



Two different methods are available for calculating the thermal radiation levels at selected positions outside the flame envelope. Each method is of a different level of complexity and each is suited to different types of applications. The major differences in methods are reflected in the description of the source of radiation. The two calculation methods summarized in this section are:

- Point source radiation model
- Solid flame radiation model

The point resource thermal radiation model is based on the following assumptions:

1. The flame can be represented by a small source of thermal energy
2. The energy radiated from the flame is a specified fraction of energy released during combustion
3. The thermal radiation intensity varies proportionately with the inverse square of the distance from the source

Expressed mathematically, the radiant intensity, q_r'', at any distance from the source is given by (see Fig. 5.45)

$$q_r'' = X_R \dot{Q} / 4\pi r^2$$

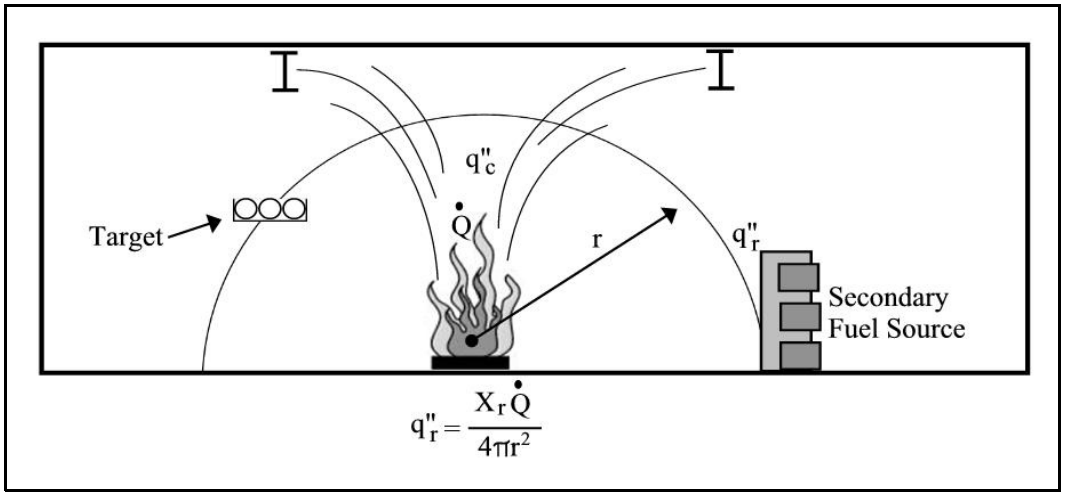
where

$\dot{Q}$ = fire HRR, kW

X_R = fraction of combustion energy radiated

r = radial distance from source to the target, m

Fig. 5.45Point Source Modeling



The most important parameter in the point source model is the fraction of combustion energy radiated to its surroundings. This fraction cannot easily be estimated theoretically. It is normally estimated using measured test data. Table 5.45 shows the estimated fraction of combustion energy radiated for various hydrocarbon pool fires from reference [26]. In most cases, for pool fires over 1.0 m in diameter, using a 35% radiant heat fraction provides a credible upper bound assumption.

A limitation in using a point source model is that the model may overestimate the intensity of thermal radiation at locations close to the fire (i.e., generally less than 2 diameters from the source). This is primarily because the nearfield radiation is greatly influenced by the flame size, shape, tilt, and relative orientation of the target.[26]

Table 5.45: Radiation Fraction of Combustion Energy for Hydrocarbon Pool Fires

HYDROCARBON	POOL SIZE (m)	% RADIATIVE OUTPUT /COMBUSTION OUTPUT
Methanol	1.2	17.0
LNG on land	18.0	16.4
	0.4 to 3.05	15.0 to 34.0
	1.8 to 6.1	20.0 to 25.0
	20.0	36.0
LNG on water	8.5 to 15.0	12.0 to 31.0*
LPG on land	20.0	7.0
Butane	0.3 to 0.76	19.9 to 26.9
Gasoline	1.22 to 3.05	40.0 to 13.0*
	1.0 to 10.0	60.1 to 10.0*
Benzene	1.22	36.0 to 38.0
Hexane	–	40
Ethylene	–	38

* In these cases, the smaller diameter fires were associated with higher radiative outputs.

LNG = liquified natural gas
LPG = liquified propane gas

Solid Flame Radiation Model

Some of the uncertainty of the point source model in modeling near-field radiant heat exposure can be overcome using a solid flame model, which assumes that the flame can be represented by simple solid geometrical shapes such as a cylinder, and that the radiation is emitted from its surface.

The solid flame model is based on the concept that the entire visible volume of the flame emits thermal radiation and that the nonvisible gases emit little radiation. The thermal radiation intensity, q_r'', to an element outside the flame envelope is calculated by the equation: [26]

$$q_r'' = \in \tau \, E F_{12}$$

where

$\in$ = flame emissivity (assumed to be 1 for a black body radiator)

τ = atmospheric transmissivity

E = average emissive power of the flame

F_{12} = geometric view factor between flame and target

The emissive power (E), also referred to as the surface emitted power or flame radiated heat flux may be estimated by the use of following alternative approaches:

- The Stefan-Boltzmann equation
- A radiated fraction of the total HRR
- Measured thermal fluxes from similar pool fires

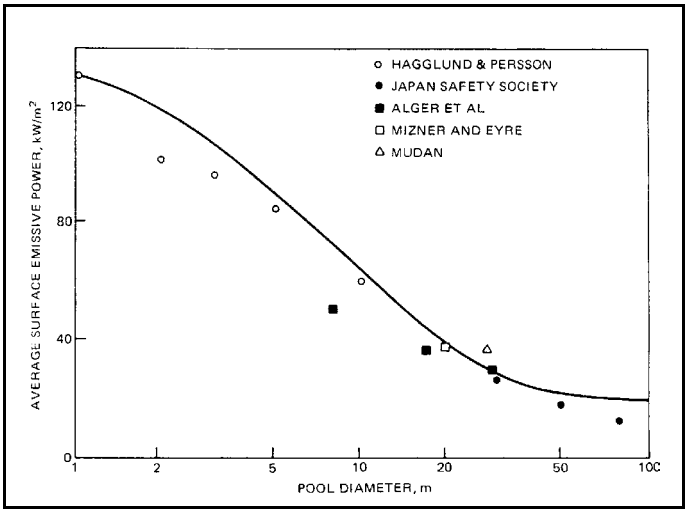
Table 5.46 provides some measured flame emissive power data from reference [26].

Table 5.46: Some Measured Emissive Powers

HYDROCARBON	POOL FIRE DIMENSIONS (m)	EMISSIVE POWER kW/m^2
LNG on water	8.5 to 15.0	210 to 280
LNG on land	20.0	150 to 220
LPG on land	20.0	48
Gasoline	1.0 to 10.0	60 to 130 (max)
JP-4	5.8	—
Kerosene	30.0 to 80.0	10 to 25 (average)
JP-5	1.0 to 30.0	30 to 50
Pentane	1.0	61
Ethylene	2.5	130

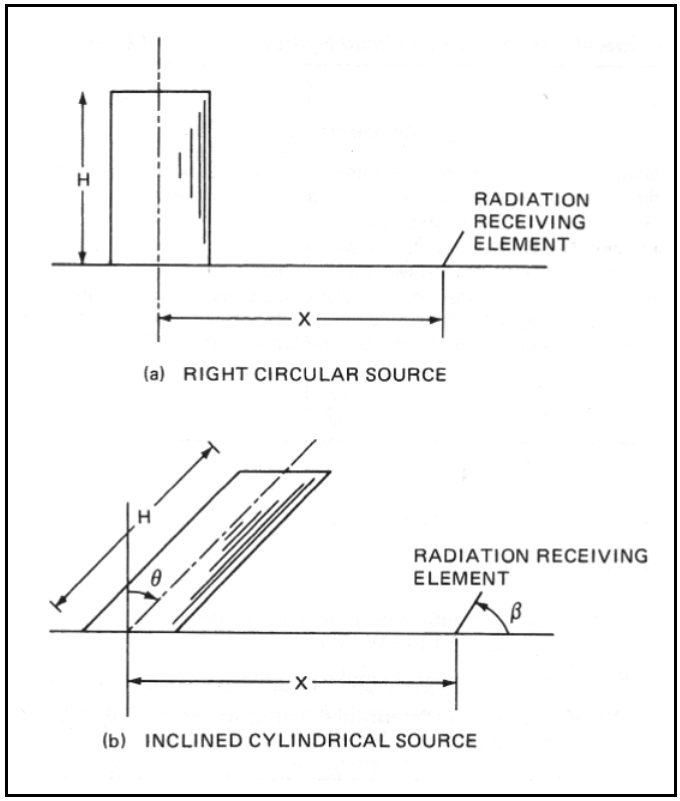
Average emissive flame power as related to pool diameter is shown in Fig. 5.46 [26].

Fig. 5.46: Average Surface Emissive Power for Gasoline, Kerosene, and JP-4 Pool Fires Versus Pool Diameter



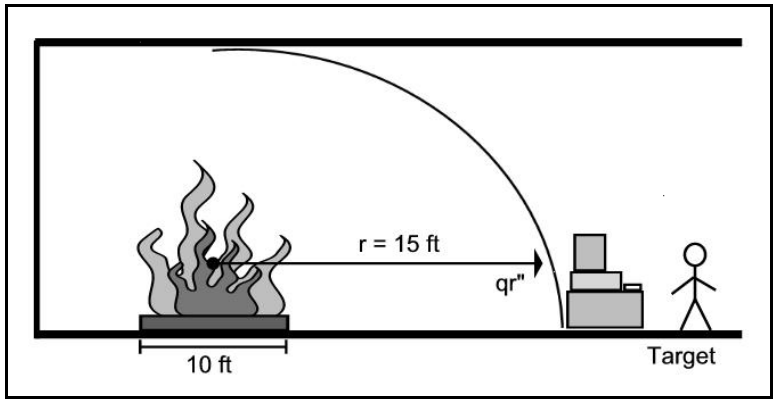
Radiant heat view factors (F_{12}) can be found in most heat transfer engineering books. A pool fire flame is commonly modeled as an upright cylinder. When ventilation or wind conditions are considered, the flame can be modeled as an inclined or tilted cylinder as shown in Fig. 5.47. [26]

Fig. 5.47: Flame View Factor Calculation Geometries for Right and Inclined Cylinders



The following provides a simple example of using the point source and solid flame modeling methods to estimate the radiant heat exposure to a target from a 10 ft diameter kerosene pool fire.

Fig. 5.48: Radiant Heat Point Source Modeling



Using point source model (Fig. 5.48):

Fuel: kerosene

Unit heat release: $\dot{q}'' = 1{,}516 kw/m^2$ (from Table 5.42)

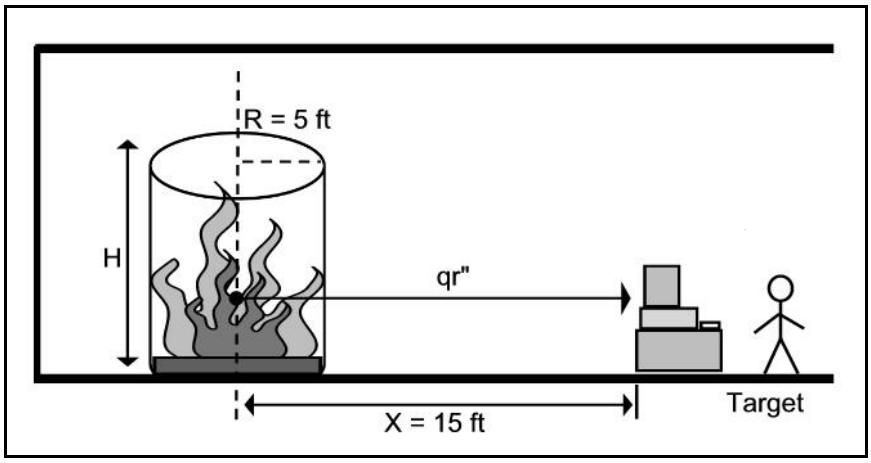
Surface area of pool: $A_S = 7.35 m^2$

Total heat release: $\dot{Q} = \dot{q}'' \times A_S = 11{,}143 kw$

Radiant heat flux to target: $qr'' = Xr\,\dot{Q} / 4\pi r^2$

r = 4.57 meters
Xr = 0.35 assumed
qr'' = 14.86kw/m^2

Fig. 5.49: Radiant Heat Solid Flame Modeling



Solid flame model: Assume cylindrical flame geometry (Fig. 5.49)
Flame height: H = 24.5 ft (calculated using Thomas equation, see Sect. 5.4.2)
Radiant heat flux to target:

$qr'' = \varepsilon\tau E F_{12}$ Assume $\in$ = 1.0
τ = 0.80
E = 100 kw/m^2 (from Fig. 5.46)

View factor F_{12} = 0.161
(View factor for vertical target, from Appendix A of Reference [4])

$$qr'' = (1)(0.80)(100 kw/m^2)(0.161) = 12.88 kw/m^2$$

Table 5.47 summarizes the radiant heat exposure level at the target versus the vulnerability of the target components (equipment, people). Target TDLs are discussed in Sect. 5.2.

Table 5.47: Summary of Example Results

RADIANT HEAT AT TARGET	EXPOSURE TO TARGET	
	EQUIPMENT	PEOPLE
Point source model: 14.86 kw/m^2	Assumed 20 kw/m^2 TDL for equipment	High chance of injury; first degree burns in 10 seconds if operator cannot immediately leave area (see Table 5.1)
Solid flame model: 12.88 kw/m^2	Negligible exposure to equipment	

Calculating the source fire's radiant heat intensity provides an assessment of the potential for ignition of secondary fuel sources in the area, potential for creating domino effects (i.e., causing thermal failures resulting in the release of flammable liquids or gases from containment), and the potential exposure to selected targets (people, equipment, structure) versus time.

The following box provides some references that provide more detailed discussions on fire radiant heat exposure modeling.

Some References

- *Assessing Flame Radiation to External Targets from Pool Fires*, an SFPE Engineering Guide, June 1999 [33]
- Krishna S. Mudar and Paul A. Croce, Fire Hazard Calculations for Large Open Hydrocarbon Fires, *SFPE Handbook of Fire Protection Engineering* [26]
- *Guidelines for Consequence Analysis of Chemical Releases*, Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, N.Y., 1999 [2]

5.7 SPECIAL HAZARD EXPOSURE MODELING

The release of flammable liquids and gases, under particular failure mode scenarios, can result in special hazard exposures such as torch fires, BLEVEs, flash fires, or vapor cloud explosions. This section presents an outline for developing exposure profiles for these hazards.

Some Definitions:

BLEVE:	A *boiling liquid, expanding vapor explosion* occurs from the sudden release of a large mass of pressurized liquid to the atmosphere. A primary cause is an external flame impinging on the shell of a vessel above the liquid level, weakening the shell and resulting in sudden rupture and large fireball.
Confined Explosions:	An explosion of a flammable vapor mixture inside a closed system (e.g., vessel or building).
Fireball:	The atmospheric burning of a fuel-air cloud in which the energy is mostly emitted in the form of radiant heat. The inner core of the fuel release consists of almost pure fuel, whereas the outer layer in which ignition first occurs is a flammable fuel-air mixture. As buoyant forces of the hot gases begin to dominate, the burning cloud rises and becomes more spherical in shape.
Flash fire:	The combustion of a flammable vapor and air mixture in which flame passes through that mixture at less than sonic velocity, such that negligible damaging overpressure is generalized.
Torch fire:	Fire type (i.e., a flame extension or jet fire) resulting from the pressurized release of gas and/or liquid and immediate ignition.
UVCE:	An *unconfined vapor cloud explosion* occurs when a flammable vapor is released and its mixture with air forms a flammable vapor cloud. If ignited, the flame speed may accelerate to high velocities and produce significant blast overpressure.

This section provides an overview of the special hazards defined above. The following references provide detailed information on quantifying these exposures.

Some References

"Guidance for Consequence Analysis of Chemical Releases," Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, N.Y. 1999 [2]

"Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs," Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, N.Y. 1994 [4]

A general approach for developing exposure profiles includes the following steps:

1. Characterize the release.
2. Identify potential incident outcomes.
3. Model the exposure.
4. Estimate consequence levels.
5. Provide documentation.

5.7.1 Characterize the Release

Characterization of the release involves:

- Identify the material of concern:
  - — Is the material to be evaluated flammable, toxic, or both? Is the material pure, or is it a mixture of several components (e.g., fuel gas containing methane, hydrogen, nitrogen,)?
- Identify the physical state of the material:
  - — What is the state of the material before release? Is it a gas, liquid, or solid? If liquid, is it superheated, refrigerated, etc.?
- Identify the release scenario to be evaluated:
  - — A continuous release is a release of material lasting a sufficient duration (usually minutes) to have a steady state discharge.
  - — An instantaneous release is a release of material of duration shorter (usually seconds) than necessary to achieve a steady state discharge.
- Identify the magnitude of the release

As discussed in Chap. 4, from a review of past fire and explosion incidents associated with the accidental release of a flammable liquid or gas, the following are known to be major causes:

- Failure of flexible hoses
- Overfilling of tanks or vessels
- Release from drainage and sampling valves
- Leaks from gaskets and pump seals
- Leaks from flanged joints and small pipe connections
- Piping failures
- Tank rupture
- Internal tank overpressures

A primary input to any release calculations is the hole size. For releases through a relief system, the actual valve or pipe dimension can be used. For releases through holes, the hole size must be estimated. No consensus is currently available for hole size selection, but some of the methodologies suggested include the following:

- World Bank suggests characteristic hole sizes for a range of process equipment (e.g., for pipes, 20% and 100% of pipe diameter are proposed).[3]

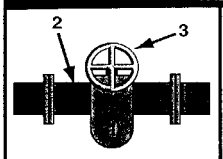
- Some analysts use a range of hole sizes from small to large, such as 0.2, 1, 4, and 6 in. and full bore ruptures for pipes less than 6 in. in diameter. [2]
- Some analysts use more detailed procedures. They suggest that 90% of all pipe failures result in a hole size less than 50% of the pipe area. The following approach is suggested. [2]
  - For small bore piping up to 1½ in., use 5-mm and full-bore ruptures.
  - For 2- to 6-in. piping, use 5- to 25-mm and full-bore holes.
  - For 8- to 12-in. piping, use 5-, 25-, or 100-mm and full-bore holes.

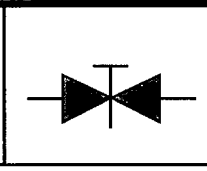
Table 5.48 presents some suggested failure mode hole sizes from reference [3].

Table 5.48: An Example of Some Suggested Failure Sizes

SUGGESTED FAILURE MODES

VALVE

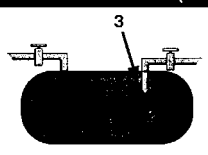


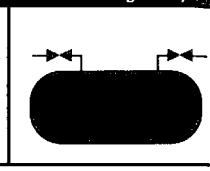


INCLUDES
Ball, gate, globe, plug, needle, butterfly, choke, relief, and ESD valves.

TYPICAL FAILURES	SUGGESTED FAILURE SIZES
1. Housing leak	100% and 20% pipe diameter
2. Cover leak	20% pipe diameter
3. Stem failure	20% pipe diameter

STORAGE VESSEL (Pressurized or Refrigerated)



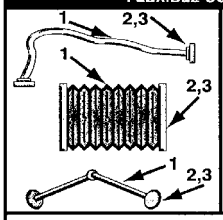


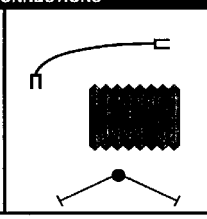
INCLUDES
Pressurized storage or transport vessels, refrigerated storage or transport vessels, and buried or nonburied vessels.

TYPICAL FAILURES	SUGGESTED FAILURE SIZES
1. BLEVE (nonburied case only)	Total rupture (ignited)
2. Rupture	Total rupture
3. Weld failure	100% and 20% pipe diameter

Note: These storage vessels may have bund walls, which should be taken into consideration in the analysis.

FLEXIBLE CONNECTIONS

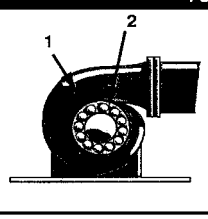


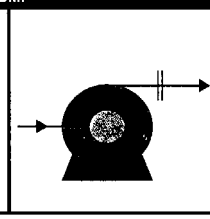


INCLUDES
Hoses, bellows, and articulated arms.

TYPICAL FAILURES	SUGGESTED FAILURE SIZES
1. Rupture leak	100% and 20% pipe diameter
2. Connection leak	20% pipe diameter
3. Connection mechanism failure	100% pipe diameter

PUMP

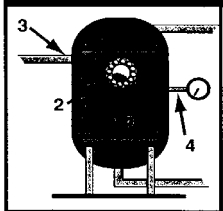


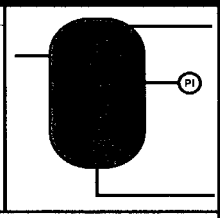


INCLUDES
Centrifugal pumps and reciprocating pumps.

TYPICAL FAILURES	SUGGESTED FAILURE SIZES
1. Casing failure	100% and 20% pipe diameter
2. Gland leak	20% pipe diameter

PRESSURE VESSEL/PROCESS VESSEL

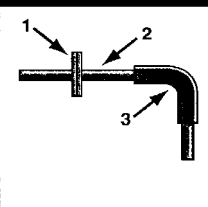


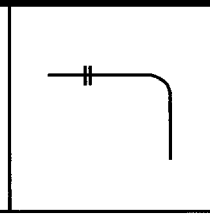


INCLUDES
Separators, scrubbers, contractors, reactors, heat exchangers, fired heaters, columns, pig launchers/receivers, and reboilers.

TYPICAL FAILURES	SUGGESTED FAILURE SIZES
1. Vessel rupture	Total rupture
Vessel leak	100% pipe diameter of largest pipe
2. Manhole cover leak	20% opening diameter
3. Nozzle failure	100% pipe diameter
4. Instrument line failure	100% and 20% pipe diameter
5. Internal explosion	Total rupture

PIPE





INCLUDES
Pipes, flanges, welds, and elbows.

TYPICAL FAILURES	SUGGESTED FAILURE SIZES
1. Flange leak	20% pipe diameter
2. Pipe leak	100% and 20% pipe diameter
3. Weld failure	100% and 20% pipe diameter

Source: Technical Ltd., *Techniques for Assessing Industrial Hazards*, World Bank Technical Paper Number 55, The World Bank, Washington D.C., 1988.

There are a number of computer models available to calculate release rates. In general, these models can estimate:

- Liquid release rates
- Gas release rates
- 2-phase release rates
- Vapor evolution (flash-off)
- Discharge size and duration

Reference [2] provides spreadsheet calculations, which include release rates. Some computer models are listed at the end of Sect. 5.7.3.

5.7.2 Incident Outcomes

As presented in Fig. 5.50, there are numerous fire or explosion incident outcomes that can result from a hazardous material accident. If a flammable gas is released under pressure, a torch fire, flash fire, or vapor cloud explosion potential may exist. If a closed container such as a pressurized tank containing liquified flammable gas is engulfed in fire, a large fireball from a tank BLEVE may occur. If a volatile flammable liquid is released and ignited, a pool fire, flash fire, or vapor cloud explosion may occur.

Structuring an event tree provides a method for identifying incident outcomes based on a defined initial event followed by a sequence of events, which may lead to various incident outcomes. Figure 5.51 presents an example event tree for identifying potential incident outcomes associated with a pressurized flammable gas release. The event tree analysis allows the input of event occurrence probabilities so we can later evaluate the likelihood of various incident outcomes and develop a risk profile for the initiating event.

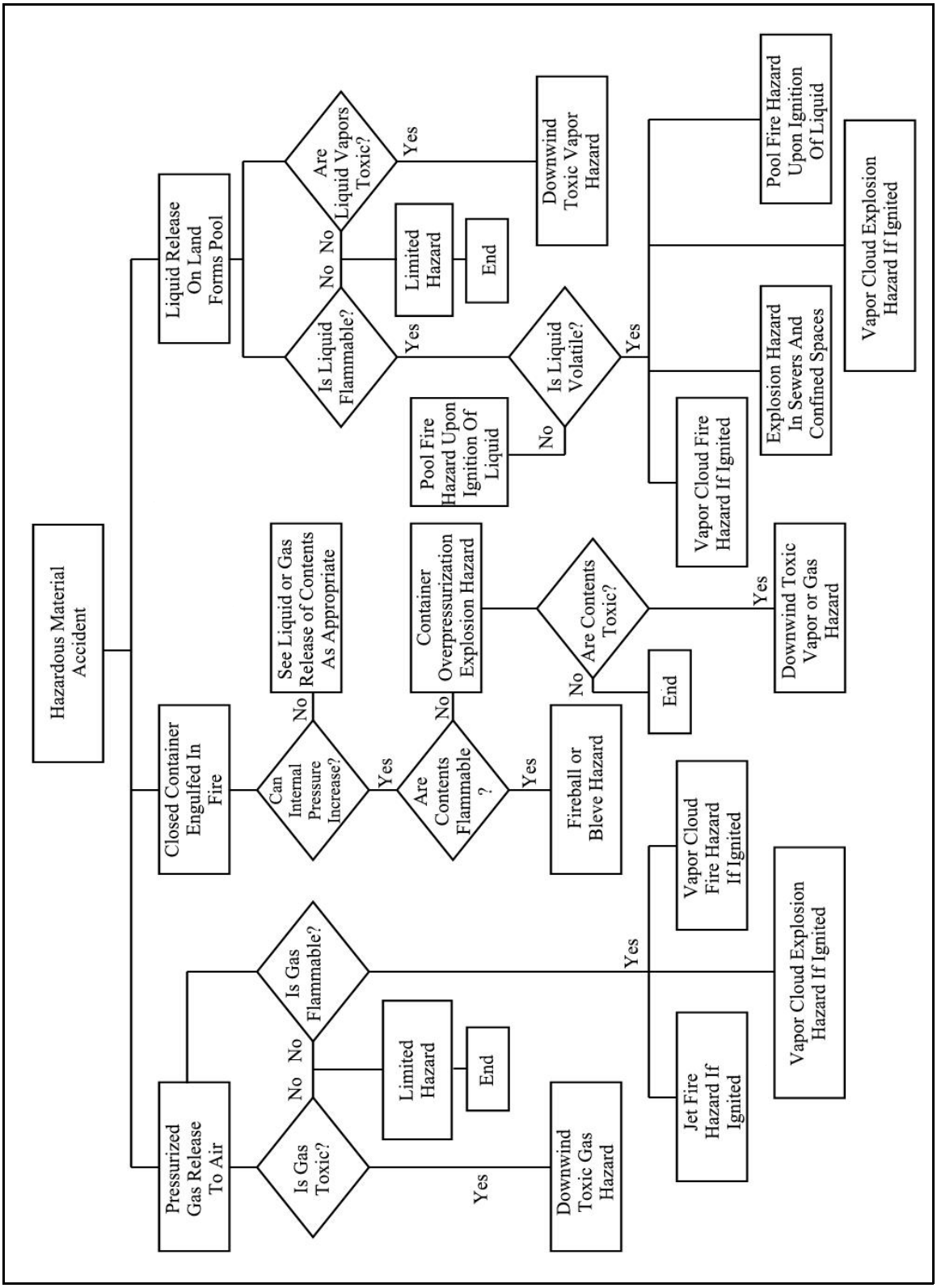
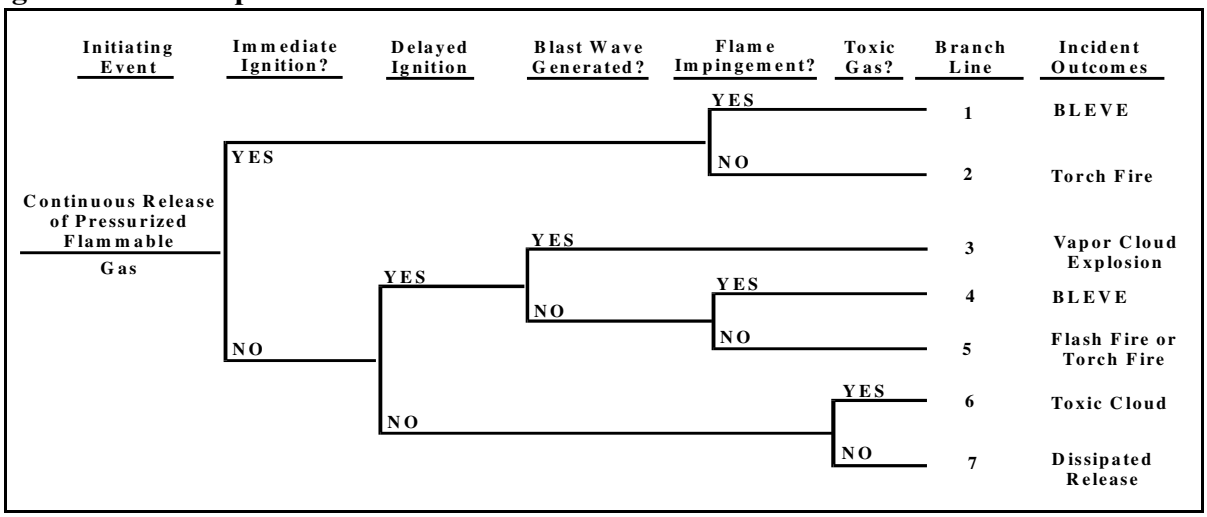


Fig. 5.50: Potential Incident Outcomes

Fig. 5.51: Example Event Tree for a Pressurized Flammable Gas Release



Following the accidental release of pressurized gas from containment, the type of potential fire or explosion event depends upon the following variables:

- Release mode (instantaneous or continuous)
- Rate and duration of gas discharge (i.e., time to emergency shutdown or loss of available inventory)
- Time to ignition (immediate or delayed)
- Initial mixing with air and cloud dispersion characteristics (flash fire versus an explosion generated blast wave)
- Performance of fire protection measures to reduce the potential of flame impingement on a vessel or tank creating a BLEVE situation.

If the gas release propagates and ignition results, the following major incidents can occur:

- Torch fire from immediate ignition of a continuous release
- Flash fire due to delayed ignition of a vapor cloud
- BLEVE fireball due to uncontrolled direct flame impingement
- Flash fire or unconfined vapor cloud explosion (UVCE) due to delayed ignition of a vapor cloud

Ignition

If the gas is ignited immediately (i.e., ignition is nearly coincident with the start of the release), the outcome will be a torch fire. Immediate ignition is most likely to occur if:

- The event that caused the release also ignites the release (e.g., drilling a hole through a pipe containing pressurized gas);
- There are potential ignition sources near the point of release (e.g., boilers or fired heaters; hot work involving welding, cutting, or grinding); or

- The escaping gas is very easily ignited (e.g., hydrogen, acetylene).

If gas is flammable but is not ignited immediately, it might still be ignited after a delay. Delayed ignition is most likely to occur if:

- The event that caused the release is incapable of igniting the gas (e.g., holes caused by corrosion);
- Potential ignition sources are well separated from the point of release;
- The escaping gas is more difficult to ignite (e.g., propane, butane); or
- The potential ignition sources are active only intermittently (e.g., electrical equipment that cycles on and off).

Chapter 4 provides information on modeling ignition likelihood. Using referenced historical data and applying linear regression analysis, Withers developed tables estimating the changes of on-site and off-site ignition and explosion probability versus flammable gas cloud release sizes. Tables 5.49 and 5.50 provide a summary of this statistical evaluation.[34]

Table 5.49: On-Site Changes of Ignition and Explosion[34]

FOR RELEASE SIZES OF OR LESS THAN (TONNES)	CHANCES OF IGNITION	CHANCES OF IGNITION AND EXPLOSION
5000	1.00	0.70
2000	0.94	0.50
1000	0.80	0.40
500	0.60	0.32
200	0.45	0.20
100	0.38	0.15
50	0.27	0.11
20	0.17	0.06
10	0.11	0.04
5	0.06	0.025
2	0.04	0.012
1	0.022	0.006
0.5	0.013	0.003
0.2	0.006	0.001
0.1	0.001	0

Table 5.50: Off-Site Chances of Ignition and Explosion[34]

FOR RELEASE SIZES OF OR LESS THAN (TONNES)	CHANCES OF EDGE		CHANCES OF CENTRAL		
	IGNITION	IGNITION AND EXPLOSION	IGNITION	IGNITION AND EXPLOSION	CHANCES OF NO IGNITION
5000	0	0	0	0	0
2000	0.05	0.04	0.01	0.01	0
1000	0.14	0.13	0.04	0.03	0.02
500	0.07	0.06	0.03	0.02	0.30
200	0.05	0.03	0.01	0.007	0.49
100	0.05	0.02	0.01	0.005	0.56
50	0.04	0.01	0.01	0	0.68
20	0.03	0.01	0.01	0	0.79
10	0.02	0.01	0.01	0	0.86
5	0.01	0	0	0	0.92

Blast Wave Generation

Under certain circumstances, delayed ignition of a flammable gas release can result in a vapor cloud explosion that produces a potentially harmful blast wave. If a continuous release of pressurized gas is ignited after a delay, the likelihood of a vapor cloud explosion increases if:

- The vapor cloud is totally or partially confined (e.g., the gas is released into an enclosed space such as a compressor building, or the gas is released outdoors in a congested area).
- The gas is highly reactive (e.g., acetylene, ethylene oxide).
- The gas has a high laminar flame speed (e.g., acetylene, ethylene, hydrogen).
- The release is ignited by a high-strength ignition source.

If a continuous release of pressurized gas is ignited after a delay, the likelihood of having a flash fire (without any blast wave) increases if:

- The vapor cloud is totally unconfined or only partially confined.
- The gas is not highly reactive (e.g., methane, propane).
- The gas has a low laminar flame speed (e.g., methane, natural gas).
- The release is ignited by a low-strength ignition source.

From a review of historical loss incidents in which LPG was accidentally released and ignited, the following relative percentages of incident outcomes occurred: [35]

Flash fire	41%
BLEVE	21%
UVCE	19%
CVE	19%

Confined vapor explosion (CVE) outcomes were incidents involving propane gas leakage into an enclosed area where ignition occurred and explosion overpressure resulted.

Flame Impingement

In certain situations, a torch fire and/or a pool fire might impinge on a pressure vessel that contains superheated liquid. If proper mitigation measures are not taken, the pressure vessel might undergo a BLEVE. The likelihood of a BLEVE is increased if:

- There are several pressure vessels near the release point,
- The vessels are not insulated,
- The vessels are not protected by a fixed water spray or deluge system, and
- The fire impinges on the vessel for more than just a few minutes.

If the distance between the release point and the nearest pressure vessel exceeds the length of the torch fire or the extent of the liquid pool fire, there is no possibility of flame impingement. In some situations, physical barriers between the release point and the pressure vessel might also negate the possibility of flame impingement.

5.7.3 Exposure Modeling

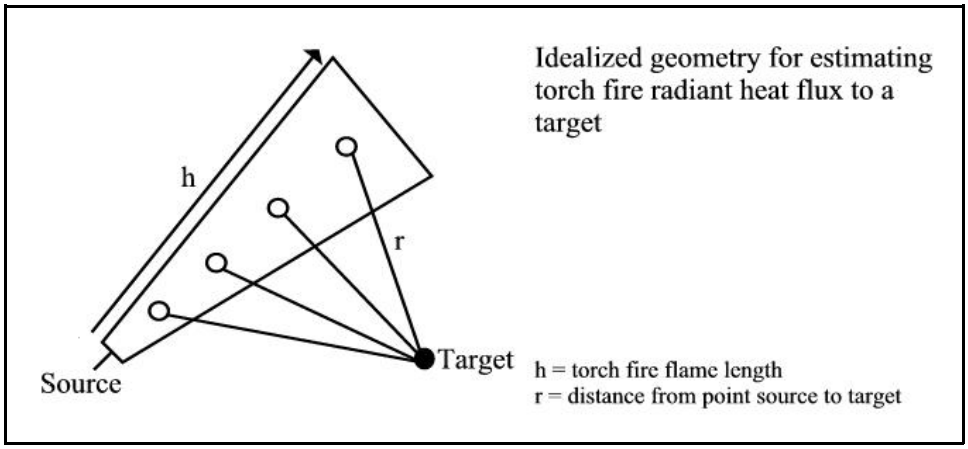
Torch Fire

A torch fire or flame jet fire is a fire extended from a point of accidental release of flammable liquid or gas that is being discharged under pressure. This is usually associated with immediate ignition and presents an intense near-field radiant heat exposure to people and equipment. The primary concern of a torch fire is that if the flame impinges on either the top (i.e., unwetted area) of a tank, vessel, or cargo truck containing flammable gas, a BLEVE could occur.

Models are available to calculate the length of torch fires and the radiant heat exposure from the torch to a target.[2]

One common method of modeling a jet flame is to presume the shape of the jet as a cylinder or a cone. An example of the cone geometry is shown in Fig. 5.52.

Fig. 5.52: An Example – Conical Torch Fire Geometry



The potential area exposed to direct flame impingement is directly related to the estimated length of the flame jet. For estimating thermal radiation, the radiation exposure from discrete sections of the flame is represented by a number of simple point sources, each consuming fuel in proportion to the volume of the flame at that location. Each point source contributes to the total radiation in accordance with the point source equation for thermal radiation.

A simplified power law correlation for estimating the dimensions for a liquefied propane gas (LPG) torch flame, assumed to be conical geometry, is given as:[2]

$$L = 9.1\dot{m}_f{}^{0.5}$$
$$W = 0.25L$$

L = length of the flame jet (m)

$\dot{m}_f$ = release rate (kg/s; subject to m < 3000 kg/s)

W = jet flame conical half-width at flame tip (m)

The torch fire HRR, $\dot{Q}$ for a release rate $\dot{m}_f$ is given by :

$$\dot{Q} = \dot{m}_f \, H_C x_e$$

H_c is the heat of combustion $\left(kJ/kg \; or \; \frac{kw-s}{kg} \right)$

x_e is the combustion efficiency

The radiation heat flux is $\Sigma_\eta q_r'' = \left(\frac{\in X_R \dot{Q}}{4\pi r^2} \right)$

where X_R is the radiant heat factor that can be conservatively taken in most cases as 0.35 and
ε is an emissivity factor that depends on the material being burnt; for jet fires ε can be taken as 0.2 – 0.5.
r is the radiant distance from the point source location in the flame (η) to the target.

The total heat flux at a distance from the flame is the summation of the radiation from each selected point in the flame. The choice of η is rather arbitrary; 4 points are usually adequate for a hazard analysis.

It should be noted that this approach does not take into account the effect of wind on the flame shape. Wind has little effect on a jet from a high-pressure source, since the velocity of the jet is much greater than that of the wind. However, the shape of a jet from a low-pressure source

can be changed significantly by the wind; the effect of the wind will be to increase the incident radiation for down-wind targets.

BLEVE

A BLEVE (boiling liquid, expanding vapor explosion) results from the overheating of a pressurized vessel by an exposure fire. This overheating raises the internal pressure and weakens the vessel shell unit until it bursts open and releases its contents as a large and very intense fireball.

This type of failure occurs not immediately but after some period of fire exposure to the vessel. In the historical BLEVE incidents reviewed by the NFPA, tank rupture occurred from 8 – 30 min (average of 18 min) after the initial fire exposure. In the historical BLEVE incidents involving more than one tank, the tanks appear to have ruptured sequentially and not simultaneously, indicating that it is reasonable to calculate blast and fireball damage on the basis of the contents of a single vessel rather than on the aggregate capacity of a bank of tanks.

With large LPG storage tanks, a BLEVE can produce a fireball several hundred feet in diameter. The size of the fireball depends on the amount of liquid gas and pressure left in the tank. In addition, the BLEVE propels metal projectiles and burning or unburnt gas for hundreds of feet. Portions of the tank may rocket several thousand feet, usually within 30° of the tank's longitudinal axis. The rocketing sections may contain fuel that may spread upon impact. The prediction of fragment effects is important, since deaths and domino damage effects are attributable to fragments. Specific work on BLEVE fragmentation hazards has been done by the Association of American Railroads which reports that of 113 major failures of horizontal cylindrical tanks in fire situations, about 80% resulted in projected fragments.[2, 4]

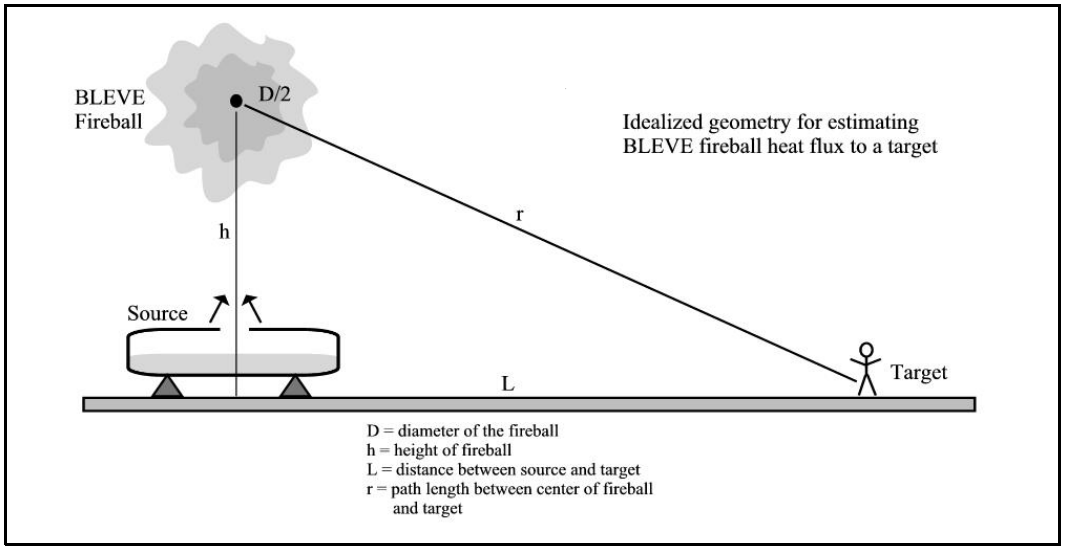
Fragments are usually not evenly distributed. The vessel's axis direction receives more fragments than the side directions with roughly 80% of fragments falling within a 1000 ft range.[2,4]

As illustrated in Fig. 5.53, radiation effects due to a BLEVE fireball depend on:

- The diameter of the fireball as a function of time and the maximum diameter of the fireball
- The height of the center of the fireball above its ignition position as a function of time (after liftoff)
- The surface-emissive power of the fireball
- The duration of combustion

The output of primary interest in BLEVE fireball exposure modeling is the radiant heat flux level at the target and fireball duration. Because of the short duration of the fireball, the radiant heat output primarily poses an exposure to people.

Fig. 5.53BLEVE Fireball



The simplest method for evaluating fireball radiant heat exposure is to adopt a point source approach, utilizing the mass of fuel involved with a constant fraction of heat of combustion radiated. A value of .25 to 0.4 has been proposed by researchers. The disadvantages of this method are that it does not provide guidance on the size of a fireball. In some cases, it is better to use a solid flame model, although it may be necessary in the absence of data to assume that the fireball is always at its maximum diameter and position for the whole of its duration, and has a constant surface emissive power. Such a method is simple to use, although it may overestimate the total radiation exposure from a fireball. The information required for this modeling method is the quantity of fuel involved, the diameter and height above ground, duration, surface emissive power, and a view factor.

References [2] and [4] provide detailed information on BLEVE fireball exposure calculations including radiant heat exposure and fragment exposure modeling with examples.

Flash Fire Exposure

Gas vapors discharging from an accidental release, if not ignited immediately, will form a plume or cloud of gas or vapor that moves downwind. If this cloud or plume contacts an ignition source at a point at which its concentration is within the range of its upper and lower flammable limits, a wall of flame may flash back towards the source of the gas or vapor, engulfing anything and everything in its path. People or property caught within the cloud as the flame passes may be severely injured or damaged if not protected. From a historical perspective, this exposure is primarily to on-site employees caught within the cloud boundaries at the time ignition occurs.

Flash fire assessment is generally applicable for a cloud or plume of heavier-than-air flammable vapor released to the atmosphere and ignited as it drifts downwind. A flame burns and propagates through the space occupied by the cloud. The hazard zone is defined by the length and

width dimensions of this cloud. It is then assumed that people at the outer edge of the cloud would be subject to burn injury and people within the flashing gas cloud subject to fatality.

To predict the radiation effects from a burning vapor cloud, it is necessary to know the size and shape of the fire, its position, the radioactive properties of the flame, and how these factors vary with time. There are no fundamental theoretical models available to evaluate this. A model that accurately represents all the features that have been observed experimentally would be very complex. Fortunately, for the determination of hazard zones, the prediction of thermal radiation from a cloud fire may not be of primary significance. This is because the size of the flammable hazard zone is essentially determined by the size of the cloud, which can be calculated from vapor dispersion models. The extension of the hazard zone beyond the cloud boundary caused by thermal radiation from the burning cloud is generally small. This is certainly the case for many heavy gas clouds where the depth of the cloud, and hence the related flame height, is expected to be small compared with the downwind extension of the cloud.

Vapor Cloud Explosion Exposure

As previously described, when a large amount of a volatile flammable material is rapidly dispersed to the atmosphere, a vapor cloud forms and disperses. If this cloud is ignited before the cloud is diluted below its lower explosion limit (LEL), a UVCE or flash fire will occur. The main consequence in a UVCE is the shock wave that results, whereas the main consequence in a flash fire is the thermal radiation. The combustion processes of large vapor clouds are not completely understood. A review of the historical record indicates that release of a small quantity of vapor is likely to result in flash fire without significant overpressure. Further, despite the UVCE name, experience and limited experimental work show that some form of confinement and cloud turbulence is needed for damaging overpressures to occur. There are also indications that the initial vapor cloud must be above a critical size (for which the values are not known) for damaging overpressure to occur. However, based on observations, various researchers have concluded the following:

- There may be some minimum mass of flammable material required to allow transition from a flash fire to UVCE. These estimates range from 1 to 15 tons.
- The presence of some confinement/obstacles may be necessary for transition to UVCE.
- UVCEs should be considered deflagrations, not detonations.

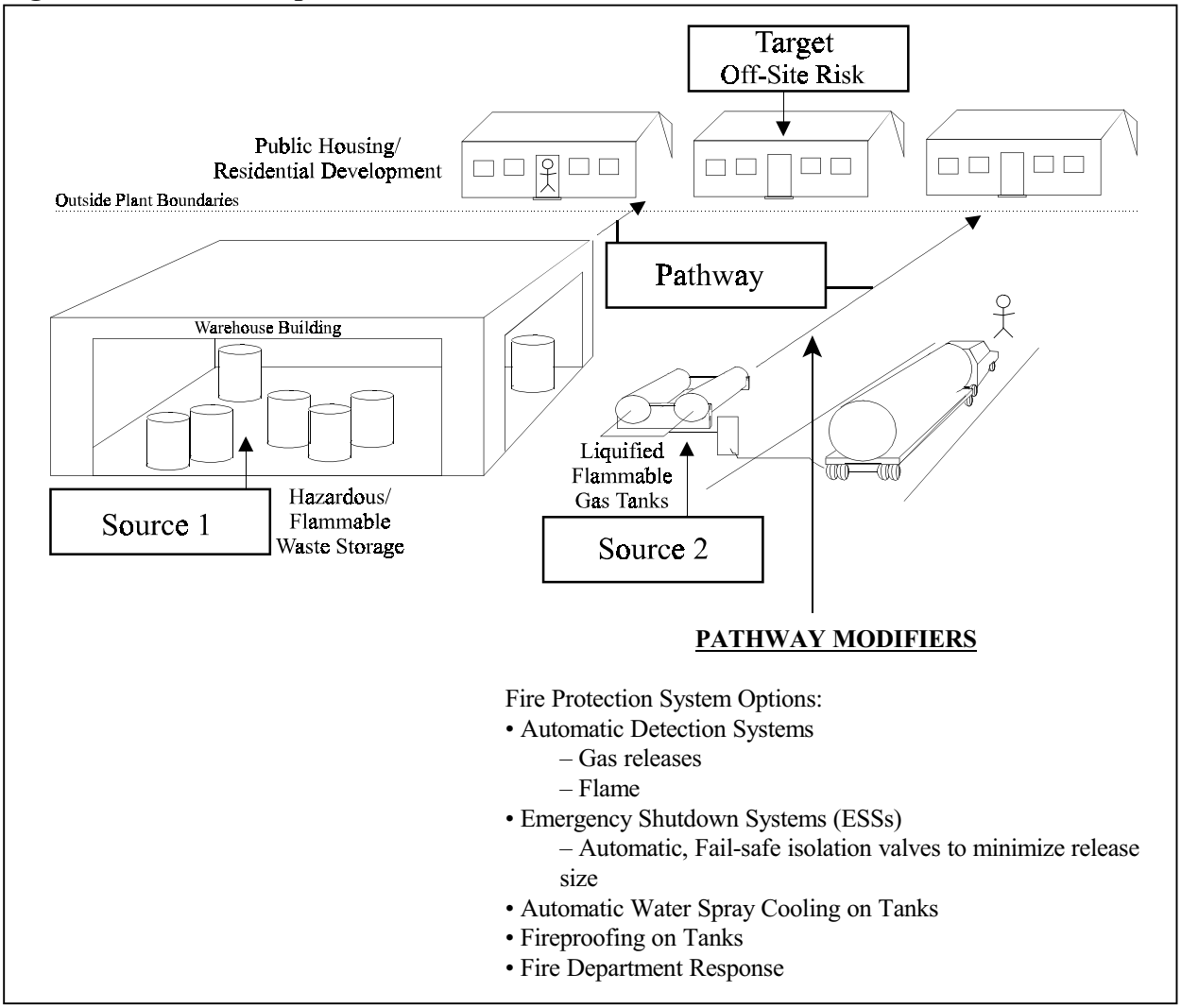
Flammable vapor clouds may be ignited from a number of sources that may be either continuous (e.g., fired heaters, pilot flames) or occasional (e.g., smoking, vehicles, electrical systems). Clouds are normally ignited at the edge as they drift. References [2] and [4] provide information on vapor cloud explosion modeling, including detailed description of the following models:

- TNT equivalency
- TNO multi-energy
- Baker-Strehlow

5.7.4 Relating Consequence Levels

Relating exposure to consequence levels is performed using the approach discussed in Sect. 5.3. The following presents a short example of evaluating off-site consequence levels and risk using the example layout in Fig. 5.54.

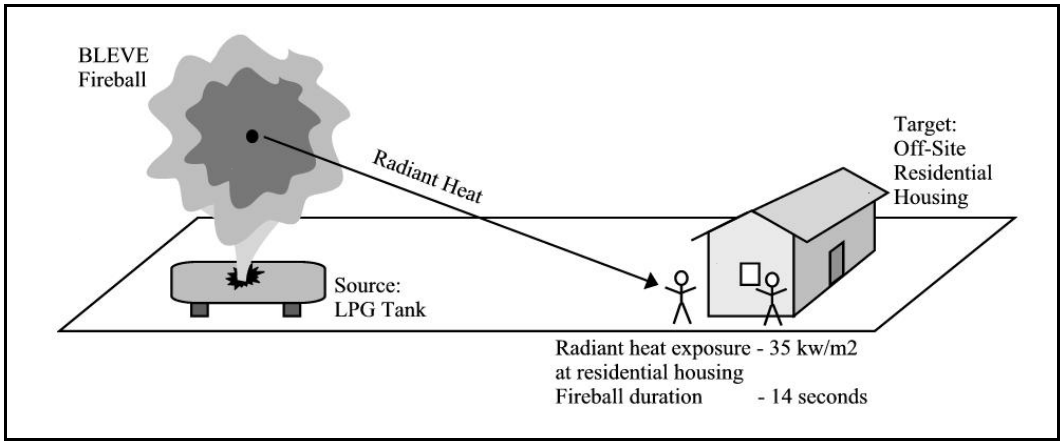
Fig. 5.54: Example of Off-Site Risk



We will assume that based on hazard screening, scenarios leading to BLEVE or UVCE potentials will require off-site risk evaluation.

Figure 5.55 presents the exposure profile modeled for the BLEVE scenario.

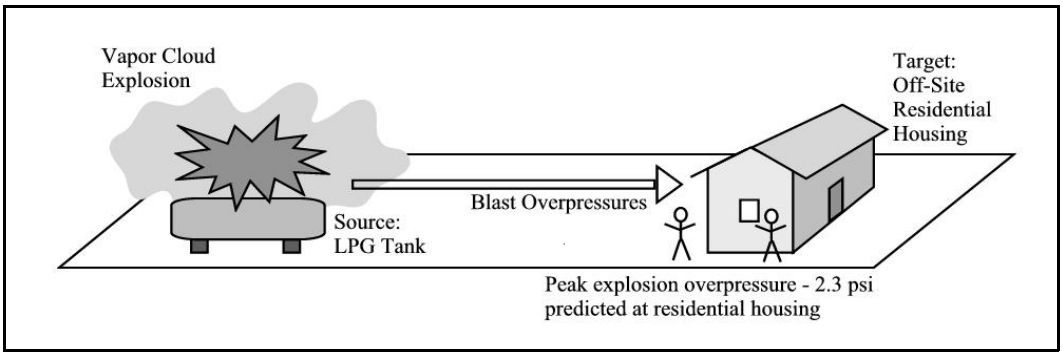
Fig. 5.55: BLEVE Fireball Exposure



The results indicated in Fig. 5.55 are a radiant heat exposure of 35 kw/m^2 for 14 seconds. This indicates a potential effect to humans of second degree burns and 1% lethality (see Sect. 5.2, Radiant Heat Threshold Damage Levels, Fig. 5.7). With the short fireball duration, significant property damage would not be expected.

Figure 5.56 presents the exposure profile modeled for the UVCE scenario.

Fig. 5.56: UVCE Exposure



The results indicated in Fig. 5.56 are a peak explosion overpressure of 2.3 psi. This indicates building occupants may suffer temporary hearing loss or injury from secondary blast effects such as building debris or flying glass. Personnel in the open are not expected to be killed or seriously injured directly by the blast, though some injuries from fragments and debris are possible. Unstrengthened buildings can be expected to sustain damage approximating 20% of their replacement cost (see Sect. 5.2, explosion overpressure effects, Table 5.19).

Based on the consequence categories in Tables 5.27 and 5.30 in Sect. 5.2, consequence levels were assigned as presented in Table 5.51.

Table 5.51: Consequence Levels For Example

INCIDENT OUTCOME	EXPOSURE PROFILE AT TARGET	CONSEQUENCE LEVELS	
		PEOPLE	PROPERTY
BLEVE fireball	35kw/m^2	3	1
UVCE	2.3 psi	3*	3

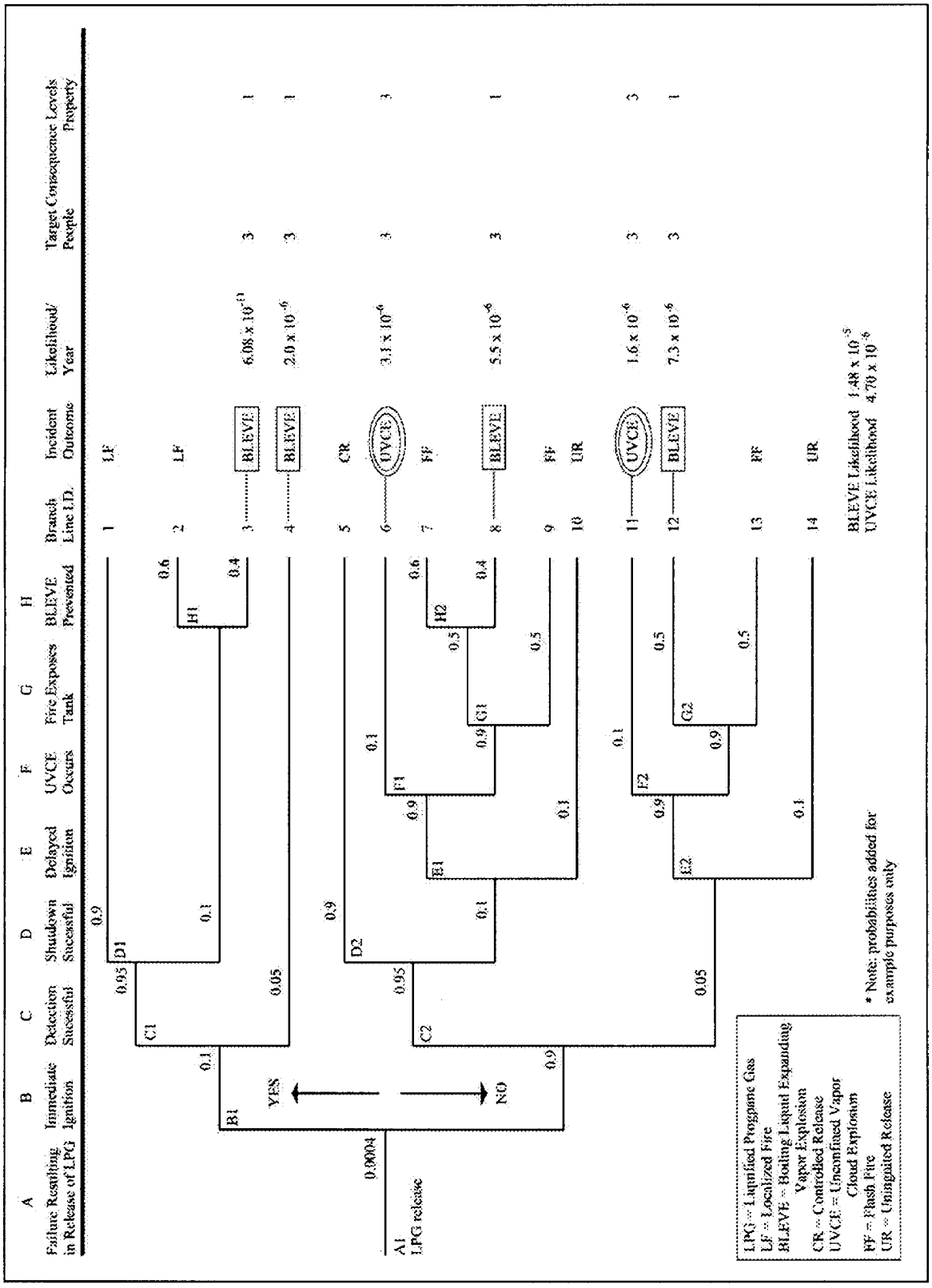
* Because of the potential for flying glass to injure people inside a house, an exposure level of 3 was chosen.

Note: For people: 3 = high exposure; moderate to severe injury potential requiring hospitable treatment

For property: 1 = limited damage does not require repair
3 = significant damage, approximately 20% to exposed buildings

Figure 5.57 presents an example ETA with the BLEVE and UVCE consequence levels inserted. The ETA assumes LPG as the fuel, installation of gas detection, emergency shutdown valves, and pre-aimed water monitors for fire brigade use. The probabilities are added for example purposes only.

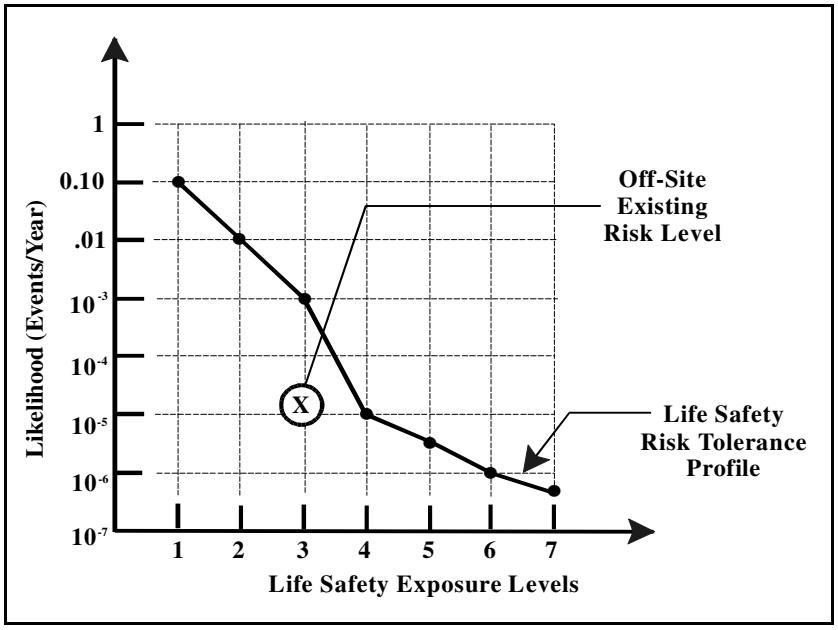
Fig. 5.57: Example Event Tree Analysis



Based on the example ETA results in Fig. 5.57, there is a combined likelihood of having a level 3 people consequence level of 1.95×10^{-5} events/year (the BLEVE and UVCE consequence level 3 likelihoods are added together).

If, for this example, we assume the life safety risk tolerance profile in Fig. 5.58, then the existing risk level is below the risk tolerance level and further risk reduction is not needed.

Fig. 5.58: Example Life Safety Risk Tolerance Profile



Computerized Models

To assist in exposure and consequence estimation efforts, computerized models can be used to calculate release rates, gas dispersion profiles, torch fire and BLEVE exposure, and vapor cloud explosion overpressures. These models, sometimes termed multi-hazard models, can range from simple computerized equations to very complex models.

The book *Guidelines for Consequence Analysis of Chemical Releases from the Center for Chemical Process Safety of the American Institute of Chemical Engineers* comes with a CD containing the equations described in the book in a computer spreadsheet format.[2]

Some previous multi-hazard free public domain models are no longer available either because they were not Y2K compliant, lost funding to support updating, or have been incorporated into commercial software products.

Table 5.52 provides a listing of some commercially available multi-hazard computer models.

Table 5.52: A Listing of Some Multi-Hazard Computer Models

MODEL NAME	AVAILABLE FROM
BREEZE HAZ Professional	Trinity Consultants Website: www.breeze-software.com E-mail: software@trinityconsultants.com Demo is available
CANARY	Quest Consultants Inc. Website: www.questconsult.com E-mail: info@questconsult.com Demo is available
PHAST	Det Norske Veritas (DNV) Website: www.dnv.com E-mail: sales.houston@dnv.com Demo of micro version available
EFFECTS – 4 DAMAGE	TNO Department of Industrial Safety Website: www.mep.tno.n1/homepage_eng_mep.html E-mail: I.heidebrink@mep.tno.n1 Demo is available
TRACE	SAFER Systems LLC Website: www.safersystem.com E-mail: safer_system@safersystem.com Demo is available

5.8 DISCUSSION

In the risk-informed, performance-based method, modeling the exposure(s) at selected targets is based on a combination of deterministic modeling and probabilistic modeling. Deterministic zone or field fire models, radiant heat exposure calculations, and special hazard models are tools used to assist the risk assessment team in developing event tree time lines, consequence levels, and the probabilities of successful FPS interaction (i.e., success of detection, emergency controls, automatic fire suppression, fire barriers, manual fire fighting, etc.).

As described in this chapter, the general approach used for exposure profile modeling involves the following:

1. Determine the vulnerability of the target or targets. Vulnerability is defined in terms of TDLs. TDLs are potential failure limits of the target subsystems and components (equipment, operators, structure, etc.) when exposed to fire or explosion impacts. Based on the TDLs of the target components, system-based exposure damage limits can be established.

2. Characterize the initiating fire or explosion source intensity. For fire scenarios, developing and quantifying the initiating source heat release rate (HRR) in a credible manner is a key consideration in the initial development of the exposure profile. The HRR is used to estimate flame height, radiant heat flux, and fire plume size and intensity, all of which affect the exposure at the target.
3. Model the event tree scenario fire or explosion incident outcomes. Pool fires, torch fires, unconfined spill fires, flash fires, BLEVE fireballs, solid materials and storage configurations can be modeled to evaluate radiant heat flux, temperatures, and smoke concentration intensities at the target. Unconfined vapor cloud explosions and confined explosion can be modeled to evaluate potential explosion overpressures at a target.
4. Establish consequence levels. By relating the exposure profile modeling (i.e., fire or explosion intensity) to the target's TDLs, potential consequence levels for property damage (equipment, stock, structure) and life safety exposure can be categorized in the ETA.
5. Develop FPS response parameters. Based on the exposure profile and consequence response times for detection systems, response times for emergency shutdown systems and automatic and manual suppression systems can be established in the event tree time line. These response times are then used in the FPS performance success probability evaluation (Step 6).

When selecting fire or explosion modeling computer software programs, be sure to review the analytical models on which the program is based and the assumptions made by the model's developer. Find out how the program has been validated. For example, has it been validated against laboratory experiments or large scale tests?

The output quality of any model is only as good as the quality of its input. Much effort should be expended in characterizing the initiating event scenario(s) (i.e., the source fire HRR profile). Documentation should be provided for the inputs, assumptions, sensitivity and uncertainty analyses, and level of quality reviews. This aids in review and reproducibility of the model by other analysts and also increases decision maker confidence in the results of the modeling.

Lastly, when using computer models, apply sound engineering judgement in the interpretation of the results. If the results don't make sense from your real world experience, then they are probably incorrect. Remember, computer models are tools to be used by experienced practitioners, and uncertain or unreasonable results should never override experience and good judgement.

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