Part VII
Fire Protection Engineering

Handbook of Loss Prevention Engineering, First Edition. Edited by J. M. Haight.

38
Fire Dynamics

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38.1
Overview

Considerable error bounds exist in all stages of fire dynamic predictions, with disagreement over some aspects of phenomenology visible in published papers and books – for example, Drysdale (1998) discusses several competing definitions of flashover in building or compartment fires.

The extent to which this error matters is a function of the application of the study.

Genichi Taguchi described well the differences between engineering and science, whereby ‘‘the objective of scientific research is to find the best way to understand natural phenomena without regard for cost’’ whereas in engineering ‘‘from all possible approaches the best one is chosen by considering the quality level and the cost required’’ (Taguchi, 1993). Note that in this sense quality does not refer to an abstract or subjective value but rather the ability of the object to ‘‘perform the desired functions.’’

Hence this chapter aims to offer a broad introduction to a wide range of issues related to fire dynamics, some first-order estimation tools, and guidance on sources of more detailed information, including advanced methods. Where – such as with the flashover example – multiple definitions exist, the guiding principal for the selections made is to focus on simple, commonly used tools and definitions, along with known shortfalls.

Before undertaking a fire analysis, the intended use must first be understood. Typically, these might be:

- experimental research and data collection
- selection of spacing between equipment
- design of ventilation (forced and natural) and explosion venting
- identification of isolation, blowdown, and process flaring/venting requirements
- selection of passive and active fire and explosion protection
- estimation of residual risk to plant, people, and the environment.

Note that the individual bullets are not exclusive, with iteration needed to assure that an optimized design is achieved.

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Also, when considering error bounds it is not automatically appropriate, or even possible, to adopt the ‘‘conservative’’ principal of using pessimistic values. This is because:

- Only utilizing conservative values at each stage in an accident chain prediction will result in a highly conservative outcome that may skew the overall understanding of risk and lead to a focus of effort on hazards with high uncertainty rather than ones with a true high residual risk.
- What is conservative for one scenario may be optimistic for another. For example, a high release rate will generate a large flame length but for a shorter duration. The duration may be critical for understanding the potential for escalation and the flame length for the limits of protection. Similarly, a high ignition rate is conservative for the prediction of fire- and explosion-related risk but may be optimistic for toxic-related risk.

Broadly, the remainder of this chapter is divided into two parts. Part A is a qualitative description of approaches and techniques associated with analyzing fire dynamics, and Part B provides some first-order estimation techniques. The separation is not particularly clean, but is aimed at making the first part rather more readable than might otherwise have been the case.

38.2
Part A – Qualitative Description of Fire Dynamics

38.2.1
Characterize the Decision

The first stage in fire dynamics is to characterize the decision to be made. As with any risk-related technique, there is no value in studying the issue if no action is intended to be taken. Put simply, analysis aids the understanding of a hazard but does not make any difference to the threat; only actions taken with respect to the design or operation of the equipment can alter risk.

The information required to define the action and distinguish between options will vary with the maturity of the project, plant, or building under study:

- If the project is at the concept selection stage and is within known risks, then a mixture of expert judgment and rule-based techniques may be sufficient to enable alternative concepts to be compared.
- If a mature plant is being expanded, then the validity of the existing design base may need to be reviewed or a more simplistic ‘‘no interaction’’ approach adopted whereby protection included with the expansion is sufficient to prevent any escalation to, or from, the existing plant. This may require more detailed consideration of consequences from the existing plant than were used for its original design.
- During the early design stages, the fire scenarios may be required to establish fire loadings and firewater demands at a sufficient level of detail to allow firewater

system selection and potentially firewater pump selection for a long lead time item.
- A new plant whose operating conditions lie outside validated data may need investment in experiments to assure the validity of the extrapolation of existing correlations.

38.2.2
Resolve Accuracy Required

The accuracy of the prediction must reflect the risk associated with the decision to be made. For example, passive fire protection is defined through the fire type and duration, but grouped into standard elements, meaning that the decision is limited to the appropriate selection, for example, H60 (60 min protection against radiant heat from a hydrocarbon fire), versus H120 or H180 (Venn, 2007).

Therefore, it is rarely necessary to resolve the difference between a 15 and an 18 min release, only between a 30 and a 60 min release.

Conversely, the error bound in the analysis must be reflected in the decision – a typical correlation-based flame length prediction of 30 m does not mean that flames will not be encountered at 31 m and classically vapor releases are not stopped by boundary fences, nor do they look both ways before crossing a road!

38.2.3
Establish the Performance Requirements

Performance requirements must be expressed functionally based on the analyses.

In fire dynamics, the functional requirement must include the functional definition (e.g., blast overpressure protection), a quantified functional failure definition (e.g., the design case event overpressure withstand capability in terms of peak pressure and impulse without damage, and with a defined acceptable damage such as plastic deformation but no tearing), and ideally a post-event requirement (e.g., must a blast wall be able to act as a fire wall after a described blast?).

A probabilistic statement may well be required to express the tolerable loss of function within a given time period or on a per demand basis. For example, a Norwegian Standard (NORSOK, 2001) sets a limit of tolerability of failure of a primary safety function of once per 10 000 years.

38.2.4
Design the Protection

An iterative process should be anticipated between the design and analysis of protective barriers against an event. In this regard, barriers are seen as being the functional grouping of safeguards with each barrier including physical, procedural, and personnel aspects (OGP, 2008).

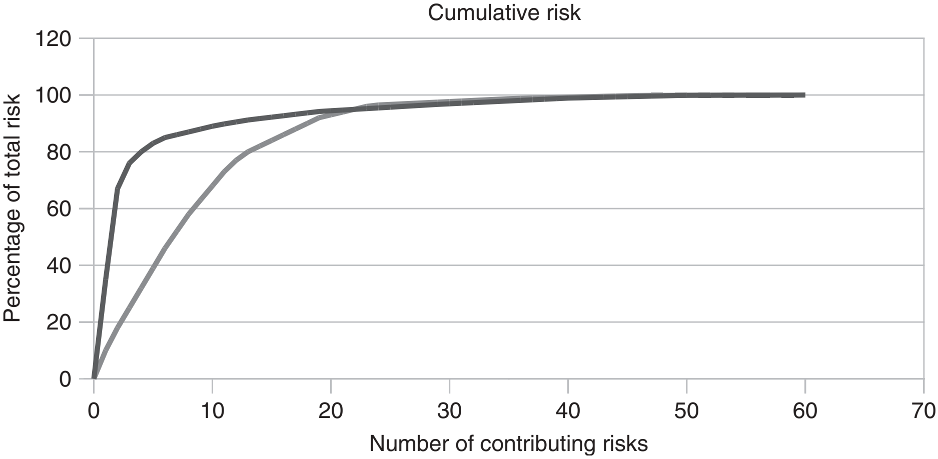

Figure 38.1 Illustrative comparison of two competing options. The upper curve demonstrates a much higher dominance of a few risks, suggesting that further risk treatment may be beneficially focused on these items. The lower curve represents a more balanced risk profile.

38.2.5
Analyze the Residual Risk

In some regulatory regimes, the overall residual risk to individuals has been used as a key metric. However, in mature regimes, recognition of the error bounds intrinsic in the analysis, plus more contentiously, perhaps, the flexibility available to the analyst when wishing to present a desirable result, has led to a reduced emphasis on absolute values. Instead, emphasis is typically placed on ensuring appropriate risk assessment with the main focus placed on managing risks, for example, Offshore Information Sheet No. 3/2006 (UK HSE, 2006).

In practice, the overall value can help when comparing options and to check the mathematics, but the real value comes in what is found in the risk analysis journey, allowing a focus on areas of known risk and investigation of areas of uncertainty.

In particular, residual risk analysis primarily permits the consideration of the balance between various risks to allow effort to be effectively directed in further reducing risk. If a plot is made of the number of risks against the cumulative sum of risk, in diminishing ranked order, then the relative dominance of the top risks is easily seen. This is illustrated in Figure 38.1.

Consider the two competing options illustrated. While the overall risk values are of interest to judge relative risk (assuming the same assumptions and methods are used in both cases), this importance plot illustrates the relative dominance of a small number of risks in the top curve. This could be indicative of a need for additional controls for a particular scenario.

Early in the design, this approach can be used to assure if sufficient barriers have been established and the benefits of adding more barriers. Occasionally, it may also be used to look at improving the performance of existing barriers (e.g., by altering the inspection frequency), but the reliance on historical data for failure performance diminishes its utility for this degree of resolution.

The combination of a number of potential scenarios, each with significant variability and uncertainty, requires much broader, simplified estimates of consequences than are used for the design of specific barriers. Equally, the level of uncertainty for any specific sequence is likely to be large in comparison with the risk under study, making the use of residual risk only really beneficial at the plant level (Venn, 2008).

38.2.6
Stages in a Fire Accident

38.2.6.1 Identify Leak Opportunities

Any element of a flowing or storage system has the potential for leakage. The frequency of leakage varies significantly with fully welded pipe subject to a strict corrosion management scheme sometimes treated as having a sufficiently low leakage rate that its external surroundings can be treated as non-hazardous (Energy Institute *Model Code of Safe Practice Part 15*; Energy Institute, 2005).

In practice, although some likelihood of leakage exists for any element, leakages are dominated by joints (flanged or hub connection), fittings (for example, small-bore connections), valves, and equipment (vessels, heat exchangers, pumps, etc.) rather than by continuous welded pipe. This is readily illustrated by considering the data presented in published analyses of historical leak data, for example, UK HSE Report HSR 2002 002 on Offshore Hydrocarbon Releases Statistics and Analysis (UK HSE, 2002).

Consideration of historical data such as the above HSE Hydrocarbon Release System (UK HSE, 2002) can also help highlight likely leak sources and hole size distributions.

Application of historical data assumes that the system under study is in broadly similar conditions and operated in broadly similar environments to the equipment in the leak database. Clearly, therefore, uncertainty increases the further from this situation the data are applied.

Equally, a general assumption of ongoing fitness for purpose of the design is intrinsic to the application of a stochastic probability of a leak per unit time.

Leak opportunities of concern are not restricted to process equipment, with many utilities capable of leading to fires, notably lubricating oils, some hydraulic oils, and heating medium oils all having contributed to fires. Indeed, in the author’s experience, more fires have been associated with lubrication systems on diesel-fueled generators than from diesel. This is further endorsed by a review of reported releases and fires in the UK offshore sector by the UK Health and Safety Laboratories (Thyer, 2005) that identified utility releases as the most common causes of fires.

38.2.6.2 Release Rate and Phase

A standard simplification applied to leak analysis is to represent the leak as an equivalent-sized round hole. Little or no research appears to have been undertaken that considers likely leak shapes and dimensions, plus their related loss coefficients.

Time and effort could be expended, for example, using published loss coefficients for non-uniform shapes (Idelchik, 2001); however, historical data are not available to support different formulations of defect shapes and the critical issue is the leak rate, which is better represented in the historical data than the defect shape.

Similarly, the way in which a defect changes with time during the leak (e.g., tearing, erosion) is also unreported and hence it is unclear if reported hole size dimensions relate to initial or final leak conditions, or more appositely are merely indications of the leak rate encountered.

Typically, therefore, analyses simplify by considering a small number of representative leaks (a typical range is 3–5 per component) with each representing a range of potential hole sizes. The representative leak may be selected in the middle of the range or at the upper bound. The latter will give higher initial leak rates, but if combined with a fixed inventory will result in a shorter leak duration.

Initial leak rates are a function of source and receiving environments with regard to pressure, temperature, and fluid properties. Where the leak rate is high enough for the flow through the defect to be choked, then only the source properties influence the leak rate.

38.2.6.3 Ignition Timing and Location

Cox, Lees, and Ang's book *Classification of Hazardous Locations* (Cox, Lees, and Ang, 1990) provided the first widely accepted ignition model. This ‘‘model’’ strictly comprised of three points – a minimum ignition probability based on judgment, a maximum based on well blowout data, and an intermediate value based on available data. The blowout data were subsequently updated by Per Holand (1997). Multiple curve fits have been produced and published for each data set.

In each instance, the principle within the data is that ignition probability increases with release rate and that a set percentage of a given release rate has delayed ignition rather than immediate ignition. This delay may be measured in seconds or hours but means that a gas cloud can develop and hence an explosion may occur rather than just a fire.

Several alternative models aim to ‘‘explain’’ the change in ignition probability with release rate and this concept appears to the author to be widely accepted as perceived wisdom. Unfortunately, insufficient validated evidence has been published to verify this assumption.

A common class of models is based on the density of potential ignition sources within the area receiving the release.

A very thorough review of ignition data and prediction models was produced on behalf of the Energy Institute in the *Ignition Probability Review* report (Energy Institute, 2006). This report goes on to propose a complex ignition density approach with series of simplified, generic, curves of ignition probability against operating environment. As is also recognized in the report, however, insufficient validated data exist to verify any of the models.

The UK Health and Safety Laboratory (HSL) (part of the Health and Safety Executive) reviewed ignition data in the UK offshore sector and also confirmed a lack of sufficient data to form a correlation. Indeed, some aspects of the data might have been interpreted as having a higher ignition with smaller releases rather than a lower one. A more consistent correlation was shown by considering ignition probabilities against hazardous area classification with the highest ignition probabilities associated with ''utilities''-type leaks, particularly in and around turbines and generators (Thyer, 2005).

In practice, the relative validity of release frequencies will vary with release rate, with more under reporting likely for small leaks and for ones associated with non-process areas; and less under-reporting of ignited leaks than unignited leaks. The impact of this will tend to make it difficult to verify or validate any ignition model.

Whatever is used, a key is consistency for any given location so that relative risks can be ascertained.

Assessing sensitivities to the ignition model assumptions is vital, especially where toxic gas is also a concern, to see if the balance of risks or hazardous locations alters with the change in model.

38.2.6.4 **Flammability**

- Flammable ranges of gases and vapors represent the conditions under which a fire can be sustained. In general, the closer the conditions come to stoichiometric (Figure 38.2), the higher the burning speed and efficiency will be, although a mixture just below stoichiometric may have some advantage. Flammability may be reduced or prevented (Drysdale, 1998) through:
  - dilution to below the lower flammable limit, although caution must be taken to ensure that local pockets of richer gas do not exist;
  - enrichment to beyond the upper flammable limit, although caution must be taken to ensure that leaner pockets do not exist, especially where air can be drawn in to the system;
  - inertion, whereby oxidant levels are separated from the fuel through displacement with an inert gas (e.g., nitrogen or carbon dioxide) or liquid (e.g., oil is used to inert some highly reactive metals such as sodium and potassium during storage).
- Liquids burn though boiling at the surface. In pool form, the supporting structure plays a significant role in flammability with high conductivity, cold surfaces (e.g., water at a temperature well below the flammable liquid flash point) able to either prevent ignition or to cause rapid extinguishment. Conversely, hot surfaces can lead to a rapid release of vapors and, if above the autoignition point, direct ignition of the liquid. As burning occurs at the surface, flammability increases by turning the liquid into an aerosol.

Figure 38.2 Near-stoichiometric flame from natural gas fire. The red glow is from a lava rock bed.

- Solids burn though local boiling of the surface and hence are very sensitive to surface area, heat transfer coefficient (heat is required to drive the combustible vapors from adjacent solid), and solid structure (e.g., wood or man-made composites may have directional burning characteristics). Actions to increase surface area and reduce thickness (such as thin slicing/chipping/powdering) greatly increase the burning rate by increasing the area from which vapors may be released.
- Ignition will only occur if sufficient energy is passed from the ignition source to the flammable item. For example, some ‘‘cold working’’ sparks of glowing metal may not have enough energy to provide ignition of some flammable gases; hot gas (e.g., from an exhaust stack) is a poor source of ignition in comparison with a hot metal surface. Detailed studies of ignition energies for different types of fuel have been undertaken and reported (Drysdale, 1998). Typically, in an industrial setting, benefit tends not to be taken of all such lowered ignition probabilities. Instead, a more conservative approach is adopted by defining areas where no-spark potential equipment and no surfaces or gases approaching autoignition are allowed. These restrictions are based on areas where a flammable cloud might be present. Examples include Model Code of Safe Practice Part 15 (Energy Institute, 2005) and ANSI/API RP 500 (ANSI/API, 1997).

38.2.6.5 Ignition Sources

- **Electrical spark**. Sparking in electrical systems can occur at any location where a potential difference occurs across an air gap – be it an intended or unintended

gap. Classically, sparking occurs at switches (including relays) and junctions (including battery posts and earthing straps). An extreme version of electrical sparking is lightning. In hazardous areas, equipment is ''zone rated'' by the avoidance of open switches and junctions. The potentially sparking elements are sealed in protective enclosures. The enclosure is designed to act in two ways:
  - The seal aims to prevent the ingress of flammable mixtures.
  - If a flammable mixture does enter and ignites, the seal acts as a flame arrestor, quenching the flame as it attempts to flash out of the enclosure, thereby preventing ignition of a flammable mixture outside the enclosure.

- Mechanical sparking may be caused intentionally (e.g., grinding) or unintentionally (e.g., contact between a rotating shaft and a guard), but in all instances is characterized by the creation and ejection of incendive material. The ability of the sparks to cause ignition is very much a function of the energy in each particle and the ignition energy of the mixture (Drysdale, 1998).
- Hot surfaces are able to cause ignition of gases and liquids if the temperature is above the autoignition point for the material. When considering autoignition, the surface area of the material and the roughness must also be considered, due to the difference in heat transfer rates and the potential for local hot spots, with mist spray releases of liquids much more readily ignited than liquid pools and hot rough surfaces more likely to ignite a gas than a smooth surface. Heating may be due to:
  - frictional heating, for example, due to a dragging bearing;
  - process heat by design or due to process or insulation (lagging) faults;
  - solar heating – particularly if accentuated by glass;
  - radiant heat (e.g., from another fire or from a radiant heat source such as a furnace or flare).

In addition to the surface temperature, the contact time will influence ignition, particularly for fuels requiring a phase change (e.g., solids). Prevention is provided by ensuring that surface temperatures are maintained below recommended limits (based on fuel type) in all areas with the potential for a flammable atmosphere (IP15; ATEX 95 (European Commission, 1994)). The potential for surface temperature controls is why ''electrically classified areas'' (Schram, Benedetti, and Earley, 2009) are better defined as ''hazardous areas'' (Energy Institute, 2005).

- Hot gas is less able to ignite flammable atmospheres than a hot surface (Kuchta and Cato, 1966). It could be postulated that that this may be due to the worse heat transfer and lack of radiative heating; however the work of Kuchta and Cato (1966) suggested that hot wire and autoignition temperatures may align with the hot gas ignition once corrections were made for the size of the ignition source. Equally, work to improve autoignition temperature estimates (Robinson and Smith, 1984) suggested that the methane autoignition temperature may in fact be 70 °C higher than given in many texts. Hence, although not generally recognized in hazardous area classifications (Energy Institute, 2005), gas can typically be vented at 100–200 °C higher temperatures than surface temperature limits based on generally used autoignition temperatures for gas without causing ignition.

However, although generally true, caution must still be taken to ensure that no particulates might be present in the hot gas stream (e.g., smoky exhaust gas) which might introduce radiative heating sources and lower ignition temperatures (Fotache, Wang, and Law, 1999; Mannan, 2004).

- A thermite reaction; thermite is the burning of a metal to form a metal oxide via the reduction of a less reactive metal oxide. Classically this is aluminum burning in the presence of ferrous oxide or copper oxide. Significant initiation energy is required but once ignition is established, the mixture is very difficult to extinguish, being able to continue burning in the total absence of external oxygen (e.g., under water). To achieve continuous burning requires the mixing of the metals – for example, powdered and mixed, plus suitable strong ignition, typically magnesium powder. The heat produced is sufficient to melt both metals and has been used for field welding. Thermite as an unintended ignition concern has tended to focus on the striking of high-purity aluminum on corroded steel surfaces, leading to a short-period thermite reaction (duration limited by the amount of metal in contact) acting as an ignition source in a flammable atmosphere. In practice, simple striking is only able to create enough energy if backed by considerable force (e.g., an object dropped from a height). However, restrictions on high-purity aluminum in potentially explosive atmospheres are generally recommended to exclude completely the opportunity for ignition (Robbins, 2005; UK HSE, 2001).
- The heat produced during oxidation of drying hydrocarbons, particularly on a wicking-type surface, can result in self-ignition. Classic examples include oily rags and oily lagging. In addition, with only a weak source of external ignition (e.g., heat), oily lagging and sooty lagging – for example, due to diesel exhaust particulate loading, or more classically in an unswept coal chimney – will burn readily, and may continue to burn with limited air through smoldering, hence proving very difficult to extinguish (UK HSE, 2008b).
- An electrostatic charge can build between any two surfaces, but is most strongly associated with the movement of, or through, a low-conductivity medium. In common situations, people are familiar with the building of a static difference between a comb or a balloon and a surface; in an industrial setting, an example is the flow of liquids with poor conductivity (Ball, 2010).

38.2.6.6 **Ignition Control**

Ignition control may be achieved through a mixture of design, maintenance, safe working practices, and housekeeping. In order of lessening effectiveness, these may be summarized as follows:

- Exclusion. For example, non-alloyed aluminum is generally excluded from coal mines and in some facilities in locations where flammable atmospheres are anticipated to be continuously, or at the least commonly, present. This removes the potential for thermic sparking. Special alloys such as ‘‘marine aluminum’’ are substituted, or non-sparking materials such as brass or bronze for tools, or composites for ladders.

- Equipment selection in hazardous areas. For example, ATEX 95 (European Commission, 1994) provides a route to certification of spark potential equipment. Note that to be effective, this must include surface temperature limitations and mechanical sparking sources, not just electrical equipment (Energy Institute, 2005).
- Maintenance, notably of earthing systems and potential hot surfaces to ensure that the original design intent is maintained through life.
- Storage. For example, self-heating of oily rags may be prevented by correct segregation, and potential exothermic reactions may be managed by separation of strong oxidants and fuels (e.g., hypochlorites and fuel oils).
- Permit control. Managing activities with the potential to cause sparking in a hazardous area through the maintenance of a permit to work system.
- Housekeeping, removal of oily residues, and prevention of build-up of fuel sources. Note that the 1987 Kings Cross London Underground escalator fire is an unwelcome example of what can happen when this is not adequately achieved.
- Purging/inerting/blanketing. All these might be summarized as active means of ignition suppression through maintaining a non-flammable atmosphere by the exclusion of oxygen or the dilution of fuel. Although effective and key measures in many settings, they are placed last on this list owing to their active nature and because the tendency of many such systems to pass through flammable mixtures, for example, during fault conditions, makes them less intrinsically safe than approaches focused on exclusion of fuel or ignition sources (Drysdale, 1998).

38.2.7
Fire Type

38.2.7.1 Vapor

Vapor releases are broadly distinguishable into two types:

- Momentum jet, where the plume is dominated by the velocity of the release. Typically plots are made of a specified concentration of gas. Viewed in this way, the initial section of the release is an expanding cone then a slowly contracting one as air is entrained. Clearly, any interaction between the plume and objects in its path will greatly alter the shape due to the loss of momentum.
- Non-momentum plume. Typically, such plumes drift and dilute with the wind, with heavier than air plumes staying close to – or falling towards – the ground, and lighter than air plumes rising as they disperse. The rate and shape of dispersion are a function of wind strength and stability.

Basic modeling of vapor releases for risk studies often assumes free-plume conditions for momentum releases to produce conservative estimates of the potential hazard range.

The simplest models use basic experiment-derived correlations and a number of these are provided later in the chapter.

Proprietary codes are available that provide more refined analyses, albeit often without visibility to the modeler of the method adopted. Some of these codes allow modeling of momentum and non-momentum releases, including transitions between the two. This has led to some modelers further maximizing downwind hazard ranges predicted by modeling momentum jets impacting the ground and acting as concentrated sources for non-momentum plumes. It is unclear whether experimental data are fully available to support the predicted maximum range.

Where such approaches are adopted, the conditional probabilities of such releases as a fraction of all potential releases must be considered to prevent excessive conservatism.

More advanced modeling using computational fluid dynamics (CFD) can represent in detail structures that may interact with plumes. However, CFD can struggle to represent the initial jet expansion and the improved graphics do not automatically mean improved accuracy.

Hence, broadly speaking, whichever method is adopted it is recommended that the model's range of validation against experimental data is considered when reviewing likely error bounds, but in general terms the complexity of the geometry should drive the selection of modeling technique.

If ignited soon after release, momentum releases will form a jet fire. Delayed ignition of momentum or non-momentum releases will cause either a flash fire or an explosion. The difference between the two is discussed in more detail later but is primarily dependent on the fuel reactivity, degree of containment and level of turbulence (e.g., caused by congestion or other turbulence generators) (Walker, 2003a,b).

38.2.7.2 **Two Phase**

Accurate prediction of a two-phase release is extremely difficult as it relies on assumptions regarding the conditions prior to release, including flow regime and extent of phase separation and phase slip during the release. Typically, estimates are therefore made using basic assumptions and then tested through sensitivities.

- Once a release has occurred, two key phenomena are of interest, spray releases and droplet rain-out:
  - Spray releases are typically modeled as gas releases but with the effective density increased leading to higher mass release rates and hence longer predicted flame lengths. Spray releases are more easily ignited than gas as ignition temperatures for most liquid hydrocarbons are lower than those of gases. When the spray is from very high pressure, or when it impacts with high momentum, the spray droplets may fracture, forming a fine enough mist to be explosive even in the absence of free gas. A classic, well-documented form of this is crankcase explosions in large reciprocating engines (e.g., ship propulsion). In this instance, the high momentum is provide by the reciprocating elements as opposed to the spray impacting a static surface. Prediction of spray formation and subsequent fire and explosion is at, or just beyond, the limit of current methods but modifications to codes are presenting potential solutions; see, for example, Arntzen *et al.* (2009).

  - Droplet rain out occurs where the droplet size is large relative to the momentum of the air flow, leading to loss of buoyancy. This may occur due to phase slippage at the choke or coalescence. The quantity raining out and forming a liquid pool is typically obtained from experiment-derived correlations and will be subject to significant error bounds (Witlox *et al.*, 2011).

38.2.7.3 **Liquids**

Liquid/aqueous releases are distinguishable as pools, running pools, and gels.

- Pools are generally further divided into bounded and unbounded cases:
  - Bounded pools are typically within bunds or natural depressions. The boundary acts to maintain a depth to the pool and, provided that the fuel consumption rate is less than the inflow, the pool will increase in depth. Any given fuel has a limiting minimum depth below which the heat transfer away to the supporting surface extinguishes the flame. The minimum depth is a function of the fuel and the surface temperature of the supporting surface. An extreme example of a bounded pool is a tank fire, typically treated as a special case. In tank fires, the depth is sufficient to allow convection currents to be established between the cooler underlying layers and the burning surface. A ‘‘hot zone’’ of preheated liquid forms and the depth of this slowly propagates downwards. With heavy hydrocarbons, this hot zone may exceed 100 °C. As the fuel is consumed, the hot zone moves closer to the bottom of the tank due to the combined effect of a reducing overall tank level and an increasing hot zone depth. If the hot zone reaches water in the tank bottom (typically some water is found in most oil storage tanks), it can lead to flash boiling of the water, causing a surge and overflow of the burning liquids (Drysdale, 1998).
  - Unbounded pools are less well studied as the number of variables involved makes prediction extremely difficult. The rate of spread of an unignited pool is a function of the viscosity and surface tension of the fluid and the friction of the supporting surface. If ignition occurs after the pool has spread to beneath its critical depth, then burning will not be supported at the edges but may be possible in areas of greater depth. If ignition occurs before this, then a quasi-stable state may be established where the rate of burning matches the rate of inflow. One area of more detailed study is the spread of LNG (liquefied natural gas), where several large-scale experiments and initial attempts at CFD modeling have been undertaken (Hansen, Melheim, and Storvik, 2007).
- Running liquid fires are specialized forms of unbounded pools. A particular phenomenon under study is a mechanism whereby the supporting surface distorts upwards due to the heat from the pool fire causing the pool to flow to a different location (UK HSE, 2008b).
- Gels are a specialized form of liquid pool fire with very high viscosity. In some instances they are designed to minimize spread to maximize impact as weapons (e.g., Napalm), in others they are for use as candles (Hamins, Bundy, and Dillon, 2005). They are not considered here in further detail.

38.2.7.4 **Solids**

Solids are distinguishable between homogeneous and laminated solids, with the latter best illustrated by wood and dust.

- All solid materials (e.g., polymers) have burn rates closely related to their orientation relative to the direction of flame propagation (Drysdale, 1998). This is considered in more detail in the Section 38.2.8 on Fire Growth. Fire spread is by the preheating of the solid by the burning section, releasing flammable vapors. Preheating may be by a mix of conduction through the solid and direct radiation from the flame. In upwards orientations, convection currents will add to preheating.
- The thickness of the material strongly influences burning; in the extreme case of paper or cardboard, burning occurs on both sides (Drysdale, 1998).
- Wood covers a broad range of burning rates and is highly directional due to the role of the grain. The burning rate is related to the relative ratios of lignin, cellulose, hemicellulose, and water (Drysdale, 1998). An indication of the variability of burning rates between different types of wood is provided by a non-academic source (The Scout Association, 1999). Heating leads to charring and release of volatiles that move preferentially along the grain, enabling wood to burn more readily when burning across the grain than along the grain surface. This impact makes the thickness of the wood critical to the rate of burning, and enhanced burning is achievable by shaving down the grain. The detailed dynamics are available in Drysdale (1998).
- Dust. Any flammable material, once in powder or dust form, can not only burn but also potentially explode (Drysdale, 1998). The circumstances that can lead to this, and predictions, have been researched in the coal mining and food handling industries. A European Initiative to develop a simulation method for dust explosions (DESC) has led to modified versions of commercially available CFD software (Skjold *et al.*, 2005).

38.2.7.5 **Metals**

Typically, metals are difficult to ignite but, once burning, are characterized by high-temperature flames and may be very hard to extinguish, particularly when they are being oxidized by a solid oxidant in a thermite reaction.

- Reactive metals. Phosphorus, potassium, sodium, magnesium, and lithium, in order decreasing reactivity, are all readily combustible. In the case of pure phosphorus, sodium, and potassium, ignition will occur on contact with water.
- Aluminum is nearly as reactive as magnesium, especially when in a very pure form. It is the one most commonly associated with thermite, where it is reacted with ferrous oxide or copper oxide. More generally, if ignited by a strong enough source in the presence of a strong oxidant (e.g., oxygen enrichment), it will continue to burn. However, the suggestion that it burnt in air contributing to the loss of warships in the Falklands war has been dismissed (Aluminium Federation, 2004). Aluminum forms a protective oxide layer and as a plate melts but does not burn in air. If finely powdered it will burn.
- Steel wool burns readily in an oxygen-enriched atmosphere but will also burn in air, particularly if heated by passage of a current.

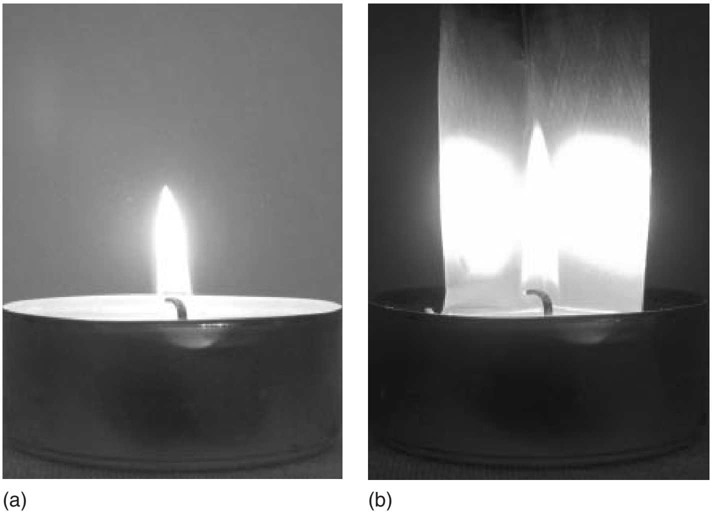
(a) (b)

Figure 38.3 Illustration of the impact of an adjacent surface on burning rate. In (b) A simple reflector has been placed behind a candle flame with a resultant increase in flame height.

38.2.8
Fire Growth

No clear definition of the nascent stage of a fire has been identified. It is best described as the phase when burning is purely dependent on the fuel involved, with no feedback established from the environment and no restriction on oxidants. This may include phases of smoldering and low flaming. Unless some degree of confinement occurs (either through walls/ceilings, or through a slope above the critical angle), then the fire will grow to a maximum burn rate whose limit will be linked to the availability of oxidant to reach the seat of the fire. This maximum is available by fuel–oxidant pairs in general texts.

Walls act to increase burning rates by reflecting back heat. This is readily demonstrated in Figure 38.3.

When the fire is within an enclosed area and inadequate ventilation is available, burning will be suppressed and unburnt gas will begin to exit the enclosed area. Eventually, if insufficient oxidant reaches the fire, the build-up of combustion products will extinguish the fire. However, if during this phase new oxidant is introduced, for example, by increasing ventilation, then a rapid increase in burning may occur – including the unburnt gas. This is termed flashback or backdraught and is a particular threat in buildings when failure, or opening of doors or windows can greatly increase ventilation (Foster and Roberts, 2003).

Flashover occurs when the interaction of the fire and its enclosure leads to a large increase in the burning rate – potentially three times higher than in an open area (Drysdale, 1998). The interactions relate to the building of a hot layer of partially

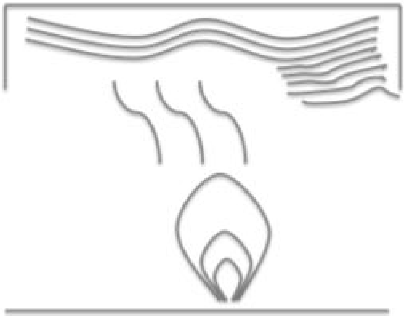

Figure 38.4 A fire produces a layer of both combustion products and part burnt/unburnt vapors. The feedback of heat from the surface increase burning rates in a phenomenon termed flashover (Drysdale, 1998). This will continue until either all the fuel has been consumed or a lack of oxygen diminishes the burning rate. In the latter, situation the layer will tend to thicken until either the fire consumes all available oxygen and self-extinguishes or a source of additional air is found, such as from a window or door being opened, allowing reignition, the phenomenon termed flashback or backdraught (Foster and Roberts, 2003).

burnt and burnt products on the ceiling of a compartment, which radiates heat back to the fire source, leading to the elevated burning rate (see Figure 38.4). In the extreme case of a fire in a tunnel the reader is referred to an appropriate specialist handbook (Beard and Carvel, 2005).

As described in Section 40.2.7.4 on Solids, the relative orientation of burning surfaces and direction of propagation also lead to large differences in burning rate. Studies into the Kings Cross London Underground escalator fire and wildfires (Sharples, Gill, and Dold, 2010) led to a greater understanding of the impact of fire attachment leading to greatly enhanced burning through feedback to the fuel source in a similar way to flashover inside a compartment. The angle at which attachment occurs depends on the degree of containment (channel versus flat surface), but appears to be in the 25–35° range (Viegas *et al.*, 2005; Dold and Zinoview, 2009). This is illustrated in Figures 38.5 and 38.6.

38.2.9
Explosion

Pressurized gas releases that ignite before a significant cloud has developed will tend to burn as a momentum jet. Lower momentum releases, and in situations where ignition is delayed until after a gas cloud has formed, may lead to an explosion. The key requirements are the coincident occurrence of a cloud in the flammable range, ignition, and some degree of containment or other form of turbulence generation.

Two types of explosion may occur, deflagration and detonation, with the potential in some circumstances for a transition between the two.

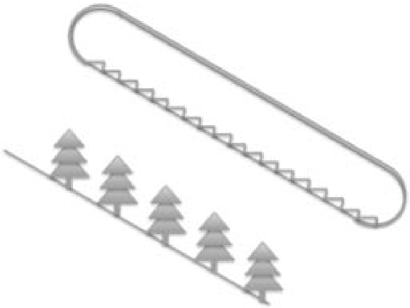

Figure 38.5 Illustration of situations where flame attachment can lead to enhanced burning. The channel created by an escalator was identified as a major contribution to the high burning rate in the Kings Cross London Underground fire (Sharples, Gill, and Dold, 2010). Similarly, forest fires are found to burn much more aggressively on slopes of around 25–35° (Viegas *et al*., 2005; Dold and Zinoview, 2009).

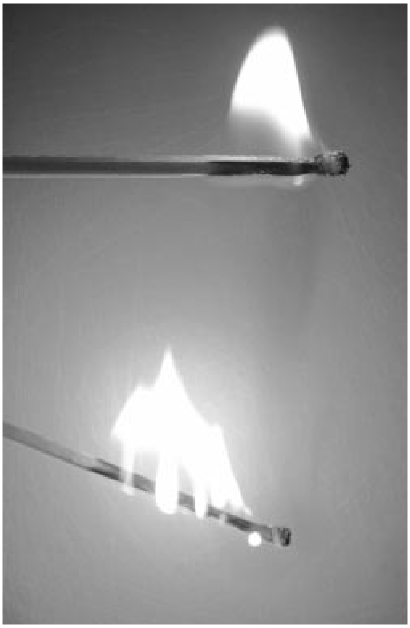

Figure 38.6 Simple illustration of the effect of slope on burning rate. Two matches were lit simultaneously but supported at different angles.

Deflagration is distinguished by rapid burning of the gas or dust cloud, with turbulence leading to acceleration of the burning flame front as the front is driven forwards by expanding combustion products. It is key to note that the actual rate of burning remains more or less constant and relates to the material reactivity, but this burning front is itself moving in the expanding gas. Turbulence may be generated by a range of items but is most strongly associated with small diameter tubular sections or similar in congested areas. Turbulence may also be generated by other flows, for example, initiation of firewater deluge in a confined area, or the expansion of a burning flame from a small volume into a larger one (often termed a bang box ignition). Maximum pressures are primarily related to the point where transition to detonation is considered likely and varies from material to material but typically falls in the range 15–20 bar (UK HSE, 2001c).

In contrast, detonation is distinguished by a sonic compression wave that acts as a compression ignition source, with the flame front traveling with the compression wave. Combustion efficiency may be low with a detonation and a second flame front traveling away from the detonation front may be apparent, leading to confusion after the event as to whether detonation occurred, or even the direction of burning (UK HSE, 2009). Detonation produces much higher overpressure (3–5 times higher than maximum for deflagration), with a higher rate of pressure rise, but with a shorter impulse. More details are presented in a separate chapter titled ''The Science and Engineering of Explosions by Dr. David G. Lilley''.

38.2.10
Fire After Explosion

Explosions by their nature are short-lived, highly damaging events. The explosion conversion rate of fuel to energy is comparatively low compared with a more controlled combustion, especially during detonation, due to the short reaction time in the flame front. After an explosion, unconsumed fuel may burn, but equally leaks from damaged equipment may lead to significant secondary fires and escalation. Hence reasonable survivability criteria need to be defined for critical process equipment (e.g., isolation, blowdown, and relief systems) and emergency response equipment (e.g., escape routes, fire-fighting equipment). Note that survivability in this sense does not imply an undamaged condition. However, it does imply a need to define a design basis load at which the requisite post-event functionality must be available. As an illustrative example, a fire water system may be required still to be operable after a defined explosion load. Rather than placing a fire pump in a fully explosion-proofed housing, this may instead be achieved by having more than one fire pump. This will require the pumps to be separated and segregated such that an explosion in one module cannot incapacitate both pumps and the fire water distribution system.

38.2.10.1 Identification of Targets of Interest

Critical equipment may most readily be defined as items necessary to fulfill critical functions in the prevention or mitigation of a major accident; or to permit egress, evacuation, and rescue. Typically, any potential accident trajectory will be controlled by multiple barriers where to be effective each barrier must consist of a mixture of hardware, people, and procedures (OGP, 2008).

Barriers may be identified by a top-down analysis from major hazards, or by a bottom-up agglomeration of components and systems. However, immense care is needed when working bottom-up to identify clearly not only the critical few, but also the critical function within the few. By way of illustration, isolation valves have multiple potential failure modes, including failing to close on demand and failing to reopen. The latter is not safety critical, hence failures leading to this are not safety critical even though the valve itself may be deemed critical.

These few, critical barriers require clearly defined performance standards for survivability and reliability. Ideally, survivability standards are set based only on consequences (e.g., worst-case explosion) but may need to be set based on survivability of a consequence at a set frequency of occurrence, typically 1 in 10 000 years per consequence type (e.g., fire, explosion, toxic ingress of a shelter in place, each considered independently). As described above, survivability is not the same as remaining undamaged, but rather refers to the ability still to perform a clearly described and required function.

Typically, for explosions this is done by the generation of exceedance curves relating release rates to expected probabilities of given overpressures at specific target locations, or in fully integrated approaches the probability of failure of a target. Note that this must include conditional probabilities and variability associated with the withstand capability of the target. This also requires careful definition of failure, ideally based on the exceedance of a specified limit within, or beyond, the target. For example, a blast wall can fail in many ways but will rarely just ''disappear'' unless able to vaporize or transition. Therefore, failure must be expressed in terms of the impact on the item protected by the wall. This means that physical impact due to back wall spalling is a failure even if the blast wall is still broadly intact. Conversely, tearing or deformation may not be deemed failure if the area behind the wall does not suffer excess overpressure and is not subject to subsequent heat or smoke damage via the tear.

For fire, the use of layout and spacing is the most common means of preventing damage to targets of interest. Spacing rules are available from major international recognized bodies such as the American Petroleum Institute (API). An excellent source of guidance is also provided by *Lees' Loss Prevention in the Process Industries* (Mannan, 2004). In addition, survivability aspects must be considered, particularly with regard to vulnerable items that are readily damaged by fire, such as power supplies, control cables, and instrument air/hydraulics. The application of ''fail-safe'' design principles can clearly help (e.g., isolation valves being designed to close on loss of power or instrument air). However, considerations of potential external common-cause failures such as fire should also ensure that rules related to proximity are established alongside those of redundancy and diversity. As an example, if reliability analysis suggests that dual control cables are necessary, then their routings should be selected to minimize the potential for fire to damage both cables (see Figure 38.7).

Finally, consideration of, and allowance in analysis for, degradation with age is required. This should result in tolerability limits being set for inspection of not only pipework, but also passive elements such as fire protection coatings (UK HSE, 2007).

Ultimately, the main target of concern is personnel, with both the period and severity of exposure requiring to be estimated. To relate the exposure to the potential

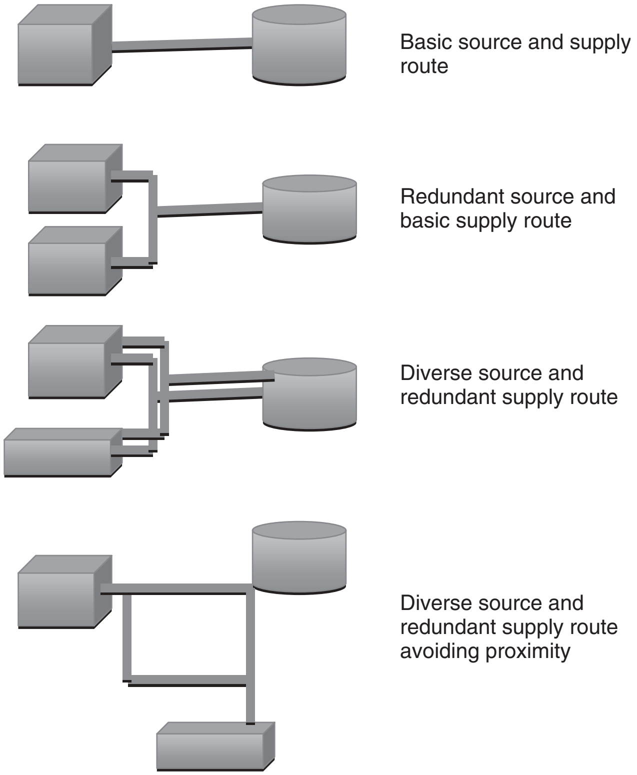

Figure 38.7 Increasing redundancy, diversity, and consideration of proximity to reduce common-cause failure.

for harm requires the use of probit functions (UK HSE, 2010). Probits are statistical interpretations of experimental data represented in the standard form of

$$Y = K_1 + K_2(\ln V) \tag{38.1}$$

where K_1 and K_2 are constants, V is the product of intensity and time, and Y is the probit that must be then turned in to a fatality fraction by looking up the probit in a table.

Values for the constants and look-up tables are available in the literature with the UK HSE having prepared one of the more comprehensive lists (UK HSE, 2010).

As a minimum, harm needs to be considered from:

- impact due to direct explosions in open areas but also impact from collapsing structures and debris missiles (e.g., glass) in most operating facilities
- flame (impingement and radiant heat)
- heat (particularly heat stress in shelters)
- toxic (including additive impacts of items causing enhanced respiration with ones leading to poisoning).

38.2.11
Conclusions

Part A has provided a largely qualitative review of the prediction of impacts from fires and explosions. It has touched on protection and control but has not looked in any detail at them as they are covered more thoroughly elsewhere in this book.

Emphasis has been placed on ensuring that the purpose of the analysis is first established, the protective barriers are identified, and survivability requirements defined. The implicit assumption is of a plant with layered protection separating personnel and the environment from the hazard. Once this framework is in place, the appropriate analytical tools can be selected.

Part B looks at some first-order predictive methods. These are often of more use as quick checks on the adequacy of protective layers already designed than for the design of the barriers themselves. However, they do provide a first insight into the tools available and perhaps also the limitations intrinsic to the methods.

38.3
Part B: Predictive Methods

Part B provides simple, first-order estimation techniques from a number of sources. For detailed analyses of fire dynamics, it is necessary to utilize more advanced methods such as those in Drysdale (1998). However, for use in quantitative risk assessment (QRA) or to provide general estimates of hazard range,these techniques are perfectly useable.

38.3.1
Liquid Release

For liquid releases, Bernoulli's principle provides

$$P_1 + \frac{1}{2}\rho V_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho V_2^2 + \rho g h_2 \tag{38.2}$$

where g = gravitational constant (9.81 m s^{-2}), h = elevation from origin in meters, V = velocity of flow (m s^{-1}), and ρ = density (kg m^{-3}).

Also, through an orifice we have

$$V = \frac{Q}{A\rho C_\mathrm{d}} \tag{38.3}$$

where C_d is the discharge coefficient of the orifice (dimensionless) and Q is release rate (kg s^{-1}).

Hence for release from a large reservoir where V_1 can be treated as zero, we obtain

$$Q = C_\mathrm{d} A \sqrt{2\rho\left[(P_1 - P_2) + \rho g\left(h_1 - h_2\right)\right]} \tag{38.4}$$

Often the height term is omitted for simplicity at the location of a leak.

Decay of pressure can either be done exponentially or time stepping-wise if there is a source of pressure hold-up (e.g., large gas cap), but care is needed as most liquids only need a small displacement of liquid to relieve pressure down to the boiling point of the next fraction and/or to the condition under which only gravity drives the leak. Hence the immediate leakage rate estimated from the starting pressure may be a gross overestimate of the rate soon thereafter. Despite this, the gross simplification of constant release rate is used by some analysts.

As described in the opening paragraphs of this chapter, care must be taken not to think of maximizing the leakage rate as pessimistic in all cases. With a limited inventory to feed a leak, overestimating the leak rate will create an underestimate of the duration, which in turn may reduce the apparent potential for the event to escalate.

Using Bernoulli's equations only at the point of release assumes no frictional loss within the leak source as the liquid accelerates towards the leak. This is a fair assumption for short pipe lengths or vessels, or where the leak diameter is small in comparison with the flowing diameter, but can be a poor simplification for long sections. Where the velocity towards the leak is significant, then a valid value for V_1 must be established iteratively, or via a time-stepping (partial difference) model, and the friction loss term estimated. This is beyond the simple approaches presented here.

38.3.2
Gas Release

The release rate from a simple orifice for a choked release in kilograms per second is given by

$$Q = C_{\mathrm{d}} A P_0 Z \tag{38.5}$$

where

$$Z = \sqrt{\left\{ \frac{M\gamma}{RT_0} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}} \right\}}$$

C_{d} = discharge coefficient, A = orifice area, P_0 = initial upstream pressure ($\mathrm{N\,m^{-2}}$), T_0 = initial temperature (K), γ = ratio of specific heats (for methane use 1.31), R = universal gas constant = 8.314472 $\mathrm{J\,mol^{-1}\,K^{-1}}$, and M = molecular weight of the gas ($\mathrm{kg\,mol^{-1}}$) (in kilograms to give release in $\mathrm{kg\,s^{-1}}$).

CMPT guidelines for QRA (Spouge, 1999) offer us a simplification, specifically for methane, of

$$Q = \frac{D^2 P_{\mathrm{bar}}}{1 \times 10^4} \tag{38.6}$$

However, caution is required when using this equation as it does not use standard units: D = leak diameter (mm) and P_{bar} = initial upstream pressure (bar).

A simple estimate may be made of the exponential decay of a release rate with time from

$$Q = Q_0 \exp\left(-\frac{tQ_0}{M_0}\right) \tag{38.7}$$

where Q_0 = initial release rate, t = time (s), and M_0 = initial mass (kg).

This gives a reasonable approximation of a simple fixed volume without other leaks in or out. The alternative is to write a small time-stepping model in a spreadsheet or simple programming language.

An occasionally used gross simplification is just to apply initial release rates. Although less inaccurate in the short term than the same simplification in a liquid-filled system, it suffers from the same fundamental concern of underestimating duration and potentially therefore underestimating escalation.

A worked example is provided at the end of this chapter.

38.3.3
Multiphase Release

Multiphase is, at best, ''interesting.'' It is sometimes avoided by treating the phases and leaks as separate. This can be accurate enough for QRA but occasionally more representative estimates are required. To do this, a number of assumptions need to be made concerning the flow within the pipe or vessel upstream of the leak and what happens in the orifice. In essence we have three conditions:

- **Liquid dominant**. The release can be modeled as a liquid release with gas flashing outside, or for slightly higher gas cuts look at the gas/liquid volumetric ratio at the release throat conditions. Then model the gas through the effective gas area and the liquid through the effective liquid area. This approach is an assumption of perfect phase slippage and only really accurate at low voidage and/or with stable separated flow upstream of the choke.
- **Gas dominant**. The release can be modeled as a choked gas but with the density adjusted to match the effective density of the mixture. This represents the assumption of zero phase slip.
- **Neither gas nor liquid dominant**. Time to get nervous! There are some standard simplified correlations from experimental work, the best known being that by Fauske, see Mannan (2004). Often the practical options are either to obtain a suitable CFD or plant process model run or to run both the liquid-dominant and the gas-dominant analyses and take the most onerous outcome. Note once again that this may not be the one with the highest release rate as the duration may be as, or more important than for medium-sized releases.

38.3.4
Pipelines

For liquid-filled pipelines, relaxation of the line will also drive the leak. The amount of relaxation is typically based on an estimate, with values in the 0.5–2% range quoted depending on line size and materials. This may be a substantial quantity for a long line, making the constant leak rate for small leaks reasonable. For shorter lines, specific modeling of the pipe may be required.

For gas pipelines, relaxation is secondary to the pressure decay.

For multiphase pipelines, it is necessary to establish the flow patterns, degree of separation, high/low points (gas/liquid traps), flash points of each component, and/or the amount of gas in solution; in other words, it is difficult to estimate even when using advanced techniques (e.g., CFD1)), and will have a large error bound. If analysis is needed, then like the multiphase leaks it is normally appropriate to try a few assumptions/correlations (Mannan, 2004), look at the sensitivity of the overall analysis and judge if the most conservative combination can be used.

Friction needs consideration, particularly for long pipelines and/or when velocities in the line are high, making simple analysis less accurate. However, with large lines the inventory (especially for gas) becomes effectively infinite once durations exceed about 1 h, making the zero friction assumption acceptable as a first estimate for most cases.

In many practical applications, advanced analysis of the flow within the pipe will already have been undertaken to establish the pipeline size and to provide assurances for slug flow. Hence this may be adopted and modified as an input to the release estimates.

38.3.5
Dispersion Modeling

38.3.5.1 External Releases

Typically, even sonic releases that can expand unimpinged are modeled in the far field by using a Gaussian model, with full CFD codes normally reserved for complex geometries.

A helpful guide is provided by New Zealand Ministry for the Environment Guide (New Zealand Ministry for the Environment, 2004), identifying suitable models for dispersion estimation based on the complexity of the dispersion and the complexity of the effects. This reveals when it is reasonable to rely on simple Gaussian dispersion and when more advanced tools should be applied.

In succinct form, Gaussian modeling is broadly acceptable provided that:

- No reactions are on-going within the plume that may alter its density or volume.
- No significant ground interactions occur due to plume attachment.

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1) CFD utilizes a grid (two- or three-dimensional) to represent the volume through which flow will occur. Numerical solutions are created in each volume for the flow for each time step for flow entering or exiting from each boundary to the volume. By ensuring that the individual volume is appropriate (typically this means small) and the time step is small in comparison with the detail of interest, a good approximation is provided even for complex geometries. However, as with any such technique, the limits of validity and model verification are key to preventing a false sense of accuracy being presented.

- The weather has moderate to high instability without significant prospects of still-air or temperature inversions.
- No structures are in the vicinity of the plume that may cause local changes in wind direction or directly block the plume.
- The release is broadly buoyant (note, for example, that releases from high pressure may cool rapidly due to the Joule–Thompson effect and hence slump).

The equations for a Gaussian plume are readily available on-line and are not reproduced here as they are only of practical use if programmed into a spreadsheet or suitable coding language. However, SHODOR (1998), a non-profit research and educational organization in the United States, makes available a simple on-line Gaussian-plume model.

Similarly, if dense gas dispersion needs to be modeled, then several models are available (e.g., UK HSE, 2008c) with both guidance and downloadable models available for use on-line from the United States Environmental Protection Agency's Support Center for Regulatory Atmospheric Modeling (US EPA, 2010).

38.3.5.2 Release in an Enclosed Area

Gas build-up in enclosed spaces or where significant congestion exists cannot be readily represented by Gaussian models. Instead, two alternative approaches are available:

- reference to correlations from experimental data
- use of CFD.

38.3.6
Gas Build-up Correlations

A UK-based Joint Industry Project (JIP) completed in May 2000 (Gas Build Up JIP Workbook, 2000) resulted in new experimental data and the generation of gas build-up correlations plus better validation of CFD models. No publication of the results has been found but the work has, for instance, been built in to the Energy Institute JIP Ignition Model and reviewed (HSL, 2006).

An alternative, more conservative, approach is offered by British Standard EN60079-10 (BS, 2009). However, both the JIP and BS methods are only considered suitable as a first-order estimation (HSL, 2006) as with both methods the answers are very dependent on the assumptions made by the user for venting areas and congestion.

CFD modeling may provide better resolution but care is needed when representing high-pressure jets in enclosed or semi-enclosed areas.

Whatever approach is utilized, it can only be considered an approximation and will ideally either need to be validated by comparison with an alternative approach, or shown to have little impact on the overall results of the analysis.

38.3.7
Fire Analysis

38.3.7.1 Jet Fire

For jet fires, flame length is easily estimated using the equation (Mannan (2004); Cowley and Johnson, 1992)

$$\text{Flame length (m), } L_\text{f} = 18.5Q^{0.41} \tag{38.8}$$

Combining this with the simplification provided earlier (Spouge, 1999) (Eq. (38.6)), specifically for methane gives us

$$\text{Flame length (m), } L_\text{f} = 0.424D^{0.82}P_\text{bar}^{0.41} \tag{38.9}$$

where D = leak diameter (mm) and P_bar = initial upstream pressure (bar).

CAUTION – this equation does not use standard units!

38.3.7.2 Fireball

Fireball sizes may be estimated either as continuously fed (e.g., ruptured riser) with two alternative equations (Mannan, 2004):

$$\text{Atkins: } \phi \approx 6Q^{0.4} \tag{38.10}$$

or

$$\text{Fay: } \phi \approx 6.36Q^{0.32} \tag{38.11}$$

where ϕ is the visible diameter in metres

Further, fireballs may be seen as instantaneous releases (e.g., delayed ignition) (Mannan, 2004):

$$\text{Roberts: } \phi \approx 5.8M^{0.33} \tag{38.12}$$

with duration

$$t \approx 0.49M^{0.33} \tag{38.13}$$

where M (kg) is the mass in the fireball available to burn and t (s) is time.

Alternatively, the US Nuclear Regulatory Commission provides a downloadable spreadsheet for calculating fireball diameter, duration, and radiant heat for a range of hydrocarbons as part of NUREG-1805, Final Report (US NRC, 2004).

38.3.7.3 Pool Fire

A pool fire area is given from the balance between inflow of oil and burning rate with the maximum pool size set when the regression rate of the pool matches the inflow. However, this simplification assumes a mature pool that ignites before it fully develops, otherwise the flame may initially be more extensive until it burns back to the quasi-stable condition. A simplification is sometimes made based on bund areas and module areas with small leaks assumed to fill the bund, medium leaks half the module and large leaks the whole module. Again, different places

Table 38.1 Regression rates.

Fuel	Regression rate ($m\,s^{-1}$)
Crude oil on water	8×10^{-5}
Crude oil	5×10^{-5}
Diesel	2×10^{-5}

will use various methods from full detailed analysis to simple rule sets. The rule sets tend to be company or location specific, and hence not published.

The actual formation of a pool requires specialist analysis, for example, with CFD, and is only validated for level surfaces.

An estimate of an unbounded quasi-steady-state pool size is given by the following equation [modified from NUREG-1805 (US NRC, 2004)]:

$$Q = \sqrt{\frac{4}{\pi \gamma \rho}} \tag{38.14}$$

where $\gamma\,(\mathrm{m\,s^{-1}})$ is the regression rate and $\rho(\mathrm{Kg\,M^{-3}})$ the liquid density.

Regression rates are quoted in NUREG-1805 (US NRC, 2004) as shown in Table 38.1.

Note that a wider range of regression rates can be estimated from the equations relating regression rate to mass burning rate:

$$\dot{m}'' = \rho\gamma \tag{38.15}$$

where $\dot{m}$ is the mass burning rate per square meter ($\mathrm{kg\,m^{-2}\,s^{-1}}$).

When in an enclosed or semi-enclosed area, consequence analysis must look at flame volumes and extent of external flaming, plus the degree that the flame is controlled by available fuel or available air.

Pool flame heights may be estimated by (Cowley and Johnson 1992).

$$\text{Height, } L = 42\phi \left[\frac{\dot{m}''}{\rho\sqrt{g\phi}} \right]^{0.61} \tag{38.16}$$

where ϕ is the pool diameter and g is gravitational acceleration. Alternatively, it can be expressed as

$$\text{Height, } L = 42\phi \left[\frac{\gamma}{\sqrt{g\phi}} \right]^{0.61} \tag{38.17}$$

Once a pool of known volume is formed, for example, in a bund, then the flame height can be estimated from the above (use equivalent area). If the flame height is greater than the module height, then external flaming may occur as the flame will form a layer along the roof. Also, it is likely that the fire will be air limited rather than fuel limited.

When impinged and contained within the module, volume may be estimated from free jet flame or pool flame approaches, then converted to an equivalent fireball within the constraints of the module, then using the fireball emissivity equation (38.19).

When the total flame volume greatly exceeds the module volume, then external flaming can be estimated by considering the external flame to form a semicircular-based tower from the nearest (or downwind) module exit. This will only give a crude first-order estimate and if the external flame size is critical then a better estimate can be formed using CFD.

Once the feeding source has been exhausted or isolated, the remaining pool fire duration may be estimated using [from NUREG-1805 (US NRC, 2004)]

$$\text{Duration, } t_\text{s} = \frac{4V}{\pi \gamma \phi^2} \tag{38.18}$$

where V is the volume of fuel in the pool.

38.3.7.4 **Radiant Heat**

Radiant heat contours from jet fires, pool fires, and fireballs need to be considered with respect to fatalities, prevention of escape, and damage to structures. Radiant heat is normally estimated using geometric view factors with weightings for emissivity using the equation

$$q_\text{i} \approx \tau F q_\text{s} \tag{38.19}$$

where q_i is the incident radiation, q_s is the source radiation, τ is transmissivity, and F is the view factor.

For QRA this is normally simplified and fatality fractions are applied based on a rule set for different flame sizes. Equations for shape factors and emissivity are available from results of experiments, some are proprietary, and some are available in the specialist literature, for example, the *CMPT Guide to QRA* (Spouge, 1999) and *Lees' Loss Prevention in the Process Industries* (Mannan, 2004).

As with the earlier fire modeling, a set of analysis spreadsheets are available to download from NUREG-1805 (US NRC, 2004).

38.3.7.5 **Smoke**

Smoke modeling is typically undertaken in the same way as a simple plume analysis, to the edge of a critical building or location of interest. The inventory will then be used to establish if impairment occurs for long enough to lead to concerns.

Smoke reaching a critical building needs to be assessed with regard its ability to enter either almost instantaneously via a failure of the ventilation to shut down and isolate, or via more slow ingress due to building leakage once the ventilation has been shut down.

Building leakage rates are generally available from design specifications, but for critical structures (e.g., shelters in place) the actual leakage rate must be ascertained through testing. Typically, this is done via pressurization and under-pressuring the building by a set pressure selected to represent the typical wind stagnation pressure at the location. Normally this results in an impairment curve based on smoke concentration and time. Actual impairment will be based on the impact of smoke on occupants and is not typically analyzed as the error-build up makes the additional analysis potentially misleading.

Note that unignited gas entering the building will also lead to impairment due either to explosion risk or to toxicity (e.g., if the gas contains H_2S or CO_2). For this reason, some critical buildings have filtered ventilation systems designed to allow pressurization to be maintained even with toxic external atmospheres.

38.3.7.6 Explosion

This section provides only a non-numeric overview of explosion modeling and links to external information. It is the author's experience that even first-order estimates tend not to be done by hand, or even by spreadsheet. Hence the equations would only be provided for academic purposes. A separate chapter titled ''The Science and Engineering of Explosions by Dr. David G. Lilley'' provides more detail on the techniques.

Typically, onshore facilities are characterized by areas of congestion within largely uncongested areas, and low occupational density in congested areas. For this reason, far-field impacts of explosions in the congested areas are of more interest than the details of the blast overpressure within the area of congestion.

A critical aspect is to ensure adequate separation between areas of congestion, with commonly applied rules described in the ''Yellow Book'' (Netherlands Committee for the Prevention of Disasters, 1997). Recent experiments undertaken on behalf of the UK HSE (UK HSE, 2005) suggested, however, that these rules may be optimistic for situations with high overpressures (>1 bar) when separations as large as half the size of the congested area where the explosion originated may be required to ensure that the congested areas do not behave as a single unit. This work also suggested that areas of congestion may be coupled by low-level congestion/channeling caused by pipe racks over even longer distances. It must be noted, however, that this is based on a small number of trials.

Two commonly used methods to analyze explosions in these situations are TNO Multi Energy and Baker Strehlow Tang (BST). Both rely on an estimate of the energy release based on fuel reactivity (burning velocity in BST), scale distance, and degree of confinement. The ''Yellow Book'' is the most readily accessible description of the methodology that is generally best undertaken using commercially available codes.

Explosion modeling for offshore on large, congested assets is, by contrast, rarely done using tools such as TNO or BST alone, owing to the issues with near-field predictions. For this reason, as a minimum, some form of proprietary phenomenological modeling is undertaken, or – increasingly commonly due to the need to reduce costs – CFD. This blending of methods allows some degree of cross-validation and subsequent scaling of simpler techniques.

Equally, questions have been raised over the effectiveness of CFD based models in the far-field as the shock wave propagation may not be adequately represented. Hence, in practice, even when a commitment to CFD modeling has been made, some far field analysis using TNO or BST is required.

The key for fire and explosion consequence analyses is obtaining an appropriate balance between each stage in the event. Hence, if simplified release estimates are used, these should be combined with experimental or phenomenological explosion and fire estimates and simple structural interaction approaches; if advanced CFD approaches are used for release calculations, these should be input to fully detailed computational explosion models, dynamic finite element modeling of structures, and fully developed exceedance tools.

38.3.7.7 **Blowout**

Well blowout represents the event with the largest possible continuous outflow of gas and/or oil and/or debris, with potentially massive resultant fireballs. Blowout can occur due to encountering shallow gas or an unexpectedly high-pressure section of a well during drilling or, more rarely, due to a loss of well control during production. The outflow may decay from the initial event to the reservoir flowing pressure but may be effectively infinite in duration due to being fed by the reservoir. There are exceptions to this such as small areas of trapped shallow gas with limited volume, but as an initial simplification, an infinite source for a blowout is normally valid for QRA.

The outflow can occur at a number of different locations on the platform, varying from controlled locations (offshore, flow may be directed outboard of the drilling unit via a diverter valve; onshore, where escape is rather easier, it is more common to allow the blowout to route upwards) to uncontrolled (e.g., drill floor), or at the wellhead, be that surface or subsurface.

The consequences of an ignited blowout, in addition to being initially massive, almost inevitably will include escalation due to the reservoir acting as the source. Examples of escalation that may need consideration include the collapse of the drilling derrick. Offshore this may result in impact on manned buildings such as the temporary refuge. Onshore, depending on the field layout, collapse of the derrick may be less of a concern.

Although the ultimate consequences may be high, a blowout is rarely instantaneous, with a well-control situation developing over time.

Shallow gas blowout may be an exception to this, particularly for rigs involved in exploration drilling. Consideration of the type of drilling and means by which gas can be returned to the rig is needed.

Massive outflows of gas beneath a floating platform may lead to flammable gas on the platform and to instabilities. The rising gas will reduce buoyancy, although little evidence exists that this will be of a sufficient level to cause a floating platform to sink. However, the upflow will also drive the floating platform away, and for moored facilities, unless mooring tensions are altered, this can lead to severe listing due to chain tension on the side of the gas release (Vinnem, 2007).

Equally, a major gas release can create severe scouring(2) which can, in theory, lead to leg base (spud can) instabilities on a jack-up installation.

38.3.7.8 **Subsea Releases**

38.3.7.8.1 Gas

Gas released from subsea will tend to lose its momentum rapidly and break up into bubbles as it rises. At the surface an affected area will be formed, approximately

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2) Scouring is the removal of material by flow. For example, it is recognized as a particular problem around bridge pillars in fast-flowing rivers.

circular, the size of which will be primarily a function of water depth and its location primarily a function of sea currents in the column between the release and sea surface.

Correlations for the surface diameter of a release relative to water depth are available from several literature sources, but are typically quoted at around 20% of water depth (e.g., Spouge (1999) suggests a cone angle of 10–12°). The resulting outflow can be estimated in terms of its ability to support a sea fire (if the flame speed exceeds outflow, then on ignition the flame will flash back to the surface and will self-extinguish). Also, the low momentum release from surface can be modeled as a plume to check the downwind hazard distance based on the flammable range.

Ignition probability for subsea releases is most readily modeled by considering the downwind flammable range; if small, then ignition is improbable; if the flammable range can reach a ship or an installation, then the ignition probability associated with the target should be used. Note that in the instance of a ship without any flammable zone protection (i.e., protected electrical equipment, flame arrestors on engine inlets, etc.), or if the gas can reach permanent sources of ignition (e.g., flares), then the ignition probability will be either unity or a simple function of the dependent probability of the gas reaching the ignition source.

38.3.7.8.2 Oil

Consequences of oil releases on water are difficult to estimate, for a number of reasons. In essence, however, the oil must have sufficient available light ends to burn and/or have sufficient heat input to continue to produce flammable vapors.

When an oil film on water is thin, the quenching effect of cold sea water may prevent any burning. Equally, when oil has risen through a water column, it may become so emulsified that burning cannot be sustained.

However, during initial releases, particularly where the oil is falling on to water or released at such a shallow depth that it displaces the water column, then a thick enough layer can form to enable burning to continue. The resultant fire can be particularly serious due to the heat and smoke impeding evacuation by helicopter or lifeboat. An example of this is the Mumbai High Field ship impact/riser fire event.

Mumbai High North was an oil and gas production complex around 60 miles (100 km) from the coast of India. In 2005, it was struck by Samundra Suraksha, a multi-purpose support vessel. The impact damaged the pipeline risers (some confusion exists between differing reports as to which and how many risers were damaged). The resultant fire engulfed the platform complex, the vessel, and an adjacent drilling rig. Twenty-two people lost their lives.

First-order estimates tend to assume that the oil rises as a cone to surface (the same cone angle normally assumed as gas) and can form a sustainable sea fire where the pool inflow equals or exceeds the regression rate. Typically, low ignition probabilities are assumed in these instances (e.g., 1%) that may balance the conservative assumptions around basic flammability.

An assumption that oil release from deep enough not to displace the column (i.e., the oil mixes with the water and does not reach the surface as a pure substance but rather has entrained water) cannot burn at the surface is reasonable for all but very light crudes. Kulkami (2000) considers the burning of oil and water–oil emulsions on water in some detail and provides experimental and predictive approaches that allow more analytical treatment if wished.

38.3.8
Conclusions

Part B has presented a number of first-order techniques for modeling fires. These approaches tend to work most effectively on simple, single-phase releases or where accuracy is less critical owing to the uncertainty in the input data.

A classic example of a situation where uncertainty dominates is the representation of individual events within a QRA. In these situations, first-order estimates of release rates and fire consequences are typically all that are required.

Approaches to modeling explosions have been described but not presented, owing both to the lack of similar first-order techniques and the more in-depth treatment of the subject in a separate chapter titled ”The Science and Engineering of Explosions by Dr. David G. Lilley“.

Finally, a worked example of a basic analysis is provided below.

Worked Example

The release rate from a simple orifice for a choked release in kilograms per second is given by the equation

$$Q = C_d A P_0 Z$$

where

$$Z = \sqrt{\frac{M\gamma}{RT_0}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

C_d = discharge coefficient, A = orifice area (m^2), P_0 = initial upstream pressure (N m^{-2}), T_0 = initial temperature (K) (use 290 K), γ = ratio of specific heats (use 1.31), R = universal gas constant = 8.314472 J mol^{-1} K^{-1}, and M = molecular weight of the gas (kg mol^{-1}) (in kilograms to give release in kg s^{-1}).

a) Select an appropriate discharge coefficient and show how, for a pure methane leak, this can be simplified to:

$$Q = \frac{D^2 P_{\text{bar}}}{1 \times 10^4} \qquad \text{(from Spouge, 1999)}$$

where D = leak diameter (mm) and P_{bar} = initial upstream pressure (bar) (note the non-standard units).

b) How large is the error for a 10 mm diameter leak from 100 bar if we use a natural gas mixture of 95% methane and 5% propane (assume the same ratio of specific heats as above)?
c) Discuss the sensitivities in leak rate of the simplifying assumptions made to form Spouge's simplification.
d) Given the Wertenbach jet flame correlation is

$$\text{Flame length (m)}, L_f = 18.5Q^{0.41}$$

e) Estimate the error bound for flame length using the Spouge simplification instead of the full equation. Discuss the significance of this for risk purposes.
f) Show, by calculation, the error bound on flame length of the Spouge simplification for 10 and 50 mm releases from a 1.5 m^3 isolated section filled with methane which starts at 50 bar (take the density of methane at 1 bar, 15 °C as 0.7 kg m^{-3}) and estimate the flame length after 5 and 15 min.

Answer

a) Use
$C_d = 0.8$, obtain
$Z = [(16 \times 10^{-3} \times 1.31)/(8.314472 \times 290) \times (2/2.31)^{2.31/0.31}]^{0.5} = 1.72 \times 10^{-3}$
$A = \pi(D^2/4) = 785.4 \times 10^{-3} D^2$ or for D in millimeters $= 785.4 \times 10^{-9} D^2$
$P_0 = P_{\text{bar}} \times 1 \times 10^5$
So $Q = C_d A P_0 Z$ becomes $0.8 \times 1.72 \times 10^{-3} \times 785.4 \times 10^{-9} D^2 \times P_{\text{bar}} \times 1 \times 10^5 = 1.08 \times D^2 P_{\text{bar}}/1 \times 10^4$
Note that this is less than an 8% difference and if we had selected a Cd of 0.74 it would be exact.
b) $M = 0.95 \times 16 + 0.05 \times 44 = 17.4$
Recalculating Z, we obtain 1.79×10^{-3}
Hence the Spouge simplification gives $100 \times 100/1 \times 10^4$ or 1 kg s^{-1}
In contrast, full analysis give $0.8 \times 1.79 \times 10^{-3} \times \pi(0.01^2/4) \times 100 \times 10^5 = 1.12$ kg s^{-1}, an error of 12%
c) The simplification gives a good first estimate for natural gas at around normal temperature. It will vary with the inverse square root of the temperature ratios in kelvin and the square root of the ratio of molecular weights. It has an error that is small compared with the uncertainty in actual hole size, discharge coefficient, or initial pressure. It will not be accurate with entrained liquids as the mass ratio between methane and the actual release will be significant. It appears generally to slightly under-predict release rate. In practical applications, this will lead to an over-prediction of duration, which means that the error may occasionally be pessimistic and occasionally optimistic depending on the sensitivity of the release location to hazard distance and duration.
d) The maximum error in b was 12%, so when raised to the power 0.41 this becomes only 5%. This error is small in comparison with the uncertainties in hole size or distribution. QRA should not assume that a 5% difference in flame

Table 38.2 Results obtained using the data provided.

Hole size (mm)	Full analysis		Spouge		Difference in flame (%)
	Leak ($kg\,s^{-1}$)	Flame (m)	Leak ($kg\,s^{-1}$)	Flame (m)	
10	0.47	13.6	0.5	13.9	2.2
50	11.9	51	12.5	52	2.2

Table 38.3 Results obtained using full analysis.

Hole size (mm)	Initial		5 min		15 min	
	Leak ($kg\,s^{-1}$)	Flame (m)	Leak ($kg\,s^{-1}$)	Flame (m)	Leak ($kg\,s^{-1}$)	Flame (m)
10	0.47	13.6	0.033	4.6	0.0002	0.5
50	11.9	51	0	0	0	0

Table 38.4 Results obtained using the Spouge simplification.

Hole size (mm)	Initial		5 min		15 min	
	Leak ($kg\,s^{-1}$)	Flame (m)	Leak ($kg\,s^{-1}$)	Flame (m)	Leak ($kg\,s^{-1}$)	Flame (m)
10	0.50	13.9	0.03	4.4	0.0001	0.4
50	12.5	52.1	0	0	0	0

length makes a situation safe/unsafe as sensitivities should always look for any such knife-edge effects. In practice, a real flame will not have a stable length and can be expected to vary by more than the 5% due to external turbulence/wind, and so on.

The error bound is less for flame than release rate due to the 0.41 power term. This whole flame correlation is also itself only an estimation based on trials and the error bound is also small in comparison with the experimental error.

e) Using the data provided we obtain the results given in Table 38.2.

f) Using full analysis, we obtain the results given in Table 38.3.

Note that "theoretical" values for the leak after 5 and 15 min for a 50 mm hole have been discounted and treated as zero. It would also be reasonable to treat 15 min for a 10 mm hole as zero as it is likely to be subsonic.

Using the Spouge simplification instead, we obtain the results given in Table 38.4.

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