5 ANALYSING THE CONSEQUENCES OF INCIDENTS

"It is easy to dodge our responsibilities but we cannot dodge the consequences of dodging our responsibilities."

Lord Stamp of Shortlands

An important aspect of risk management following hazard identification is the task of consequence analysis. Hazards and operational problems often lead to the release of energy and hazardous materials. What is of importance is the knowledge of "how big?" or "what impact?" will flow from hazardous events. This is the area of consequence analysis and there are several key issues that are discussed in this chapter as a prelude to the more detailed discussion in Chapters 6 and 7. What will be evident from these discussions is that current practice relies heavily on the use of mathematical models to predict a range of physical effects as well as potential impacts on vulnerable receptors.

5.1 EVENTS, INCIDENTS AND SCENARIOS

In discussing consequence analysis it is helpful to clearly distinguish between individual events, incidents and scenarios. We adopt the following conventions in this book:

event: a single action or outcome from a system failure

incident: a chain of related events with an initiating event and a termination event.

scenario: a collection of one or more incidents related to a risk analysis investigation.

5.1.1 Events

This is a single action or outcome which characterizes a failure and potentially its subsequent propagation. What is important is the view that each event is a system with its own inputs, outputs, states and parameters as seen in Figure 5-1.

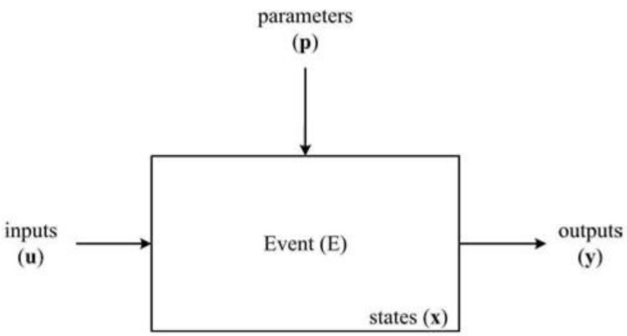

FIGURE 5-1 EVENT SYSTEM

EXAMPLE 5-1 FIRE EVENTS IN CONSEQUENCE ANALYSIS

It is possible to categorize fire events into several classes such as:

- pool fire, where burning liquid is in the form of a contained or uncontained pool
- torch or jet fire, where high pressure gas or flashing liquids form a jet fire of varying shape and dimension
- flash fire, where a flammable gas cloud is ignited and burns rapidly.

These are all common events analyzed for industrial and transport operations.

There are many classes of events that could occur in the process industry, ranging from release of material from the process, through to intermediate material behaviour (pool formation, vapour dispersion) and then impacts on people, property and the environment. Due to the systems nature of events, these are amenable to representation in the form of mathematical models that relate outputs (y) or predictions to given inputs (u), parameters (p) and model form (M).

For the event E, we can write simply that the outputs are a function of inputs and parameters:

$$y = E(u, p) \tag{5.1}$$

The event states (x) are implicitly included in the event E.

For the model (M) that seeks to represent the event behaviour we have in simple terms

$$y^M = M(u, p) \tag{5.2}$$

where y^M are the predicted outputs, and M is the model used to predict the outputs. Clearly, model predictive quality is related to the difference.

$$| \; y^M - y \; | \tag{5.3}$$

which can vary significantly depending on the complexity of the actual situation and the sophistication of the model used to predict its behaviour. Typical values of y^M can be a factor of 2 to 5 from the real value y. Outputs from the model are typically physical effects such as release flowrates, thermal radiation levels, gas concentrations and explosion overpressures. The inputs and parameters for each event are specific to that event. For a gas release the inputs could involve system pressure, aperture size and material being released. Parameters could include material properties such as specific heat capacities and specific volumes. There are uncertainties in both the inputs, parameters and the model form. Hence there are output or prediction uncertainties. This is discussed more fully in Chapter 10.

To illustrate the potential events, Figure 5-2 gives an overview of possible events associated with hazardous substances and other operational and natural events. The left half of Figure 5-2 traces a number of key events after a substance is released from either fixed sites or transport operations. This includes both "safety" related events with impacts on people and plant as well as "environmental" impacts on air, water resources and the like. The right-hand side deals with other key events, common to process systems, including the influence of operational failures, structural failures and natural hazards such as earthquake and storm.

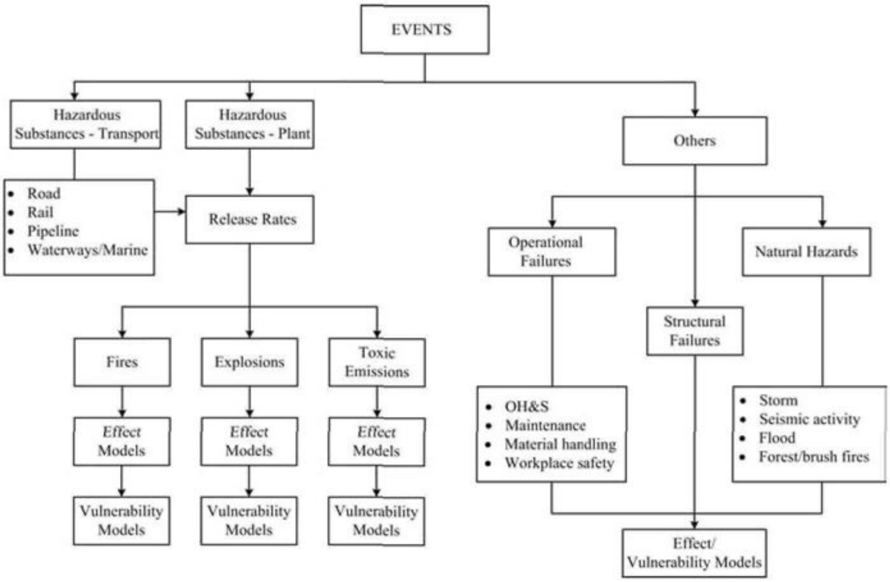

FIGURE 5-2 CONSEQUENCE ANALYSIS OVERVIEW

5.1.2 Incidents

An incident (I) is a chain of events with an initiator and a terminator event. Figure 5-3 shows a simple toxic gas incident (I_1) whereas Figure 5-4 shows a more complex liquefied gas incident (I_2). Individual events are denoted by a single circle whilst the double circle denotes an impact event for the vulnerable receptor under consideration.

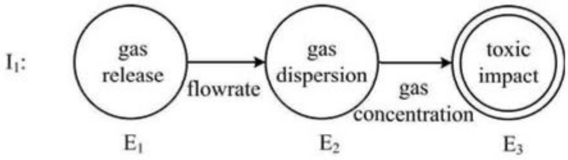

FIGURE 5-3 SIMPLE GAS INCIDENT

As seen in Figures 5-3 and 5-4, incidents can be simple to very complex. The events E_i $(i = 1,\ldots,n)$ are also linked by edges or arcs in specific ways depending on various environmental and processing conditions such as ignition sources. Hence, these edges can represent probabilities dependent on many contributing factors. In Chapter 8 formal methods of event tree and fault tree analysis are used to understand the causal relationships that could exist. It is also clear that propagation of event chains depends on the presence and probabilities of the edges or arcs.

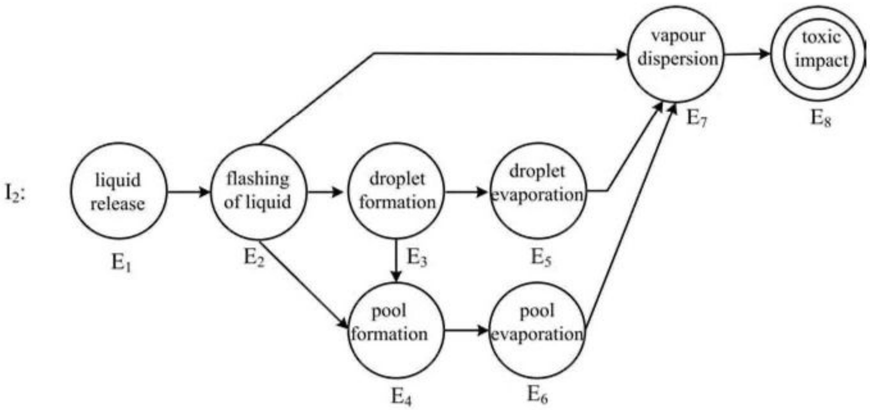

FIGURE 5-4 COMPLEX LIQUEFIED GAS INCIDENT

EXAMPLE 5-2 COKEMAKING ENVIRONMENTAL INCIDENT

Contamination of flushing liquor, used to cool coke ovens gas in a cokemaking battery led to massive blockages of the spray system with carryover of tar products. The use of copious amounts of fresh water eventually led to an environmental accident through release of contaminated water into a local creek. The simplified incident consisted of the following events (Figure 5-5).

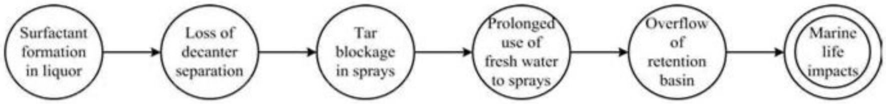

FIGURE 5-5 ENVIRONMENTAL INCIDENT

5.1.3 Scenarios

These relate to a set of incidents that could be used to assess overall impact from system failures. Scenarios are commonly used in quantitative risk assessment where impacts from all potential incidents are used to assess individual, societal or other nominated risks.

For example, a set of incidents I_i (i=1, … , n) might be defined for a particular situation that have the potential for individual fatality impacts. Another scenario could relate to a set of incidents I_j (j = 1, … , m) that could have purely environmental impacts on air or water resources. In some cases, incidents can have multiple impacts such as the release of a toxic, flammable substance that causes injury or death through fire or toxic dose impacts.

5.2 EFFECT AND VULNERABILITY MODELS

One of the key issues arising from the identification of hazards is to estimate the magnitude of the effects that might flow from them. This could be related to a release of material from a rupture or leak, the effects of a fire on people or structures, or the effect of gases which disperse in the surrounding area.

When considering this issue there are two distinct parts which must be addressed. These are:

- the magnitude of the physical effects,
- the damage caused by these effects.

The first considers the effects arising from the actual release and subsequent events. These are quantified in terms of measurements like: concentrations of toxic gases, radiation levels from fires or over-pressures from explosions. There is a plethora of models available in the literature of varying degrees of fidelity and sophistication (CCPS 2000, TNO 1997, Lees 2001). Major journals such as:

- Journal of Hazardous Materials
- Journal of Loss Prevention in the Process Industries
- Reliability Engineering and System Safety
- Transactions of the Institution of Chemical Engineers (UK), Part B.
- Process Safety Progress
- Chemical Engineering Progress
- American Institute of Chemical Engineers Journal

provide useful sources for recent information in model development and application. Chapter 6 discusses some of the key effect models often used in quantification of physical effects.

The second aspect considers what impact these effects have on the receptors we are considering. The receptor might be a plant structure or people or an eco-system. Mathematical models are normally used for these estimates.

The first type of model is an "effect" model whereas the second is known as a "vulnerability" model.

Figure 5-6 illustrates the relationship between these types of models and how they are applied. In Figure 5-6 the "effect" models help to predict the magnitude of the phenomenon associated with the event such as heat radiation levels from a fire. These effects then impact on the environment or the vulnerable receptors. The role of the "vulnerability" models is to take the magnitude of the phenomenon and estimate the damage to people, structures or eco-systems. The overall concept of consequence analysis is given in Figure 5-6 which shows how the incidents are used to obtain a damage quantification.

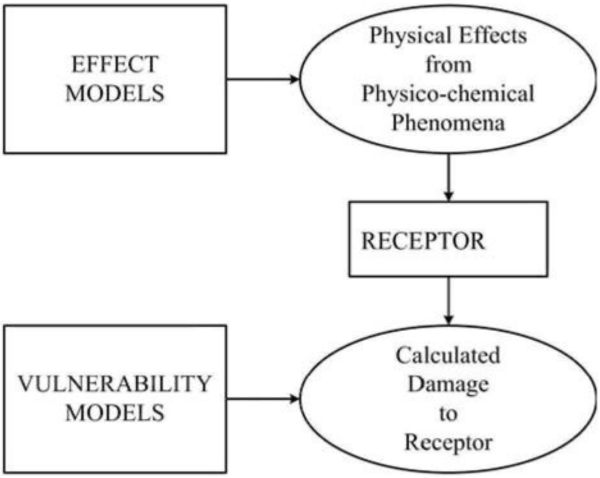

FIGURE 5-6 EFFECT AND VULNERABILITY MODELS

Consequence analysis provides:

- information to industries on effects of events.
- details for designers as to what consequences could occur and should be minimised.
- details to competent authorities on possible effects of events and then aids in appropriate planning decisions.
- workers with details of their personal situation in the event of an incident.
- a basis for emergency planning and emergency response.

In section 5.2.2 we briefly consider the types of events which commonly arise from accidental releases of materials and the consequences that can flow from these events. In Chapter 6, details are given of the models frequently used in estimating those effects. Vulnerability assessments are described in Chapter 7. Of particular importance in consequence analysis is eco-system impact and this is now considered.

5.2.1 Consequence Analysis for Eco-Systems

Process systems can have significant impacts on eco-systems over a range of time scales. Acute, short term impacts from accidents can have a range of consequences depending on the release mode, quantity and toxicity. Longer term, chronic impacts are also possible and should be considered under environmental risk assessment (ERA) methodologies (DOE 1995; Benjamin and Belluck 2001; Standards Australia 2000).

Eco-system impacts can be extremely complex to analyse and often more difficult to quantify. Figure 5-7 shows the key aspects for consideration in ERA. This is a particular instance of the general effect-vulnerability framework given in Figure 5-6. The principal issues in Figure 5-7 that require comment are:

(i) Sources

- For ERA, sources of chemicals of concern (COC) or chemicals of potential concern (COPC) derive from loss of containment through system failures, handling of wastes, storage failures of raw materials or spent materials. The sources can be both acute and chronic and the COC is delivered into the environment in many ways.

(ii) Fate and transport

- Once in the environment, COCs can migrate between various media. The interaction of the COC with the environment can be complex and specialised models for air, water and soil pathways are needed to track transport and the fate of chemical species. Typical of these models are many available through government agencies such as the US EPA (www.epa.gov/epahome/models.htm).

(iii) Impact

- An organism or receptor will encounter the COC by means of a medium (soil, air, water, ...). Ecological receptors include fish, birds, insects and the like. Human receptors include children, adolescents and adults. Models for COC uptake into the receptor are needed in this phase as well as the definition of the ecological endpoints. These endpoints are specific characteristics of a receptor affected by the COC. They could be mortality in a fish population or cancers in humans.

In all these cases, models and data are necessary to provide risk estimates for a given source, transport pathways and final impacts. Specialist advice is nearly always needed for such ERA studies.

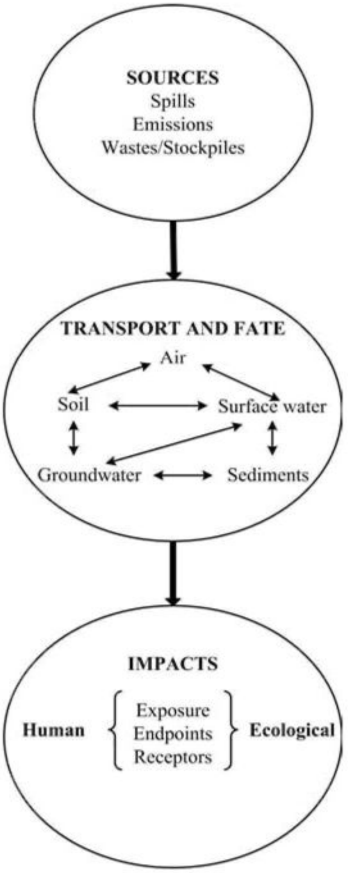

FIGURE 5-7 KEY CONCEPTS IN ENVIRONMENTAL RISK ASSESSMENT

5.2.2 Major Effects in Consequence Analysis

There are several classes of events which are important to consider. The first category we consider are the releases of material into the environment.

5.2.2.1 Release, fire, toxic emissions and explosion

Releases can be in the form of:

- Vapour/gases
- Liquid (normal and superheated)
- Solids

These releases can be from systems which operate at high pressure such as a storage vessel or reactor. They can be spillages from trucks, specialised transport vehicles or conveying systems. In some cases, like LPG, the release is a liquefied gas under pressure (superheated) which rapidly vaporises once it is released. These "flashing" materials can be particularly difficult to analyze.

These foregoing events are typically the initiators for a range of incidents and their rate of release and form are the key aspects in consequence analysis. They are commonly referred to as "source terms".

Fires of various types can occur, related to the way flammable materials are released or the nature of the material itself. We can identify a number of events including:

- flames on pools
- flash fires
- jet fires (also known as torch fires)
- Boiling Liquid Expanding Vapour Explosions (BLEVE)

Each of these events produces different impacts on the surrounding vulnerable receptors, which should be considered.

Of importance here is the level of thermal radiation produced by flames and the duration of the radiation. The directional aspects of the flame are crucial to impact analysis.

EXAMPLE 5-3 BLEVE–CAIRNS, QUEENSLAND

In 1987 at a LPG storage terminal in Cairns, Australia, a mechanical failure in the transfer line from a 40 tonne LPG rail tanker led to a BLEVE event that resulted in significant building damage and the death of 1 person.

(Source: Queensland Fire Service, 1987)

Toxic gas emissions to the atmosphere are important although equally, releases of liquids and solids to watercourses are also important. The types of emissions that could be considered include:

- toxic gases
- flammable substances
- toxic products of combustion

In many cases, these releases are complicated by obstructions or confinement as well as the physical nature of the material released. In the case of solid releases complicated dissolution mechanisms come into play. Clearly, toxic emissions with subsequent dispersion into the environment lead to concentration levels which can have catastrophic impacts such as those seen at Bhopal, India.

EXAMPLE 5-4 CHEMICAL WAREHOUSE FIRE

In 1989 a fire at a chemical storage warehouse led to an explosion and subsequent dispersion of toxic fire combustion products with impacts on the local community.

Doctors' health warning after factory explosion

By FRANK WALKER

DOCTORS fear the health of some residents in Sydney's western suburbs could have been seriously damaged by the massive toxic smoke cloud which swept the area yesterday during a six-hour chemical plant fire.

Police and emergency services personnel evacuated thousands of people from homes in Pendle Hill, Toongabbie, Old Toongabbie and Wentworthville – some up to four kilometres from the blazing plant – as the poisonous cloud spread south.

The blaze began when a series of explosions ripped through the Diversey Industrial Chemicals plant on Abbott Road, Seven Hills, at 3.30 am.

"It was like an atomic bomb going off," said Valerie Middleton, who lives across the road from the Diversey plant.

"We were in bed when I heard this enormous bang. I thought someone was going around the house ramming it with a truck. Then I looked out the window and saw these enormous explosions. They just went up, woomph, like huge mushroom clouds with flames in the middle."

Kim Charles said the heat from the flames 50 metres away was terrifying.

"It was like standing directly in front of a huge bonfire. Luckily the wind was blowing away from us or we would have been caught in it."

Police Sergeant Paul Garner said the man who first reported the fire, Mark Haesman, had difficulty breathing and was taken by ambulance to Blacktown Hospital.

At least six other nearby residents were rushed to hospital suffering breathing problems and eye irritation. Many others were treated at the scene.

Fire brigades from eight stations were confronted with a solid wall of fire. Two hundred one-litre drums of toxic chemicals exploded, sending flames soaring several hundred metres.

BALL OF FIRE: Firemen tackle the blaze at the Seven Hills chemical plant yesterday. Picture: ANTON CERMAK

(Source: The Sun-Herald, December 3, 1989, by permission)

Explosion events can be particularly devastating and blast effects need to be considered when designing and planning operations that could potentially generate these impacts.

In particular, we can categorize explosions under the following headings:

- vapour cloud explosions (eg. deflagration or detonation)
- dust explosions (eg. flour, coal, powders)
- condensed phase explosions (eg. TNT, RDX)

The estimation of explosion effects is quite complex. First, it is necessary in the case of vapour cloud explosions to realise that the degree to which the flammable vapour cloud is confined by process equipment, buildings and trees or determines the type of explosion (detonation or deflagration). Detonations are sonic events and result in very fast (2km - 10km per second) pressure waves. Condensed phase explosions often result in detonations. On the other hand, deflagrations are sub-sonic events, resulting from much slower burning processes (less than 300 metres per second). The damage resulting from these explosion types is quite different, with detonations producing significantly more damage than deflagrations.

Second, the damage pattern can be quite varied where there are many obstructions, buildings or vegetation. One area might receive very high damage, another almost nothing. Hence the need to be wary about results from simplistic models. For some complex cases there are sophisticated tools to predict these effects and this is discussed in Chapter 6.

Finally, of importance are incidents that lead to environmental damage. In some cases this can be due to direct release of toxic substances to ground or watercourses. Another important case is when secondary material such as contaminated fire water from fire fighting operations escapes site containment and enters water courses or causes ground contamination.

EXAMPLE 5-5 FIRE WATER CONTAMINATION OF THE RHINE RIVER

In November 1986 a fire occurred in the Sandoz chemical manufacturing plant in Basel, Switzerland. There were over 90 different chemicals, including 20 pesticides stored on the site. These included substances such as parathion, thiometon, captafol and endosulfan. Up to 15,000 m^3 of contaminated fire water was discharged into the river during this incident. Marine life in the river was greatly affected for over 170 km downstream.

5.2.2.2 Effect models for consequence analysis

As seen in section 5.1, effect models that help predict outputs of events are of the general mathematical form:

$$y^M = M(u, p) \tag{5.4}$$

The model M transforms or maps the given inputs (u) and model parameters (p) to the outputs (y^M). It is clear that the form of M and its internal structure are very important in generating the predictions. Some models are completely empirical such as BLEVE size and duration predictions, whilst release models are normally mechanistic being based on mass and energy conservation principles. Many effect models are a mixture of mechanistic and empirical - the so-called "grey box" model.

There is a plethora of effect models in the literature (Lees, 2001) with many being implemented into software tools. Some are extremely simple, easily implemented on standard spreadsheet tools, others such as computational fluid dynamics (CFD) models can require significant computation time for complex 3D situations.

The principal considerations in using models for any event type are:

- The inputs u:
  - what are they and how easy are they to obtain?
  - what uncertainty is associated with those inputs?
  - what effect does input uncertainty have on the predictions?
  - what is the range of uncertainty or its distribution?
- The parameters p:
  - are these well known or easily obtained?
  - what uncertainty is associated with these values?

- how is the parameter uncertainty reflected in the model predictions?
- what is the range of parameter uncertainty?

- The model form M:
  - what fidelity of model is really needed for the purpose of the study?
  - is the model empirical, mechanistic or "grey box" in nature?
  - what validation has been made on the model?
  - what is the application range of the model?

There are important formal means of addressing issues such as parametric and model structure uncertainty. One of the key aspects in using mathematical models is an assessment of input and parametric uncertainties. For changes in p and u, it is important to assess the corresponding changes in y^M. Hence we can define at least two sensitivity measures for event models:

Parameter sensitivity:
$$\frac{\partial y_i^M}{\partial p_j} \cong \frac{y_i^M(u, p_j + \Delta p_j) - y_i^M(u, p_j)}{\Delta p_j} \tag{5.5}$$

Input sensitivity:
$$\frac{\partial y_i^M}{\partial u_j} \cong \frac{y_i^M(u_j + \Delta u_j, p) - y_i^M(u_j, p)}{\Delta u_j} \tag{5.6}$$

By perturbing p_j by an amount Δp_j the parameter sensitivity on output y_i^M: $\frac{\partial y_i^M}{\partial p_j}$ can be estimated as seen in equation (5.5). A similar sensitivity study for inputs u_j can be made.

Sensitivity estimates can be ranked and then attention given to the most critical inputs and parameters. This can be a vital step in carrying out consequence analysis in order to show the effect of prediction uncertainties due to inputs and parameters. It is an area that is often poorly addressed in risk management practice.

5.2.2.3 Vulnerability models for consequence analysis

Vulnerability models are representations of dose-response situations, where a vulnerable target receives a "dose" or impact in various forms that include:

(i) thermal radiation dose (radiation level for a specified duration)
(ii) toxic dose (toxic gas concentration for a specific duration)
(iii) explosion impulse (overpressure and duration)

There are a number of ways that impacts can be assessed that include:

a) Dose-response curves that represent the mean value response of a human or animal to toxic doses. Doses are typically in terms of mg substance/kg body weight.

If the response is plotted against the logarithm of the dose a typical sigmoidal or 'S' shaped curve is obtained, as seen in Figure 5-8.

b) Use of probit or probability unit functions that fit dose-response data to the mathematical form (CRC, 1968):

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} \exp\left(-\frac{1}{2}w^2\right) dw \tag{5.7}$$

where	P	= percentage or fraction of resource affected
	Y	= probit variable (related to the dose)
	w	= independent variable in the integral

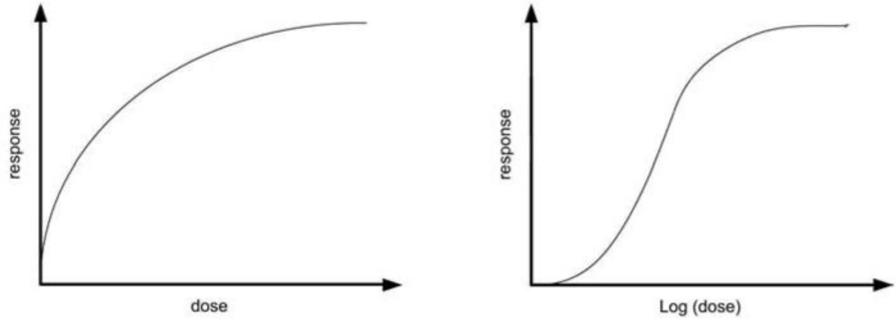

FIGURE 5-8 DOSE RESPONSE RELATIONSHIPS

Probit equations provide a useful mathematical function to compute impacts on vulnerable receptors. Probits are available for a limited number of impacts of toxic gases as well as thermal radiation and explosion impacts. Further details are given in Chapter 7.

c) There are several toxic gas exposure indices for injury effects:

TLV = Threshold limit value for occupational exposure to gases and vapours, defined as "the average airborne concentration of a particular substance when calculated over a normal eight-hour working day, for a five-day working week". The TLV is also referred to as the Time Weighted Average (TWA).

STEL = Short term exposure limit for occupational exposure, defined as "a 15 minute TWA exposure that should not be exceeded at any time during a working day even if the eight-hour TWA average is within the TWA exposure standard. Exposures at the STEL should not be longer than 15 minutes and should not be repeated more than four times per day. There should be at least 60 minutes between successive exposures at the STEL".

IDLH = Immediately dangerous to life and health gas concentrations levels at which, if exposure occurs for more than 30 minutes, irreversible injury may occur.

ERPG = Emergency response planning guidelines defined at 3 levels of concentrations, used for possible civil evacuation purposes.

The above toxicological indices are useful in assessing injury potential and emergency planning for evacuation purposes, but not applicable when estimating lethal effects on individuals or groups from accidental releases.

Care must be exercised in using the probit methods for toxic impact assessment as significant extrapolation from animal studies is often used in arriving at specific toxic index values. An example of this is given in Chapter 7.

Table 5-1 summarizes the initiating events, the physical effects and the type of damage on different receptors. Some details are given in TNO (1992). Chapter 7 gives more detail on the specific vulnerability models that can be used within process risk management applications.

TABLE 5-1 VULNERABILITY MODELS

Damage Causing Event	Physical Effects	Resource Affected	Type of Damage
FLASH FIRE	Thermal radiation	People	Death Injury
POOL BURNING	Thermal radiation	People	Death Burns
		Structures	Failure
JET FIRE	Flame impingement	Structures	Failure
	Thermal radiation	People	Death Injury
EXPLOSION	Blast overpressure Blast impulse Thermal radiation Flying fragments	People	Death Injury Ear/lung damage Fractures Punctures
		Structures	Structural damage Glass breakage
TOXIC RELEASE	Toxic vapour concentration dose	People	Death Injury Irritation Distress
		Biosphere	Death Damage

5.3 LIMITATIONS AND UNCERTAINTIES IN CONSEQUENCE ANALYSIS

There are some significant limitations on the use of effect models. This is simply because:

- most of the mathematical models are based on idealized systems. That is, they often do not take into account irregularities. In the case of ideal dispersion models, no account is taken of the effect of buildings in breaking

up or concentrating gases flowing around them. The same is true of most fire models and explosion models. Sophisticated models are needed in circumstances where fidelity is desired. Even then limitations must be recognized. Sophistication should not be equated to fidelity.

- most models are empirical or semi-empirical, being based on a limited set of experimental data. Predictions outside the validation range is often dangerous.
- many models have only been verified by small scale tests and as such have significant uncertainties attached to them when applied to new situations where the physical size of the event is much larger. An example is the prediction of evaporation rates from very large spills using models based on 1 metre diameter experimental pools.

The result of these issues is that there can be significant uncertainty in the results from such model predictions. Also much of the input data to these models has uncertainty associated with it. For example the size of the hole leading to the release or the windspeed for dispersion calculations. Typically we can expect predictions to vary by a factor of 2 to 5.

This is not to say that the predictions are useless. It just means that we need to appreciate the variability of the predictions and carry out sensitivity checks to see how the model output varies with our assumptions on the input data. In that way we get a "feel" for what is important and what is not. This is considered in Chapter 10.

5.3.1 Need for Assumptions

Like any area of analysis, it is vital to either explicitly state the assumptions underlying the methods used or refer to modelling and analysis assumptions that are implicit in the work.

Stated assumptions allow both the analyst and the reader to assess the appropriateness of the methods used in consequence analysis as well as the input data and model parameters. The assumptions should include:

(i) The event sequences (incidents) used.

(ii) The effect models used for each event in the incident.

(iii) The input data assumed for the models and an estimate of the uncertainty for those inputs.

(iv) The parameters for the models with estimates of their uncertainty in terms of parameter ranges or specific distributions eg. (Gaussian or log-normal etc.).

(v) Assumptions relating to excluded events or incidents and their justification for their exclusion in the analysis.

5.3.2 Quality of Assumptions

The quality of the assumptions is vital. In some cases, lack of insight and understanding can lead to inappropriate assumptions being made and applied in a risk assessment study. The underlying assumptions can be improved by:

(i) Ensuring a clear physico-chemical understanding of the phenomena relating to release scenarios (see Example 5-6a).

(ii) Appreciating the limitations of the effect models and their applicability in specific circumstances (see 5-6b).

(iii) Improving the knowledge concerning the sensitivity of outputs to inputs and parameters for a specific model. This can force the user to improve initial estimates of key inputs and parameters for an application.

(iv) Over-simplification in the case of mixtures that have been released. In some circumstances, mixtures of substances are approximated by the dominant component. This might be due to limitations within software systems such as the inability to handle physical properties or phase equilibria predictions of mixtures. These assumptions should be scrutinized carefully for adequacy and the appropriate model used when initial assumptions are inadequate.

(v) In the case of vulnerability models, particular care must be taken when assuming the legitimacy of dose-response or probit functions. In particular, the extrapolation or modification of animal toxicological data for human response predictions can be wildly amiss. "Hidden" conditions such as partial clothing in certain probit functions affects thermal impact assessments.

(vi) Assessing assumptions concerning escape and shelter from various effects such as gas concentrations or thermal radiation impact. Where appropriate these assumptions can make major differences in impact outcomes if they are not adopted.

The message is simply, check sources and the basis on which the models were established. Use the model "fit for purpose", meaning that it must be no simpler or complex than needed. The concept of parsimony applies. Overly complex models can give the appearance of sophistication, an illusion of accuracy and a false sense of security. They can be totally inadequate if applied incorrectly.

EXAMPLE 5-6 HF CHEMISTRY

a) Release of HF gas-liquid mixtures requires special consideration because of the complex behaviour of hydrogen fluoride. In particular, HF forms higher molecular weight oligomers $(\text{-HF})_n$ that make HF releases behave as a dense gas. Reaction with ambient moisture generates heat whilst dilution with air cools the mixture. Using simple models for such releases can lead to significant errors.

b) Fire radiation models that assume a "point source" for energy transmission grossly underestimate nearfield effects when more appropriate "view factor" methods that consider flame shape and flame luminosity should be applied.

5.4 ASSESSMENT OF EVENT PROPAGATION

Section 5.1.2 considered the definition of an incident as being a sequence of interconnected events. Event propagation occurs due to a number of characteristics including:

(i) The form of the initial release (gas, liquid, solid)
(ii) Presence of contributing factors (ignition sources)
(iii) Absence of mitigation systems (bunds/dikes, drainage systems, emergency shutdown devices)
(iv) Human intervention/lack of action (failure to isolate, inability to diagnose in time or correctly)
(v) Meteorological conditions (windspeed, direction, atmospheric stability)
(vi) Presence of personnel or the public in the vicinity.

Some or all of these factors can play important roles in performing credible consequence analysis.

5.4.1 Domino Effects

When certain events propagate into other systems then there is the likelihood of "domino" effects taking place. Typical events that can spawn domino events include:

(i) Explosion (missiles, overpressure effects)
(ii) Fire (pool, jet, fireball or flash fire events)
(iii) Toxic releases (gases and liquids)

Domino effects have become increasingly significant in process risk management due to tighter process integration, tighter spatial designs such as offshore facilities and the establishment of large scale integrated production sites consisting of many adjacent production units. Domino effects have been the subject of several recent studies (Khan and Abbasi, 2001; Cozzani and Salzano, 2004a,b). They are also the subject of major regulatory frameworks such as Seveso II.

Domino effects can be seen as a cross-linking of an event sequence (incident) into another incident through effects generated at any event in the original incident. In Figure 5-4 schematic illustration of this cross-linking or event propagation is given, where the original incident, I_1 potentially spawns incident I_2 and so on.

Key factors that contribute to the potential for domino effects can include:

(i) The form of effect associated with a particular event E_i in an incident I_j. This includes thermal radiation, overpressure, impulse or missiles (vessel fragments)
(ii) The magnitude of the physical effect as predicted by effect models.
(iii) The vulnerability of primary receptor to the physical effects from the incident I_i that leads to the initiation of a new incident I_k. This relates to the probabilities P_{12}, P_{23}, P_{1x}, ... that the incident I_i is successful in initiating incident I_k.

For example, in assessing missile effects, Hauptmanns (2001), provides a modelling and estimation approach to obtain fragment ranges and trajectories for a variety of scenarios.

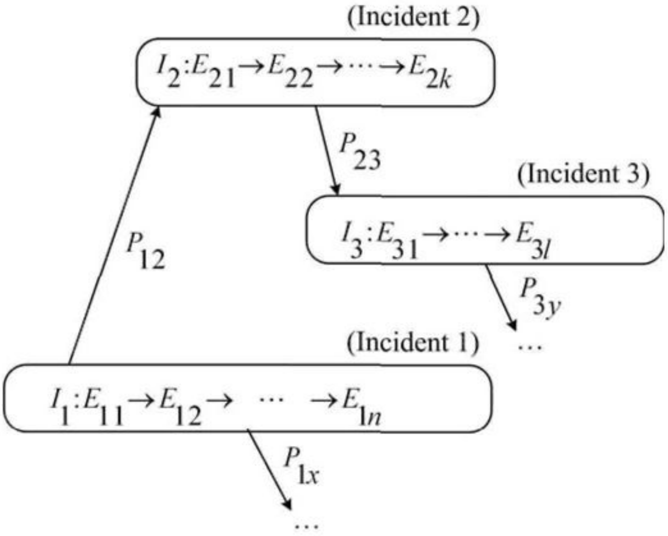

FIGURE 5-9 DOMINO EFFECT REPRESENTATION

It is clear that effect and vulnerability models play an important role in assessing domino effects. Their consideration is of growing importance in contemporary risk management especially in circumstances of tight spatial integration within a plant and across sites.

EXAMPLE 5-7 DOMINO INCIDENTS

a) Failure in internal vessel integrity of an acid droplet separator in an ammonia absorption unit led to carry over of an acidic solution to a decanter. The acid reacted with decanter contents, emulsifying the decanter and losing separation of tar components that eventually recycled to a coke making operation causing massive blockages. As a result of the blockages large amounts of fresh water were needed to cool hot coke ovens gas. The contaminated water eventually overflowed a retention basin causing an environmental accident in the local waterway.

b) The initial LPG fire and explosion at Pemex, Mexico in 1984 propagated through the complete facility over a period of 8 hours leaving over 500 people dead, the majority of the site destroyed and major damage to surrounding housing areas. Over 200,000 people were evacuated.

A major factor in domino effects was the extremely close layout of vessels on the site and the amount of flammable materials that were stored. Inappropriate housing development was a major contributing factor to the high number of deaths off-site. In this instance domino effects were extreme (TNO 1985).

5.4.2 Models to Represent Propagations

There are two primary cases to consider where propagation is important. These are:

a) Event to event propagations via effect models (Type I) .
b) Event to event propagations via vulnerability models (Type II) .

In case a) the incident is formed from an initiating event E_1 whose physical effect is used as a partial input to event E_2 and so on until reaching the terminating event, normally represented by a vulnerability model.

In case b) one or more events in an incident sequence spawn other incidents. This is the domino issue where new incidents are generated from a single initiating incident. In this case the linking across incidents is done through a vulnerability model.

In both cases it is necessary to effectively link the submodels together in the incident so that event propagations are established. One key issue in doing this is that outputs from one model must be within validity limits of the inputs to another model. Otherwise it is possible to generate invalid or nonsense results. This is reinforced by Cozzani and Salano (2004a) where the use of inappropriate vulnerability models can lead to errors of up to 500%. This was in the context of vessel response to explosion overpressures.

Figure 5-8 illustrates the two key propagation types that have been discussed showing the use of specific models, their inputs (u_i), parameters (p_i) and linkages. Again, models "fit for purpose" is the principal requirement in obtaining credible outcomes from such analyses. Some of these modelling issues are addressed in Chapters 6 and 7 where consideration is given to effect models and then vulnerability models.

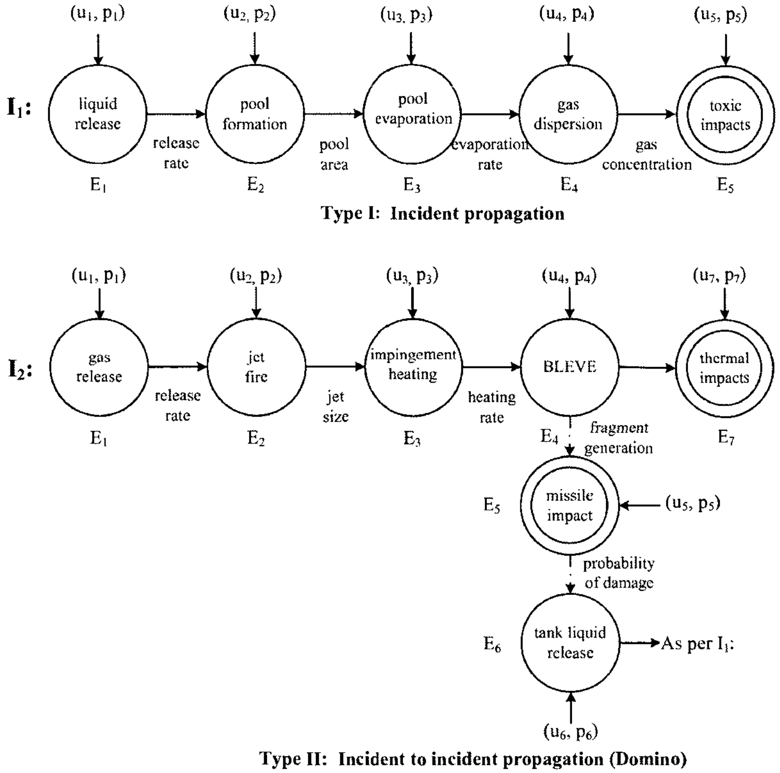

FIGURE 5-10 EVENT PROPAGATION MODELS

5.5 REVIEW

This chapter has introduced a number of key concepts in consequence analysis. In particular, the two principal models of effect and vulnerability were discussed. Both play an important role in process systems risk analysis.

Events, incidents and scenarios were introduced and the accompanying models that allow quantitative estimates to be made were discussed in general terms. Each model has its application area and its own limitations and validity ranges. This must be appreciated. A knowledge of these factors is vital in generating credible results from the use of such models.

It was emphasized that considerable uncertainty can be associated with various models particularly when they are used outside their validation limits. The use of input and parameter sensitivity studies should be carried out in order to gauge the importance of these inputs. Efforts in tying down key inputs and parameters to better estimates can be then made. For all model use we must appreciate the parametric and structural uncertainties present in the models and address them effectively.

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5.7 NOTATION

AS	Australian Standards
BLEVE	Boiling Liquid Expanding Vapour Explosion
CCPS	Center for Chemical Process Safety, AIChE, USA
CFD	Computational Fluid Dynamics
COC	Chemical of Concern
COPC	Chemical of Potential Concern
DOE	Department of Environment

ERA	Environmental Risk Assessment
ERPG	Emergency Response Planning Guidelines
HF	Hydrogen Fluoride
IDLH	Immediately Dangerous to Life and Health
km	kilometre
LPG	Liquefied Petroleum Gas
m^3	Cubic metres
RDX	Cyclo-trimethylene-trinitramine explosive
Sdu	Director-General for Social Affairs, the Netherlands
STEL	Short Term Exposure Limit
TLV	Threshold Limit Value
TNT	Trinitro Toluene