HEALTH HAZARD ASSESSMENT AND DECISION MAKING FOR DISASTER RESPONSE

Drs. Dik De Weger
Dr. Ertu□rul Alp

1.1 INTRODUCTION

Increased use of toxic or flammable dangerous goods in recent years as a source of energy or industry chemical feedstock has pushed the need for government and industry to develop (and be able to implement) disaster preparedness plans. Prevention and damage mitigation plans, for both accidental and non-accidental releases of toxic or flammable substances, will improve community cooperation near government and industrial facilities utilizing these substances, and potentially minimize adverse health consequences and property damage.

An industrial emergency, whether it be a fire, an explosion or a release of hazardous materials, disrupts normal plant operation and normal social life. The effects may be limited to the plant site (an on-site incident or event) or extend to the surrounding community (an off-site incident or event). On-site emergency events, in general, only directly affect employees; off-site emergency events affect on-site employees, the local communities, and all commerce and travel being conducted in the area. Off-site emergencies generally are more severe than on-site incidents, and require a greater sharing, between industry and local authorities, of knowledge, responsibilities, personnel and equipment.

The preparation of sound, practical, disaster preparedness plans requires the use of mathematical models. The planning process permits the examination of possible release scenarios of dangerous goods. Mathematical models permit estimates of the nature and extent of potential damage for the release of a given quantity of a known substance. A knowledge of the nature and extent of possible damage can then be used to determine the type and magnitude of the response effort that would be required to minimize the undesirable impact of the accident.

Accurate mathematical models, which incorporate knowledge from previous experience and the essentials of basic physical-chemical principles, form a cornerstone of disaster preparedness planning.

To define the nature and magnitude of a potential emergency, the following steps need to be carried out:

a) identification of the nature of the unwanted event (type of accident, type of hazardous materials and their associated hazards, e.g., fire, explosion);

b) determination of the magnitude of the physical phenomena (calculation of "hazard levels"); and

c) determination of the acute and chronic (long-term) biological or physical damage caused by the physical-chemical phenomena to the environment and to the exposed population ("damage or impact calculations").

The term **Consequence Analysis** is commonly used in referring to hazard level and damage calculations. In addition, probabilities associated with the occurrence of hazardous events may also be determined. **Frequency analysis** refers to this step. While the results of consequence analysis help determine the emergency response zones should a hazardous event occur, the frequency information helps put the importance of each potential event into perspective. **Risk analysis** is an integration of the probability of occurrence and the magnitude of the consequences of hazardous events. Probability and consequence information, integrated into a risk measure, is commonly used as a basis for land use planning from a public safety perspective.

In this chapter, the types of hazards of most interest in disaster preparedness planning will be reviewed first, and then the mathematical models used in consequence calculations will be discussed.

1.1.1 Hazards Associated with Releases of Dangerous Goods

Dangerous goods are contained in storage or process vessels in liquid, gas or solid form. Releases can occur from fixed facilities, or during transportation by truck or rail, by ship or barge, by pipeline or during air transport.

If the spilled dangerous good is in **solid** form (storage temperature is below the freezing point of the substance at atmospheric pressure) this solid material will pose

- a potential blast (pressure) wave hazard (i.e., an explosion), if it is inherently unstable, or unstable under certain conditions,

- a fire hazard, if it is combustible, and its combustion products may pose potential acute toxic and/or long-term (e.g. chronic respiratory or carcinogenic) health hazards or,

- a toxic threat, if the material is in powder form, producing acute or chronic effects, and if soluble in water the spill can be absorbed into the potable water supply, posing an even larger potential health hazard.

If the spilled dangerous good is in **liquid** form (storage temperature is below the boiling point of the substance at atmospheric pressure), a liquid pool would normally form and spread on the spill surface. This pool will pose

- a thermal radiation hazard, if the liquid is flammable and a pool fire occurs, the combustion products also potentially pose acute and chronic health hazards; in case the fire is carried back to the release point, and the flames find their way into the containment vessel, a confined vapour explosion can result producing a blast wave hazard.

- a direct health hazard, if the liquid and its vapours are themselves toxic.

If the dangerous good released is in gas form (containment temperature is above the critical temperature), a gas cloud can be formed which will be carried by the wind and disperse in the atmosphere. This gas will pose

- a fire hazard, if it is flammable, and if it ignites, it will result in a flash fire, causing a thermal radiation hazard in the area engulfed in the gas cloud and its immediate vicinity; if the fire is carried back to its source, it could result in a jet fire,

- a direct toxic health hazard, if it or its combustion products have toxic properties.

The release of a pressure-liquefied gas from pressurized containment (storage temperature is between boiling temperature at atmospheric pressure and the critical temperature) will rapidly flash-off, absorbing heat from the liquid and cooling it to its boiling point. The release is usually in the form of a two-phase jet. Depending on the liquid content of the two-phase jet, some of the liquid may fall to the spill surface and form a spreading liquid pool. The smaller droplets (sometimes termed an aerosol) and the gas will form a cloud which is colder and denser than the air around it. Such a gas cloud is called a heavy gas cloud, which remains close to the surface, spreads laterally under the influence of gravity, and takes much longer to disperse than a buoyant or neutrally-buoyant gas cloud. The cold liquid pool will also continue evaporating and contribute to the gas cloud. If the heavy gas is

- toxic or carcinogenic, the cloud will pose a direct health hazard, and

- flammable and it ignites, it could result in a flash fire, or a semi-confined or unconfined vapour cloud explosion (VCE) depending on the amount of pre-mixing with air of the heavy gas-aerosol mixture and the degree of confinement by nearby structures; if the release is very violent, such as in the presence of an external fire surrounding the pressurized containment vessel, a boiling liquid expanding vapour explosion (BLEVE), a fireball, and, upon fragmentation of the containment vessel, "tub rocketing" (pieces of the vessel flying like missiles) can also occur.

When a refrigeration-liquefied gas, in refrigerated storage, is released in a non-controlled manner it forms a cold heavy gas cloud as a result of rapid boil-off of the liquid; a liquid pool on the spill surface may also occur. The hazards associated with this type of release are similar to those from release of a pressure-liquefied gas, except that the aerosol content of such a cloud will be much less than that due to release of a pressure-liquefied gas. If the material is flammable, the lowered aerosol content minimizes the chances of a vapour cloud explosion, or a fireball.

Based on the above description of hazard events associated with various types of releases, these events can be classified into the following general groups for the purposes of disaster preparedness planning:

- events that result in **thermal radiation hazards**, where a receptor will be affected by radiation at a distance even though it may not be physically within the fire (pool fire, jet fire, fireball),
- events that result in **blast wave hazards**, where a receptor will be affected by the pressure wave at a distance (explosions, BLEVEs, VCEs),
- events that result in **missile hazards** (tub rocketing), and
- events that result in a **gas cloud**, where the primary hazard to a receptor is by virtue of being physically within the cloud (toxic clouds, including nuclear radiation, and flash fires-- the extent of the flammable region of a cloud is usually sufficient to define the extent of damage due to flash fires, the damage outside this region being rather minimal; these events are therefore classified in this group rather than within the "thermal radiation" group in anticipation of the ensuing modeling requirements for these hazards).

Theoretical and empirical models can be used for estimating the extent of potential damage due to these hazardous events. The first step is the estimation of source strengths (quantities) of releases. The second step requires hazard models to be used to estimate levels of hazard at receptor points for a given type of accident and substance. For example, a hazard model for a fire will give the heat radiation level as a function of time and distance from the fire location. An explosion model will give the degree of over pressure as a function of the distance from the explosion point. An atmospheric dispersion model will give concentrations of the hazardous substance in air over time and distance. The hazard levels estimated using such models can then be used in vulnerability models specific to the hazardous substance and the selected type of receptor (e.g., people, plant units, buildings) to determine the level of potential damage. The Probit approach, described in the next section, provides a common means of relating hazard levels to the level of damage or impact.

1.2 HAZARD MODELING

1.2.1 Introduction

A model describing physical phenomena such as release and dispersion can be created which describes the characteristics of the released substance(s) and their interaction(s) with the environment e.g., outflow, gas dispersion, evaporation from a liquid pool, etc. A release of a hazardous material is described by a source term model followed by other models which describe and integrate other physical-chemical properties, events and effects.

1.2.2 Source Term Modeling

The strength of the source means the amount of the substance released. The release may be instantaneous or semi-continuous. In the case of instantaneous release, the strength of the source is given in kilograms (kg); in the case of semi-continuous release the strength of the source depends on a function of outflow time expressed in terms of kilograms per unit of time (kilogram per second or kg/s).

In order to determine the strength of the source, the physical state (solid, liquid or gas) of a substance in containment must be defined and described. The physical properties of the substance, together with containment pressure and ambient temperature, determine the physical state.

1.2.2.1 Release from Containment

Releases of Solids

Spill estimates of solid dangerous goods can be made by on-site observation or percent loss estimates or calculations [such estimates are often used in planning exercises]. If the material ignites, however, estimation of partial and complete combustion products is more complex. Chemical properties, and chemical reactions and interactions are a function of the spilled substance. Information from past incident(s) and past experience(s) must be available and considered in the response development decision-making process.

Releases of Fluids (Liquids or Gases)

An accidental release of a hazardous fluid material may occur instantaneously or semi-continuously. Instantaneous release implies that the entire contents are released in a very short time.

Outflow may continue following an instantaneous release, resulting in a secondary semi-continuous release. Responses to instanteous releases vary, depending upon whether a secondary semi-continuous release occurs.

Instantaneous Release

Instantaneous release will occur, for example, if a storage tank fails. Depending on the storage conditions the following situations may occur:

- *Instantaneous release of a gas*

The source strength is equal to the total contents of the storage system.

- *Instantaneous release of a pressure-liquefied gas*

In the case of a pressure-liquefied gas, a flash-off will occur. A flash-off means that as a result of the reduction of the pressure to atmospheric pressure the liquid will spontaneously start to boil. The necessary heat of evaporation for this is drawn from the liquid which will, as a result, cool down to its boiling temperature at atmospheric pressure. The consequence of a flash-off is that an instantaneous gas cloud will occur, possibly carrying a significant amount of liquid in the form of droplets. The remaining cold liquid may form a spreading pool which will continue to evaporate due to heat supplied from the ground, forming a semi-continuous vapour source (see below, Evaporation).

- *Instantaneous release resulting from a BLEVE*

A BLEVE (boiling liquid expanding vapour explosion) is a physical explosion which occurs when the vapour side of a storage tank is heated by fire (e.g., a jet fire). As a result of the heat, vapour pressure will rise and the tank wall will weaken. Subsequently, the weakened tank wall may no longer be able to withstand the increased vapour pressure and burst open. As a result of the sudden expansion and flash-off a pressure wave occurs. With flammable gases, a fireball will also follow.

- *Instantaneous release of a liquid*

In the event of instantaneous release of a liquid, a pool of liquid will form. The evaporation can be calculated on the basis of this liquid pool (see below, Evaporation).

Semi-continuous Outflow

In the case of a semi-continuous outflow it is again necessary to determine whether it is a gas, a liquefied gas or liquid that is being released. The release rate from a breach in the containment wall will be proportional to the square root of the pressure difference between the containment and ambient pressures, and the area of the hole. The following situations can occur.

- *Gas release*

If there is no liquefied gas in the system, and if no gas is being supplied to the tank, the containment pressure will start decreasing as soon as the breach takes place. As a result, the strength of the source will decrease as a function of time.

- *Vapour outflow, liquid containment*

If the outflow point is located above the liquid level, vapour outflow will occur. In the case of a pressure-liquefied gas, the liquid will start boiling as a result of the drop in pressure (flash-off). In the equilibrium situation, the pressure of the vapour which has formed in the storage tank is equal to the saturated vapour pressure. The necessary heat of evaporation will be drawn from the remaining liquid which thus cools down to its boiling point at atmospheric pressure.

The source strength of the releasing vapour is a function of the pressure in the storage system; after the temperature of the liquid has reached its boiling point, the source strength will remain relatively constant until all the liquid is depleted.

In the case of the outflow of vapour from a pressure-liquefied gas, a Champagne effect may occur. A two-phase (gas & liquid) jet occurs when the liquid starts to boil and droplets are carried along with the releasing vapour resulting in a considerably increased or "more effective" source strength.

In the event of the outflow of vapour from a refrigeration-liquefied gas, the source strength will be equal to the volume of liquid which evaporates per unit of time. Since the storage is cooled, this evaporation will be minimal. If the cooling shuts down, evaporation will occur as a result of the heat supplied from the surroundings.

- *Liquid outflow*

If the outflow point is located below the liquid level, liquid outflow will occur.

In the case of a pressure-liquefied gas, liquid outflow will result in a flash-off. The release will generally be so violent that the liquid jet will be broken into drops as a result of the intensity of the release and form a two-phase jet. Air will be entrained into this jet as a result of turbulent mixing with the surroundings. The heat present in the entrained air will cause the drops to evaporate. If there is not much flash-off (the saturated vapour pressure is then not much higher than the atmospheric pressure) the remaining liquid which is cooled down to the boiling point (or below) will start spreading on the ground and form a pool. Evaporation will also occur from this pool, resulting in a second semi-continuous vapour source (see below, Evaporation).

In the case of the release of a non-boiling liquid, the outflow is determined by the pressure above the liquid level (saturated vapour pressure) plus the hydrostatic pressure of the column of liquid. The releasing liquid will form a pool from which evaporation takes place (see below, Evaporation).

- *Turbulent jet*

When gas or vapour flows from a vessel, a turbulent jet may occur. Due to the direct mixing of air with the outflowing jet, a cloud will form. This cloud may be toxic and/or explosive depending on the characteristic(s) of the outflowing substance(s). If the turbulent jet is ignited, a jet fire results.

- *Two-Phase Releases*

In recent years, special emphasis has been given to two-phase discharges due to the complexity and importance of such releases in disaster preparedness planning (Ianello et al., 1989). Ianello developed a computer program called RELEASE to address the complexities of such releases. Further experimental work is being carried out to validate this model (Johnson, 1991).

In two-phase releases, the instantaneous flash fraction "f" can be obtained from an overall enthalpy heat energy balance. Some of the liquid will be in the form of fine droplets (mist) and become suspended within the gas cloud. The remaining liquid will form a liquid pool on the spill surface. The distribution of the liquid portion between the mist and the liquid pool will be dependent on (a) the material, (b) the storage conditions, and © the orientation of the discharge jet. For releases of pressurized ammonia, Kaiser and Griffiths (1982) found that virtually all the liquid formed a mist when the jet had an upward vertical orientation. However, when a jet is directed vertically downwards, impingement of the liquid on the surface occurs, causing a significant fraction of the liquid to form a pool which then evaporates to form a secondary source (Blanken, 1980). An accurate estimation of the distribution between the mist and liquid pool, and evaporation of the droplets within the mist which is carried by the wind, is important in determining the hazard zones associated with dangerous goods releases. A detailed aerosol dynamics model which can predict the evolution of droplets and their evaporation and deposition has been reported by Kukkonen and Vesala (1991). A thermodynamic model, which simulates evaporation and condensation of droplets within a gas cloud, has been included by Alp and Matthias (1991) in their heavy gas dispersion model COBRA (see also below, in dispersion models).

1.2.2.2 Evaporation of Spilled Substance from a Liquid Pool

In the evaporation models, a distinction is made between the evaporation of:

- refrigeration-liquefied gases,
- pressure-liquefied gases, and
- non "boiling" liquids.

If a pressure-liquefied gas is released, flash-off will occur (see above, "Instantaneous Release"), resulting in an instantaneous gas cloud. If there is little flash-off, the remaining liquid which has cooled to its boiling point at atmospheric pressure, will spread on the ground and start evaporating. Under these circumstances, the same model also can be used for the evaporation of a refrigeration-liquefied gas spilled on a surface.

From the surface (ground) pool which has formed, evaporation will take place as a result of the heat flow from the ground and any solar radiation. The evaporation model need only take account of the heat flow from the ground since, in general, the heat resulting from solar radiation is negligible compared with the heat from the ground.

The rate of evaporation depends on:

- the kind of liquid, and
- the kind of subsoil.

Consideration needs to be given to whether the pool is confined. If a confined pool exists (e.g., outflow into a tank pit), then the surface area of the pool remains constant after the initial phase. If the area of the pool is not confined, then a freely spreading pool exists. In an evaporation model, it is usually assumed that the pool will spread until a minimal layer thickness is reached (this depends on the subsoil). This pool will then start shrinking again because the ground at the edge of the pool has cooled less than the centre (because of a shorter contact time with the liquid).

If a non "boiling" liquid flows out, a pool forms. One way in which the area of this pool can be determined is by assuming a layer thickness. If the pool is confined by a tank pit or "bund" the area of the pool is equal to the area of the tank pit. In the case of non boiling liquids, no evaporation occurs as a result of heat drawn from the ground, but the vapour present above the pool as a result of vapour diffusion is "skimmed off" by the prevailing wind. The amount of vapour removed in this case depends on:

- the partial vapour pressure of the liquid;
- the prevailing wind velocity; and
- the area of the pool.

Evaporative cooling and differential boil-off of various constituents of a spilled substance may be complicating factors in estimating gas source strength (and ultimately damage) from liquid pools.

1.2.2.3 Generation of Toxic Combustion Products

One of the hazards of an industrial fire is the release of toxic substances. These toxic substances may be present in the industrial facility or result from the toxic combustion products generated by the fire. Whether these materials are released and/or formed depends on the nature of the substance(s) and on the circumstances prior to and during the fire.

Release of Stored Material

The products in a storage facility, in many cases, are mixtures of the active substance and some inert material; this mixture is called a formulation. Formulations may be divided into two categories: solutions or mixtures of solids with some other solid inert material. In either case the product may be flammable.

A solution of a flammable solvent will burn easily; the dissolved product will be more or less completely combusted, and toxic combustion products may be released. (Whether this will occur depends on the composition of the burning material.)

If a solution of a solid material in water is involved in a fire, the water will evaporate; during this process, a concentrated solution is formed and finally the (solid) product remains behind. The solid will either burn (partially or completely) or will disperse into the air if in powder form. A mixture of a liquid product with water will generally evaporate as a whole, unless the boiling point of the liquid is very high, in which case a similar concentration process will occur; the evaporated product, based on its physical-chemical properties can be partially or completely combusted.

Formation and Release of Toxic Combustion Products

In addition to the toxic products that may be released, under certain circumstances, toxic combustion products may also be formed and dispersed. A review of the literature indicates that little attention has been given to the combustion products of pesticides and hydrocarbons until recently. In general, in those instances where experimental data are available, the actual experimental conditions are very poorly described, making replication experiments extremely difficult. Recently, the TNO have been involved with carefully conducted combustion product research. They have studied the combustion properties of pesticides such as parathion, and different 2,4-D-compounds.

Generation of toxic combustion products occurs when the burning products contain atoms other than carbon, hydrogen or oxygen (so-called hetero-atoms). Hetero-atoms include: nitrogen, sulphur, and the halogens (chlorine, fluorine, iodine, bromine) - all components of pesticides. The possible toxic combustion products are summarized in Table 2-1 (compounds are listed in the relative order in which they are generated during combustion); in all cases carbon monoxide and hydrocarbons are also formed.

TABLE 2-1

Possible Toxic Combustion Products

CATEGORY	TOXIC COMBUSTION PRODUCT
Halogen containing compounds	HX (e.g. HCl, HF), Cl_2, $COCl_2$
Nitrogen containing compounds	NO_x, HCN, NH_3
Sulphur containing compounds	SO_2, H_2S, COS
Cyanide containing compounds	NO_x, HCN, NH_3
Polychlorinated aromates ($COCl_2$)	HCl, PCDD, PCDF, Cl_2
Polychlorinated biphenyls ($COCl_2$)	HCl, PCDD, PCDF, Cl_2

Thus, in addition to carbon monoxide and hydrocarbons, the most important compounds that may be formed during partial or complete combustion include:

- hydrogen chloride (and more generally hydrogen halogens), hydrogen cyanide, hydrogen sulphide;
- oxides of sulfur and nitrogen;
- ammonia;
- chlorine;
- phosgene; and
- polychlorinated aromatic hydrocarbons.

The generation of combustion products is a function of the combustion mixture (relative amounts of combustible material, packaging material and oxygen initially available), the continuing oxygen supply and other combustion conditions. The greater the combustion temperature, the more complete the combustion. Usually, from a health effect point of view, complete combustion is more desirable than incomplete combustion. Thus, the means of extinguishing a fire can directly influence the occurrence of combustion products -- as the temperature decreases, and as available oxygen supplies are depleted or minimized, a greater amount of products of incomplete combustion will result. Therefore, fire fighting strategies must include an appreciation of the effects of the fire retardant/suppressant materials and procedures to be utilized in the containment and elimination of a fire involving hazardous materials, or their byproducts.

From the combustion experiments, it appears that the temperature of intermediate scale pesticide fires are low (< 700°C). Due to the lack of oxygen in the flame root and to the low maximum temperatures, the combustion of the different pesticides studied was incomplete for all conditions investigated. Under these circumstances, components emitted in large quantities are:

- CO: between 3 and 15% of the available carbon content;
- SO_2: in parathion only (conversion of the available sulphur approximately 60%);

and

- HCl: in chlorfenvinphos, dichlobenil and 2,4-D compounds (conversion between 35 - 84% of the available chlorine).

Between 4 and 16% of the pesticides are also emitted as solids. Furthermore, hydrocarbons are formed in amounts of more than 10%, and approximately 1 - 30% of the pesticides remain as unreacted residues.

The emission of NO_2 varies from 1.1 - 2.5% of the available nitrogen. Of the available cyanide group in dichlobenil, 1.8 - 3.8% is converted into HCN.

The emission of PCDD/F (polychlorinated dibenzo-p-dioxins/furans) is lower than 12 - 36 µg TEQ **(Toxic Equivalent)** per kg pesticide. Only small quantities of NH_3, H_2S, Cl_2 and $COCl_2$ are formed.

Damage due to Release of Toxic Combustion Products

Serious health and environmental consequences may result from the release of toxic complete and incomplete combustion products because of individual (e.g., plant employees, fire fighters, and local residents) and environmental (e.g., waterways, ground water and soil) exposure. Run-off fire fighting water can become an important environmental pollution problem -- this was the major cause of damage in the 1986 Sandoz fire. In this event, fire in a warehouse containing numerous chemicals (pesticides) was fought by the fire department with large amounts of water. The fire fighting water became contaminated and, due to the absence of containment facilities, caused a severe pollution of the river Rhine.

PESTICIDE FIRES

As an illustration of the hazard potential of fires in installations and buildings involving chemicals, descriptions of a few accidents that occurred during the last 15 years are presented.

CASE HISTORIES

(a) In 1977, in Laytonsville (USA), (description in Isman, 1977, pp. 36-38) an electrical fire occurred in a garden centre. Due to the warm weather, fire fighters removed their protective gear while they were combating the blaze. Later, they were informed that toxic chemicals, including malathion and lindane were present and being burnt. Ninety-four persons, including 76 fire fighters and 7 policemen, required medical care and treatment. The immediate area was evacuated; 5 days later, the groundwater was found to be contaminated with sevin, kelthane and metasytox.

(b) In 1981, in a chemical pesticide plant in Groningen (Netherlands), a fire occurred in a mixer containing 2000 kg of a variety of chemicals, including chlorine, chalk, thalonyl and maneb. Ignition may have been caused by an overheated mixing shaft. During the fire a dense cloud was formed, but measurements indicated that there was no immediate danger to the residents in the surroundings. At 100 m downwind the sulphur dioxide concentration was measured to be 4 ppm (this is twice the NIOSH - US National Institute for Occupational Safety and Health - 10-hour occupational exposure limit and 80 % of the 15-minute exposure limit).

© In 1987, a fire occurred in an agricultural-chemical warehouse in Minot, North Dakota (USA). Over 60 different types of pesticides, herbicides and other agricultural chemicals were stored in the warehouse, the most dangerous being malathion, parathion and lindane. A dense smoke cloud developed and drifted over the town, requiring the evacuation of 10,000 residents. The cloud traveled more than 80 kilometres before it dissipated. One fire fighter required hospital treatment because of poisoning by chlorinated pesticides and 34 other people were sent to the hospital with a variety of symptoms.

At the time of the fire, local authorities decided to contain the fire, but permit it to "burn out" in order to limit the quantity of contaminated fire-fighting water. About 53 m^3 of runoff water was collected in a plastic-lined temporary lagoon at the site. Some runoff water contaminated a nearby stream. Local authorities dammed it about 1600 m downstream from the warehouse. Creek water samples showed a significant increase in concentration of 2,4-D. Soil samples from the warehouse premises indicated high concentrations of herbicides.

(d) In 1984, a fire occurred in a furniture warehouse in Sheffield (UK). The polyurethane upholstery intensified the initial fire. The fire fighters were hampered by the railway tracks within the building as they became obstacles to the movement of fire fighting equipment. The fire spread in several sections of the warehouse, into the roof voids or crawl spaces. The asbestos roof coating was ignited, contributing to the fire spread. The roof of the units where chemicals were stored completely collapsed. The particulate asbestos "fall-out" affected the public as far as 16 km from the fire, and 31 schools were closed until environmental health teams established that the schools were safe. During the weeks following the accident, at least 20 firemen complained about illness, especially tightness of the chest muscles, and skin and eye irritations.

From the case histories that have been studied by the TNO, it is estimated that in approximately 20% of the incidents, injuries occurred as a result of inhalation of toxic substances and another 20% were attributable to "unknown causes". In approximately 25% of the incidents, environmental pollution resulted from the release into the air of toxic substances and their by-products or contaminated fire-fighting water not being adequately contained. Fire-fighting water run-off containment by building temporary basins or dikes therefore appears to be a significant component of hazard mitigation/response plans.

1.2.3 Dispersion

Dispersion of gas or vapour released either instantaneously or continuously to the surrounding areas is a function of the quantity of the material released and the dispersive characteristics of the atmosphere (such as wind speed, stability). Gas concentrations in the surrounding areas must be calculated (or estimated) to determine the potential hazards to the population and live stock downwind from the hazardous event.

In the case of gas dispersion, a distinction must be made between:

- passive gas dispersion, and
- dense gas dispersion.

1.2.3.1 Passive Gas Dispersion Models

The passive gas dispersion models are usually based on the Gaussian plume model (this type of model assumes a normal distribution for concentrations within the plume; its standard deviation is specified as a function of atmospheric stability - the so called Pasquill classes - and distance from the source). In Gaussian models, dilution by the wind is taken into account through division by wind speed, but no consideration is given to the difference of the density between the ambient air and the gas, other than to calculate an initial plume rise if the release is hot. Because of this, the model must only be used for gases with a density approximately the same as air, or if the gas concentration at the point of release is low.

The Gaussian model is based on a point source. Continuous and instantaneous releases can be modeled. In case of area sources, such as a liquid pool, an imaginary (virtual) point source is assumed upwind of the actual source, so that the size of the cloud matches the source dimensions at the site of the actual source.

The limitations of Gaussian models include:

- calm wind conditions cannot be modeled; and

- they apply only to flat terrain; allowance is made, however, for the roughness of the terrain. The influence of trees, houses, etc. on dispersion can be determined by means of the roughness length.

1.2.3.2 Dense Gas Dispersion Models

If the gas has a higher density than air (because of a high molecular weight or marked cooling), it will tend to spread, because of gravity, in a radial direction. This results in a "gas pool", and, in contrast to a passive gas, the gas released may spread against the direction of the wind. Downwind from the source area, a dense gas will lead to a wide low-lying cloud, which is more difficult to disperse than a passive gas cloud. Whether the cloud will behave like a dense gas or not depends not only on its density relative to the air but also on emission flux, wind speed, and atmospheric turbulence. State-of-the-art models are the SLAB model developed by the U.S. Lawrence Livermore Laboratories (Ermak, 1990), the HGSYSTEM developed by Shell International in the Netherlands (McFarlane, et al., 1990), and the

COBRA model developed for the Canadian Atmospheric Environment Service (Alp and Matthias, 1991).

1.2.4 Models for the Calculation of Heat Load and Pressure Waves

If a flammable gas or liquid is released, damage resulting from heat radiation or explosion may occur if the released liquid or gas cloud is ignited. Models for the effects in the event of immediate ignition (jet fire, pool fire and BLEVE) and the ignition of a gas cloud are discussed in this section. These models calculate the heat radiation or peak pressure increase as a function of the distance from the jet fire, BLEVE, the ignited pool or gas cloud.

1.2.4.1 Jet Fire

If a releasing gas forms a cloud with concentrations between the lower and upper explosion limit (turbulent free jet) and ignition takes place, a jet fire occurs. A jet fire can also occur if a liquefied flammable gas flows out and is ignited.

Empirical models, to determine the degree of potential destruction, exist; these models consider the length of a jet fire and the thermal load for the surrounding area can be calculated (TNO, 1983; AIChE, 1989). The shape of a jet fire is assumed to be an ellipse; the volume of the jet fire is proportional to the outflow. In order to calculate the thermal load, the jet flame is simulated by a point source in the centre of the flame.