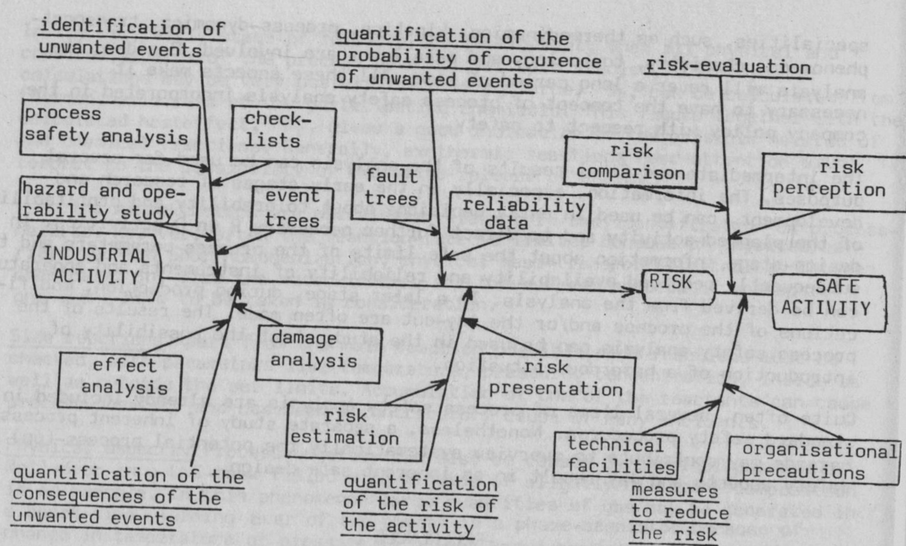

Figure 1 Review of a safety study

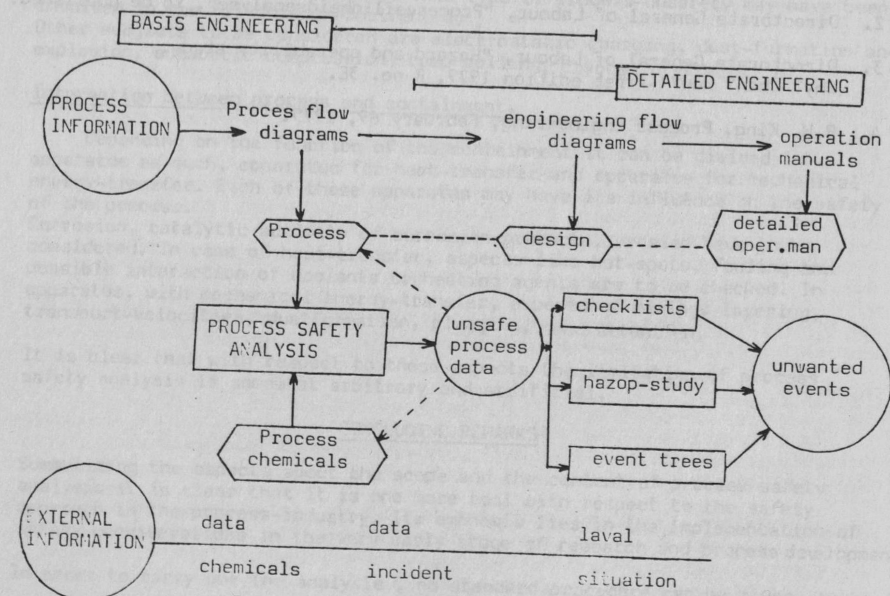

Figure 2 Relation between process safety analysis and the project-stages of a planned industrial activity

BULK STORAGE OF LPG - FACTORS AFFECTING OFFSITE RISK

M Considine, G C Grint, P L Holden*

Refrigerated storage of LPG is usually considered to be less hazardous than pressurised storage. In this paper the offsite risks posed by a 3000Te butane storage facility are examined. This quantity is such that either storage mode could be economically viable. Refrigerated storage in a single tank and pressurised storage in two equal capacity spheres are considered. Individual and societal risks are estimated for an urban site, with population encroaching to within 100m of the site boundary, and for a remote site, with population excluded from within 1km of the storage facility.

INTRODUCTION

It is often thought that the bulk storage of LPG in the refrigerated state poses less of a risk to members of the general public than were it to be stored at ambient temperature under pressure.

In order to examine this concept the offsite risks will be evaluated for a 1 x 3000 te refrigerated butane tank and for 2 x 1500 te pressurised butane spheres on an urban and a remote site. Whilst it is recognised that factors other than offsite risk play a major role in the choice of storage facilities these will not be considered further here although the quantity of 3000 te is such that neither method of storage would necessarily be precluded solely on economic grounds.

DESCRIPTION OF SITES AND FACILITIES

Site Locations and Descriptions

The hypothetical sites for the storage facilities are depicted in Figure 1.

Both sites have been taken as a square of side 500m with the storage facility located at the North West corner. The urban site is surrounded by a population of density 4000 per km^2 and housing encroaches to a distance of 100m from the boundary fence. For the remote site an exclusion distance for dwellings of 1 km centred on the storage tanks has been assumed.

*Safety and Reliability Directorate UKAEA, Culcheth, Warrington WA3 4NE.

For the refrigerated storage the edge of the tank is at a distance of 45m from the North and Western site boundaries and for the pressurised storage the surface of the sphere is at a minimum distance of 30m from the North and Western site boundaries. These distances were selected as representative of the minimum requirements under the various codes of practice (eg reference (1)).

Description of Plant

The refrigerated storage tank is a single skinned cylindrical fixed roof tank of height 12.6m and diameter 25.2m. It is surrounded by a layer of fire resistant insulation held in place by cladding and sits in a 2m high square bund of side 50m designed to contain 100% of the maximum tank contents (reference (2)). An outline of the main features of the facility is shown in Figure 2(a). The tank is instrumented for temperature, pressure and level readings and protection against overfill is by a second level gauge which at high level initiates an alarm and at a still higher level operates an emergency shutdown valve in the 150mm fill line and electrically isolates the pump. The liquid offtake line can be remotely isolated by a shutdown valve in the event of a serious leakage downstream from the storage tank. The tank is also fitted with a pressure vacuum relief system to prevent damage to the tank in the event of internal vacuum or overpressure. The relief system is designed to cope with expected gas flow rates in the event of the tank being engulfed in fire.

The pressurised storage consists of two spherical pressure vessels each of diameter 8.95m and each capable of holding 1500 tes butane. The spheres are separated by the minimum distance suggested in the codes (1) of 4.5m and have only a low kerb surrounding the storage area. An outline of the main features of the storage facility is shown in Figure 2(b). The 150mm liquid fill and offtake lines serve both tanks. The spheres are instrumented for level and pressure measurements and, as in the case for the refrigerated storage a second level gauge operates sequentially an alarm and emergency shutdown system in the event of overfill. Both spheres are fitted with drain valves, pressure relief valves and remote operated shutdown valves (ROVs) on the liquid offtake lines.

DESCRIPTION OF RELEASE EVENTS AND FREQUENCIES

Pressurised Storage

The simple assumption has been made that each sphere has 0.5 probability of containing the maximum inventory and 0.5 probability of containing half the maximum inventory at the time of failure. It is recognised that storage facilities will usually operate at lower inventory levels. The same total inventory probability distribution has been used in the refrigerated case. The frequency of catastrophic failure of a pressure storage vessel is taken to be 10^{-5} per year (as in reference (3)). A proportion of these failures are assumed to be explosive events producing fragments which will cause severe damage to the adjacent sphere, instantaneously releasing the inventory of both spheres. The remainder of the catastrophic failures are assumed to be failures of the main six inch diameter nozzle, or equivalent in size, i.e. leading to liquid flow through a six inch diameter orifice.

Complete severance ("guillotine") pipe failures are assumed to occur with frequency 3×10^{-7} m^{-1} yr^{-1}(4) leading to a flashing flow continuous release. An allowance for failures of pump and valve casings equivalent to full bore pipe discharge is included. In this instance operator action to close the remotely operated emergency valves is assumed to succeed in limiting the

release to the line contents with probability 0.8 (i.e. the operator fails to actuate the valve one time in ten, one ROV per storage vessel).

Overfilling a storage vessel produces a liquid release via the relief system. The release rate may be less than the filling rate depending on the relief arrangements (a multi-port relief valve system is assumed) and the pump characteristics. It has been assumed that the maximum pump head is not capable of causing vessel failure by overpressure. A high integrity level trip system would therefore not be installed - the overfilling frequency has been assumed to be 10^{-4} per vessel year, i.e. 2×10^{-4} per year total.

Guillotine failures of the 50mm diameter vapour return lines produce a prolonged release at nominally 1 kg s^{-1}: the only possible emergency action is to transfer the sphere contents.

The most likely operational failure leading to a release is associated with draining water from the spheres, or sampling, via a one inch line. A flashing flow release at 1.5 kg s^{-1} results. The frequency at which these operations are carried out would depend on the storage duty: draining has been assumed to be carried out once per week, sampling twice per week. The chance of error per operation, leading to a spill, is assumed to be 10^{-4}, implying a well designed and operated system. One in ten releases arising from drainage and one in a hundred arising from sampling are not isolated promptly.

The frequency of leaks from flanges, cracked lines, valves and pump seals, at nominally 1 kg s^{-1}, is estimated to be about 3×10^{-2} per year, based on component failure rates shown in Table 1. This category includes minor maintenance errors.

The basic release events and frequencies are summarised in Table 1.

Release rates are based on conventional discharge calculations, for example as reviewed in the Second Canvey Report (3).

Refrigerated Storage

The assumptions regarding total inventory are the same as for the pressurised storage case. Major failures of refrigerated vessels are assumed to occur at a similar rate to plant studied in the Second Canvey Report (3).

Catastrophic failure of the single walled vessel (e.g. due to fatigue) is assumed to occur with frequency 5×10^{-6} per year.

Rollover events, i.e. contact of cold and warm liquid due to stratification, resulting in a sudden vapour production surge, are assumed to occur, with sufficient severity to cause tank failure, with frequency 1×10^{-5} per year. As the vessel does not have a frangible roof joint, shell-base junction failure, producing a release equivalent to catastrophic vessel failure, is possible and has been assigned a probability of 0.25. The remaining failures are assumed to occur at the shell-roof junction, producing a vapour only release, with the possibility of a tank fire.

The basic overfilling frequency is assumed to be similar to the pressurised case, i.e. 1×10^{-4} per vessel year. However, a 50mm diameter overflow is provided, so that initially this event produces a liquid spill into the bund. Usually the operator will observe this and cease the filling operation, but one in ten of these events is assumed to continue until the tank is overpressured. As the relief capacity would be specified for fire engulfment it is most unlikely that the liquid filling rate could be accommodated and therefore tank failure occurs with frequency 1×10^{-5} per year. The distribution of tank failure modes is the same as for rollover.

Fractured liquid lines occur with the same frequency as in the pressurised case, but where in the pressurised case flashing flow determines the release rate the question of failure location and pump operation arises in the refrigerated liquid release case. One quarter of the pipework associated with the storage vessel is assumed to be inside the bund wall. The filling and discharge pumps are assumed to be immediately outside the bund. As the detailed pumping duty is not specified, the pump characteristics are not defined. The simplifying assumption has been made that all releases are driven by hydrostatic head, the pumping rate against low head would not be significantly different. Remote isolation within one minute is assumed with probability 0.9, as in the pressurised case.

Leaks from valves, flanges and pump seals, at nominally 1 kg s^{-1}, are assumed to occur at the same frequency as in the pressurised storage case, i.e. 3×10^{-2} per year. As there are less valves and pipework on the refrigerated installation, adoption of the same overall frequency implies a slightly higher base failure rate for these items on the refrigerated plant. This is considered to be in line with experience, although the data to support this view is limited. Pump seals on low temperature duty do have a higher failure rate than on pressurised service, but at the temperature of refrigerated butane storage this will not be significant.

Fractured vapour lines on the refrigerated installation are assumed to produce negligible releases.

A possible failure mode particular to the refrigerated storage case is by overpressure following a prolonged refrigeration failure. This fault would take some time to develop and a standby compressor is assumed to be available. Further, the relief system is assumed to consist of several manifolded valves, of which multiple or common mode failure would be required. Tank failure has occurred in similar circumstances (5) but this particular failure mechanism can be avoided by suitable design and so has been assigned a negligible frequency in this analysis.

The release events and frequencies are summarised in Table 2.

TABLE 1 - Pressurised Storage Releases

Failure Mode	Release Description	Basic Event Frequency	Release Quantity or Rate Against Frequency per year
1. Catastrophic Vessel Failure (Explosive)	Instantaneous release of contents of both vessels	3×10^{-6} per vessel year	3000Te – 1.5×10^{-6} 2250Te – 3×10^{-6} 1500Te – 1.5×10^{-6}
2. Catastrophic Vessel Failure (Equivalent to 6 inch nozzle failure)	Continuous liquid flow discharge at 15 Te min^{-1}	7×10^{-6} per vessel year	15Te min^{-1} for 100 min–7×10^{-6} 15Te min^{-1} for 50 min–7×10^{-6}
3. Fractured 6 inch Liquid Line (includes pumps, valves etc)	Flashing flow. Rapid release of line contents plus continuous release from storage if emergency shut off fails.	Pipework: 3×10^{-7} m^{-1} yr^{-1} Equivalent failure of fittings: 5×10^{-6} per item yr Emergency shut off failure probability 0.2	1Te instantaneously – 9×10^{-5} 1Te + 50 kgs^{-1} – 2×10^{-5}
4. Liquid Overflow from Relief vent due to overfill.	Release at approximately filling rate.	System designed for 10^{-4} per vessel year	30 kgs^{-1} – 2×10^{-4}
5. Fractured 2 inch vapour return lines.	Vapour release.	3×10^{-6} m^{-1} yr^{-1} for small diameter pipes.	1 kgs^{-1} prolonged – 6×10^{-4}
6. Serious Leaks from flanges, valves, cracked pipes, pump seals, etc.	Flashing liquid release at nominally 1 kgs^{-1}.	3×10^{-4} per flange, 6×10^{-6} m^{-1} yr^{-1} 6 inch pipe, 6×10^{-5} m^{-1} yr^{-1} 2 inch pipe, pump seals 5×10^{-3} yr^{-1}	1 kgs^{-1} – 3×10^{-2}
7. Maloperation: eg failure to isolate following draining or sampling.	Equivalent to flashing flow release from 1 inch line.	10^{-4} per operation. 10^{-1} fail to recover (draining), 10^{-2} (sampling). Drain 50 yr^{-1} sample 100 yr^{-1}.	1.5 kgs^{-1} – 6×10^{-4}

TABLE 2 - Refrigerated Storage Releases

Failure Mode	Release Description	Basic Event Frequency	Release Quantity or Rate Against Frequency per year
1. Catastrophic Vessel Failure (eg fatigue)	Refrigerated liquid spill, with possibility of bund overtopping	5×10^{-6} per vessel year	(1), (2) and (3a) 3000 Te : 2.5×10^{-6} 2250 Te : 5×10^{-6} 1500 Te : 2.5×10^{-6} Shell-roof failure: 1.5×10^{-5} (For overfill case release rate 50 kgs^{-1} prolonged)
2. Rollover		Severe rollover frequency assumed 10^{-5} per year. 0.25 probability shell-base junction failure, 0.75 shell-roof failure	
3a Overfill		Overfill frequency 10^{-4} per year, but 9 in 10 observed by overflow, see 3b. Tank failure modes as for rollover.	
3b Overfill	Liquid spill via 2 inch overflow.	Operator action to switch off pump limits to bund release 9 times in 10	Bund release 9×10^{-5} (50 kg s^{-1} for 1 min)
4. Fractured liquid 6" lines, includes nozzle failure, pumps,	Liquid spill inside or outside bund, pumped or hydro-static head. Operator action to close Rov limits most releases.	3×10^{-7} m^{-1} yr^{-1} pipes 5×10^{-6} yr^{-1} valve, pump casings.	In bund: 50 kgs^{-1} for 1min 2.2×10^{-5} 50 kgs^{-1} prolonged 2.2×10^{-5} Outside bund: 50kgs^{-1} for 1min: 2.8×10^{-5} 16kgs^{-1} for 1min: 4.2×10^{-5} 16kgs^{-1} prolonged: 5×10^{-6}
5. Leaks from flanges, cracked pipes, valves, pumps seals.	Liquid release at nominally 1 kgs^{-1}	Assumed similar to pressurised case.	1kgs^{-1} : 3×10^{-2}

IGNITION PROBABILITIES

The following factors were taken into consideration when assigning ignition probabilities to the various releases.

1. Size of the release - because of the size of the large releases delayed ignition at source was considered to be independent of wind direction and a large probability assigned as more ignition sources would be encompassed by the cloud.

2. Wind direction - for the small releases the probability of delayed ignition at source was reduced for those wind directions carrying the cloud/plume away from the site.

TABLE 3 - Ignition Probabilities before Population is reached

Release	Immediate Ignition at Source	Delayed ignition at Source	
		Wind over site	Wind not over site
Large Instantaneous	0.25	0.25	0.25
1 Te	0.25	0.25	0.1
250kg/s	0.25	0.25	0.1
50kg/s	0.25	0.25	0.1
30kg/s	0.15	0.15	0.05
16kg/s	0.15	0.15	0.05

The above table is applicable for both pressurised and refrigerated releases. The probability of ignition at the edge of population was taken as 0.7, and the probability of ignition over the centre of the population taken as 0.2. Both of these probabilities are conditional in that ignition must not have occurred previously.

VAPOUR CLOUD FORMATION AND DISPERSION

Pressurised Releases

The flash evaporation of commercial butane has been modelled by a mixture of butane and propane which gives a similar vapour pressure to the highest specified for commercial butane. An ambient temperature of 15°C has been assumed in the calculations and, at this temperature, instantaneous releases are found to entrain sufficient air (based on observation of rapid releases of large quantities of ammonia) to vaporise essentially all of the LPG released.

The dispersion characteristics of instantaneous releases resulting from vessel failure were evaluated using the SRD computer code DENZ (6). The dispersion ranges for the continuous releases, such as pipe breaks, were evaluated using reference (7).

Refrigerated Releases

When an atmospheric storage tank fails due to massive rupture or complete wall collapse a substantial portion of the tank contents may overflow the bund wall. Reference (8) provides empirical and theoretical solutions for the fraction of the inventory which overtops the bund. Using equations derived from reference (8) the amount of bunded and unbunded butane was calculated for each specified inventory. The SPILL code (9 and 10) was then used to evaluate the vaporisation characteristics for each case and the results combined to give the overall vaporisation characteristic for each inventory. Appropriate vapour evolution rates were taken from the combined SPILL results and the dispersion ranges calculated using reference (7).

Releases resulting from pipe breaks were also evaluated using Reference (7).

Dispersion Ranges for Pressurised Releases

TABLE 4(a) - Instantaneous

Release Size (Te)	Weather Category	Downwind range to LFL (m)
3000	D F	2530 4070
2250	D F	2260 3590
1500	D F	1940 3090
1	D F	117 140

TABLE 4(b) - Continuous

Release Rate	Weather Category	Downwind range to LFL (m)
250 kg/s	D F	437 691
50 kg/s	D F	200 309
30 kg/s	D F	151 239

TABLE 5 - Bund Overflow for Refrigerated Releases

Tank Inventory (Te)	Mass overflowing bund (Te)
3000	1500
2250	878
1500	375

TABLE 6 - Dispersion Ranges for Refrigerated Releases

Release	Weather Category	Downwind Range to LFL (m)
3000 Te	D F	1124 1793
2250 Te	D F	927 1465
1500 Te	D F	654 1035
50 kg/s	D F	207 327
30 kg/s	D F	117 185

NB All the refrigerated releases are continuous.

The SPILL results are shown graphically in Figure 3.

DAMAGE - INJURY CRITERIA

Injuries and Damage caused by blast

The Canvey Reassessment (3) provides a table of structural damage and casualty probability for various over-pressure ranges. This table (reproduced below) takes into consideration casualties as a result of flying fragments of glass and falling masonry as well as direct blast injuries.

TABLE 7 - Blast Damage Criteria

Peak Overpressure (psi)	% Casualties	Structural damage
<1	0	Window breakage
1-3	10	Walls collapse
3-5	25	Reinforced structures distort Atmospheric storage tanks fail
5-7	70	Wagons and plant items overturned
>7	95	Extensive damage

Injuries and Damage caused by Thermal Radiation

For long duration exposures (> 30 seconds) we have adopted the following criteria:

q_t > 12.6 kW/m^2 secondary building fires possible people both indoors and outdoors at risk

q_t > 4 kW/m^2 people outdoors at risk

The latter figure represents the flux which would cause skin blistering after ca 30 seconds this time being taken as representative of the time it may take to seek shelter.

For durations < 30 seconds the fluxes necessary to cause skin blistering and fibreboard ignition (11) were adopted as the criterion for injury to people outdoors and secondary fires respectively.

All people inside the secondary fire radius are assumed to become casualties. Only those outdoors will be at risk between this radius and the radius for hazard range to people. The probability of being outdoors is taken as 0.15 as in reference (3).

COMBUSTION MODES FOR LPG RELEASES AND ASSOCIATED HAZARD RANGES

Combustion modes

The way in which LPG releases burn is dependent on a number of factors amongst which are

(i) the conditions under which the material is released eg temperature, pressure, rate of release, quality of release, distribution between gaseous and liquid phases etc.

(ii) the nature of the flammable cloud at the point of ignition eg its size, shape, composition, degree of confinement etc.

(iii) the nature of the ignition source.

The modes of combustion can conveniently be described in terms of whether the flames are (a) premixed or diffusion and (b) stationary or propagating.

Pool fires and "torches" are examples of stationary diffusion flames. Both represent combustion of the release at source. A necessary prerequisite for pool fires is that the release gives rise to the formation of a liquid pool. Pool fires are, therefore, more likely for releases of liquids stored below their boiling point or for pressurised releases with low flash fractions. Torches describe the combustion of gas or liquid spray from pipework. They will be most likely for pressurised releases.

Fireballs and diffusion flash fires are examples of propagating diffusion flames. They occur following the ignition of a cloud the bulk of which is above the UFL. The edges of the cloud, however, will be within the flammable range due to diffusion with the surrounding air. Ignition is possible at such points and may be followed by rapid flame propagation through the flammable regions so that the central rich core of the cloud is enveloped in flame. Subsequent burning is controlled by the rate of entrainment of air and its mixing with fuel and will be a relatively slow process. Rather than having a well defined "flame front" the whole of the cloud will appear to be on fire - combustion taking place at eddy boundaries where the fuel/air composition is in the flammable range. Under these circumstances the cloud burns as a fireball. Where the cloud is of large diameter to height ratio then diffusive burning at the point of ignition may be complete before flame is able to propagate around the whole of the cloud surface. The cloud will then burn more as a flash fire with a thick band of flame making up the reaction zone. Fireballs are more likely following ignition of a hemispherical or spherical cloud such as will exist shortly after a pressurised release. Diffusion flash fires are more likely following ignition of clouds with heights much less than their maximum width or lengths eg those formed by "slumped" hemispherical clouds, by evaporation from liquid pools or plumes from "continuous" releases.

Propagating premixed flames occur when a cloud of gas mixture inside the flammable range is ignited. The flame propagates outwards from the ignition source consuming the mixture. For very low propagation speeds the rate at which hot combustion products are generated is low and so expansion can take place easily without any significant overpressures being generated. Under these circumstances the cloud will burn as a flash fire.

As flame speeds increase combustion products are generated more quickly so that pressure is built up both ahead of and behind the flame front. At flame speeds > ca 170-200 m/s the overpressures are sufficient to cause extensive damage both within the cloud and outside it as the pressure waves propagate and decay in the atmosphere beyond the burning cloud. In this paper we have referred to an event that produces damaging overpressures as an explosion.

The following method has been used in defining the combustion mode for clouds and is diagramatically represented in Figure 4.

(i) Determine whether the bulk of the cloud is above UFL at the point of ignition. For pressurised releases the approach adopted in reference (3) in determining the source cylinder prior to cloud slumping and atmospheric dispersion suggests that sufficient air is entrained during formation of the source cylinder to take the mean concentration of the cloud just below UFL. In the case of pressurised releases combustion at any point other than at source is likely to be of the premixed kind.

For refrigerated spills the range to a concentration of twice UFL was taken as the onset of premixed burning. This value was chosen to reflect uncertainties in the amount of air entrained during the evaporation phase and concentration inhomogeneities in the cloud.

(ii) For diffusion flames determine whether the cloud burns as a fireball or diffusion flash fire. The cloud size and shape, nature of fuel and location and timing of ignition may all have a bearing on whether the cloud burns as a flash fire or fireball.

The nature of release will influence the cloud shape. If the release is from a burst pressurised container the rich cloud is likely to be hemispherical or even spherical. For evaporating liquid pools the rich cloud often takes the form of a "pancake" with large diameter to height ratio. Prolonged releases give rise to a "cigar" shaped plume. In the case of pressurised bursts burning diffusively the cloud shape is such that a fireball is most likely whereas for evaporating pools and pipework releases a diffusion flash fire is more probable.

(iii) For premixed flames determine whether the cloud explodes or not. Mechanisms are as yet not well developed for the flame acceleration processes that give rise to the high flame speeds required for overpressure effects. Hydrocarbon reactivity, cloud concentration, homogeneity, size and configuration, confinement, turbulence, strength of ignition source are all believed to be contributory factors in determining the flame speeds and one has to make a judgement on the probability of overpressure developing. Historical experience shows that for an explosion the following requirements are necessary (12).

(1) the vapour cloud must be large ~ 5 te or more for hydrocarbons

(2) the rate of release of vapour must be large ~ 1 te/min or more and

(3) a significant delay before ignition usually greater than ca 30s is required.

The original Canvey report (13) adopted a philosophy based on historical data that took account of cloud sizes and reactivity in assigning a probability of explosion, P_E, following ignition. The following values were employed for hydrocarbons and have been used in this paper:

For release < 10 te, $P_E = 0$

For release 10-100 te, $P_E = 0.1$

For release > 100 te, $P_E = 1$

Where the vapour cloud is formed from a pressurised burst the whole of the release is assumed to make up the cloud. Where the vapour cloud is formed over several minutes then the inventory in the cloud is taken as the product of the release rate and residence time of material in the cloud.

Thermal radiation will pose a hazard from all of the above modes of combustion. For fast propagating premixed flames blast damage also needs to be taken account of.

The general approach adopted in determining thermal radiation and blast damage is reviewed in the following sections.

Thermal Radiation Hazards

Heat transfer from a flame to a "target" outside the flame will be primarily by thermal radiation. The radiative flux at a target q_t is given by the expression,

$$q_t = F_{ts} \ \tau \ \alpha_t \ q_s$$

where q_s is the flux from the surface of the flame, τ is the atmospheric transmissivity, α_t the absorptivity of the target and F_{ts} the view factor.

F_{ts} is dependent solely on the geometry of the flame and receiver. For an infinitessimally small target area ie a differential area the view factor will depend on the size and shape of the flame and the range and position of the target relative to the flame. Tables and analytical expressions are available in heat transfer text books for a wide variety of flame shapes.

Now rearranging the above expression we get

$$F_{ts} = \frac{q_t}{q_s . \alpha_t . \tau}$$

If we define the thermal radiation hazard as corresponding to a given target flux q_t then in order to determine the range of this hazard we need

(a) q_s, α_t and τ to evaluate F_{ts} and

(b) Flame shape, size and relative position of target to flame to evaluate the hazard range from F_{ts}.

For simplicity τ and α_t have been taken as unity although for long hazard ranges τ can have a value significantly less than one.

Source Fluxes. For pool fires we have adopted a value for q_s of 170 kW/m^2 (14). Recent work on large LPG pool fires does, however, indicate that volumes of dense black smoke may be responsible for reducing this value to as little as ca 50 kW/m^2.

For diffusion flash fires one would expect the radiative flux to be similar to that from a pool fire although reference (14) indicated the flux from LPG vapour fires to be as high as 260 kW/m^2 and we have used this figure in this paper. Similar behaviour in LNG vapour fires was attributed in reference (15) to a degree of "premixing" in the vapour fires.

Fireballs and torches usually emanate from ignition of a pressurised release close to source when there is still a high degree of turbulence remaining. Values quoted for q_s are typically in the region of ca 350 kW/m^2 (3).

Premixed flash fires are perhaps the hardest to place a value of q_s on. If the cloud is well mixed the flame will be non luminous and relatively thin so that emissivities much less than unity are possible. On the other hand the flame will be much hotter. Inhomogeneities in the cloud may mean that pockets may still be rich, see Maurer et al (16). Here we have chosen the value that has been ascribed to diffusion flash fires of 260 kW/m^2.

Evaluation of Thermal Radiation Hazard Ranges

Pool Fires and Torches. For unbunded spills the diameter of the pool can be determined using the SPILL code (9). For bunded spills the maximum diameter of the pool is limited by the size of the bund. Flame heights have been determined using the Thomas correlation (17).

For torches the length and diameter can be determined using the approach set out by Craven (18). Although primarily for gas releases the methods can be successfully used in predicting the size of fires from flashing liquid releases, reference (19).

Knowing the size, shape and radiative output from the flame permits hazard ranges to be determined. In the case of torches the flame length has been used to define the maximum range of a release that would give rise to flame impingement on a pressure vessel with the possibility of a BLEVE.

In this study we have not considered the effect of wind on flames. For very large fires likely to give rise to an offsite hazard the effect of wind can increase the hazard range. The overall impact on the risks, however, is not dramatic. A wind that blows the flame towards one section of population will in the examples considered in this paper also be blowing the flame away from another section of population. Furthermore when taking into account the effects of wind one must also account for the probability that the wind is of a certain strength and blowing in a given direction.

Fireballs. In order to evaluate fireball hazard ranges we initially need to know their duration in order to set a value for q_t corresponding to the effects in which we are interested. Using the value of q_s as suggested in the previous section enables a corresponding value for F_{ts} to be determined.

A knowledge of the fireball diameter and F_{ts} then yields the hazard ranges for injuries to people outside and for secondary fires. Correlations for size and duration are given in reference (2), (21) and (22).

Diffusion and Premixed Flash Fires and Explosions

For pressurised bursts the cloud is assumed to be of cylindrical shape of height and diameter determined as in reference (3). For clouds generated over a period of time the plume will be "cigar" shaped. This has been approximated to a rectangular box when evaluating thermal radiation hazard ranges.

For rich clouds ignition at the edge causes a thick band of flame to propagate through the cloud. The view factor for a given target will vary with the relative position of the flame and target.

Hazard ranges have been evaluated on the following basis:

(i) Determine maximum cloud width, R, and height, δ, at time of ignition

(ii) Evaluate flame height H_f, width R_f and thickness W_f using empirical expressions (reference 15)

$$H_f \simeq 5\delta$$

$$R_f \simeq R$$

$$W_f \simeq H_f$$

(iii) Determine maximum view factors for person perpendicular and parallel to direction of flame propagation.

(iv) Evaluate hazard ranges on basis of 10 second exposure to maximum flux. Although exposure times may well be somewhat lower for premixed burning for simplicity the above criterion was adopted to take account of uncertainties in the value of q_s for premixed flash fires.

Blast Hazards

Blast hazards arise only from fast propagating premixed flames and the method employed here is to determine hazard ranges based on the TNT model described in reference (23).

EVALUATION OF RISKS

For each release four cases were examined viz immediate ignition at source, delayed ignition at source, ignition at the edge of population and ignition over the centre of population. In each case risks were evaluated for the urban and remote sites.

Immediate Ignition at Source

Immediate ignition of a quasi instantaneous pressurised burst was assumed to always give rise to a fireball. Immediate ignition of a "continuous" pressurised release was assumed to always give rise to a torch. In all cases the torches by themselves presented no direct risk to population although all within range of one of the butane spheres were considered to pose a threat of vessel BLEVE. For each release the probability of escalation to a BLEVE was evaluated taking into account such factors as the chance of ignition at source, whether the torch length and direction was such as to impinge on the vessel, the rate of heat input into the vessel and duration. The total frequency of torching was estimated at 3.4×10^{-3} per year and the frequency of vessel BLEVE as 7.1×10^{-5} per year (50% 1500 te BLEVE's, 50% 750 te BLEVE's).

Immediate ignition of a refrigerated spill was assumed to give rise to a pool fire. For the large "instantaneous" release the possibility of bund opertopping may result in a proportion of the burning release spreading beyond the bund confines. All prolonged spills that burn in the bund were assumed to eventually escalate to a full bund fire as a result of distortion and failure of the bottom outlet. It was considered that the presence of the fire resistant insulation would preserve the integrity of the tank itself under such circumstances. Only those releases able to overtop the bund or to give rise to a full bund fire posed any offsite risk from burning at source.

For each release the individual and societal risks from immediat ignition at source were evaluated using the following expression:

$$\text{Individual risk (I.R.)} = \text{Probability of release } (P_{rel}) \times \text{Probability of immediate ignition } (P_{ii}) \times \text{Probability of becoming a casualty } (P_c)$$

A person directly North of the installation and on the edge of population was chosen as being the individual who would be at most risk and all estimates of individual risk were based on this person.

Releases as a result of escalation (eg full bund fires and BLEVE's) were also assessed in this manner.

For societal risk it is necessary to determine the probability of an event (in this case a fireball or pool fire) and the associated number of casualties, N.

The probability of an event, $P_e = P_{rel} \times P_{ii}$

and the number of casualties, $N = \Sigma N_c P_c$ where N_c is the number of people within each casualty band of probability P_c.

Drifting Clouds

Where ignition is not immediate any vapour cloud formed may drift on the wind before subsequently igniting. This ignition may be local to the release (termed here delayed ignition at source) at the edge of population or over the centre of population.

For a delay in ignition as opposed to immediate ignition at source two factors need to be considered in determining risks.

(a) There may be a transition from diffusive to premixed burning and

(b) The quantity of material in any vapour cloud formed may increase with time.

For quasi instantaneous pressurised bursts only a short delay is necessary before premixed combustion becomes possible. The transition from diffusive burning occurs near the end of the formation of the initial cloud. In those cases where rupture of one vessel may fail a second then the inventory of this second vessel may also contribute to the mass of fuel in the cloud. In this study explosive failure of one of the butane vessels was assumed always to lead to rupture of the second. The quantities of fuel making up the cloud are all much greater than 100 te and therefore the probability of explosion on delayed ignition has been taken as unity.

In the case of refrigerated releases or pressurised pipework releases the vapour plume is formed over a period of time and can remain attached at source. In these cases ignition at source would lead to flame propagating through the plume followed by continued burning at source (either as a pool fire or torch). The burning at source will have similar consequences to those described under immediate ignition at source.

Where the plume reaches population before it is ignited then the consequences of subsequent ignition at source or at the edge of population will be similar. The possibility of delayed ignition at source as opposed to at population when a cloud has passed over the edge of population was considered low.

There will, however, be intermediate cases where ignition takes place at source for plumes of substantial size but yet unable to reach population. These cases are most important for the larger vapour evolution rates (>50 kg/s) and where the population is remote (ie 1 km in this case from the storage site). To take account of such events it was assumed that delayed ignition always occurred so as to maximise the risks from such an event. A condition for ignition was that the plume had not travelled beyond LFL.

For each of the three ignition cases individual risks were determined for every release in the following manner

(i) Define a wind direction and weather category (D or F) with associated probabilities P_{wind} and $P_{weather}$. In this assessment 12 wind sectors were considered and all were assigned an equal probability (.083). The probability of category D weather was taken as 0.9 and of category F weather as 0.1.

(ii) For edge, central and delayed ignition at source the probability of casualty, P_c was determined for the defined individual. Edge and central ignition were conditional on the population being within range of LFL for the particular release

(iii) For edge and central ignition

$$\text{I.R.} = \Sigma P_{rel} \times P_{weath} \times P_{wind} \times (1 - P_{ii} - P_{dis}) \times P_{ip} \times P_{FF/EX} \times P_c$$

where P_{dis} is the probability of delayed ignition at source for the defined wind direction and P_{ip} is the probability of ignition at the edge or centre of population.

$P_{FF/EX}$ is the probability of the release burning as a flash fire/fireball or explosion (based on cloud inventory and concentration) and P_c the associated probability of becoming a casualty.

The sum is over all wind directions for both edge and central ignition and it was necessary to repeat the calculation under weather categories D and F and for flash fires/fireballs and (where appropriate) explosions.

(iv) For delayed ignition at source

$$\text{I.R.} = \Sigma P_{rel} \times P_{weath} \times P_{wind} \times P_{dis} \times P_{FF/EX} \times P_c$$

Again the calculation was repeated for D and F weather categories and for flash fires/fireballs and (where appropriate) explosions.

(v) Where burning at source ensues then this must be taken into account when setting a value on P_c.

Societal risks were evaluated for each release on the following basis.

(i) Define a wind direction, weather category and associated probabilities.

(ii) The probability, P_d, of a drifting cloud burning at the edge of or over population was evaluated for each wind direction by the expression for edge and central ignition.

$$P_d \text{ (for each wind sector)} = P_{rel} \times P_{weather} \times P_{wind} \times (1 - P_{ii} - P_{dis}) \times P_{FF/EX} \times P_{ip}$$

where the remaining terms are as previously defined. Again this expression is conditional in each case on the cloud reaching population whilst remaining flammable.

(iii) The total number of casualties N was determined by taking the sum of products of casualty probability P_c and number of people N_c in each probability band.

$$\text{ie } N = \Sigma N_c P_c$$

This procedure was repeated for D and F weather categories for edge and central ignition and for flash fire/fireballs and (where appropriate) explosions.

(iv) The probability of a drifting cloud undergoing delayed ignition at source P_d^1 was evaluated for each wind sector by the expression

$$P_d^1 \text{ (for each wind sector)} = P_{rel} \times P_{weather} \times P_{wind} \times P_{dis} \times P_{FF/EX}$$

(v) In each case the number of casualties was evaluated as above.

(vi) Again the calculations were performed for D and F weather and for flash fires/fireballs and (where appropriate) explosions.

(vii) In all cases where continued burning at source ensues the additional casualties from this were also taken into account.

Individual and Societal Risk Values

The Individual and Societal risks determined in the above manner are presented in Tables 7, 8 and 9 for pressurised and refrigerated releases on remote and urban sites.

TABLE 7 - Individual and Societal Risks for Immediate Ignition

	Urban Site					Remote Site				
	$IR\times10^{-6}yr^{-1}$	$SR\times10^{-6}yr^{-1}$ For more than N casualties				$IR\times10^{-6}yr^{-1}$	$SR\times10^{-6}yr^{-1}$ For more than N casualties			
		>10	>100	>1000	>5000		>10	>100	>1000	>5000
Pressurised										
1500 Te	34	36	36	36	36	5.4	36	36	36	36
750 Te	5.4	36	36	36	-	5.4	36	36	36	-
Refrigerated										
3000 Te	0.59	0.63	0.63	0.63	0.63	0.094	0.63	0.63	-	-
2250 Te	1.19	1.25	1.25	1.25	-	-	-	-	-	-
1500 Te	0.59	0.63	0.63	0.63	-	-	-	-	-	-
Full Bund Fire	2.19	2.30	-	-	-	-	-	-	-	-

TABLE 8 - Individual and Societal Risks for Delayed Ignition

Release	Urban Site IRx10^{-6}yr^{-1}	Urban Site SRx10^{-6}yr^{-1} For more than N casualties >10	>100	>1000	>5000	Remote Site IRx10^{-6}yr^{-1}	Remote Site SRx10^{-6}yr^{-1} For more than N casualties >10	>100	>1000	>5000
Pressurised										
3000 Te	0.86	0.95	0.95	0.95	0.95	0.18	0.94	0.94	0.94	0.04
2250 Te	1.7	2.0	2.0	2.0	2.0	0.36	1.84	1.84	1.84	0.09
1500 Te	0.86	0.95	0.95	0.95	0.95	0.13	0.93	0.93	0.93	0.004
1 Te	5.22	-	-	-	-	-	-	-	-	-
250 kg/s	10	10.6	6.7	0.21	-	0.0002	0.022	0.022	-	-
50 kg/s	6.61	10.2	0.18	-	-	-	-	-	-	-
30 kg/s	37	62	1.6	-	-	-	-	-	-	-
Refrigerated										
3000 Te	1.1	1.1	1.1	1.1	0.91	0.12	1.1	1.1	0.025	-
2250 Te	2.2	2.3	2.3	2.3	0.05	0.033	0.23	0.23	0.05	-
1500 Te	1.1	1.1	1.1	1.1	-	0.009	0.09	0.09	-	-
50 kg/s	4.94	5.29	.083	-	-	-	-	-	-	-
50 kg/s (1min)	20.1	51.5	-	-	-	-	-	-	-	-
16 kg/s	0.13	0.19	-	-	-	-	-	-	-	-
16 kg/s (1min)	0.26	-	-	-	-	-	-	-	-	-

TABLE 9 - Summary of Individual and Societal Risks

Storage Mode	IRx10^{-6}yr^{-1}	SRx10^{-6}yr^{-1} For more than N casualties >10	>100	>1000	>5000
Urban Site					
Pressurised	102	159	84	76	40
Refrigerated	35	66	7.1	7.0	1.6
Remote Site					
Pressurised	12	76	76	76	36
Refrigerated	0.26	2.0	2.0	0.08	-

DISCUSSION

The intention of this paper is to demonstrate the potential of risk assessment methodology for identification of the important factors affecting offsite risk, for comparison of alternative designs and for evaluation of the importance of siting considerations. Because a limited number of cases, involving simplified assumptions, have been studied, specific conclusions may not necessarily translate to other installations on other sites. In comparing the risks in Table 9 the reason for the relative values in the four basic cases studied must be carefully considered, particularly where the results have been strongly influenced by the basic assumptions.

Considering the estimated risks for the urban site, there is less than a factor of three between the maximum individual risk in the pressurised case and in the refrigerated case. There is a similar factor between the frequencies at which significant offsite casualties (ie more than ten casualties) are estimated to occur for each case. This factor has no great significance in risk assessment terms. This similarity between the pressurised and refrigerated cases arises because the frequency of a serious accident is similar for each installation and the population is so close that, in either case, the most exposed individual is very likely to be affected. However, accidents leading to large numbers of casualties (ie more than 100) are an order of magnitude less likely in the refrigerated case. This is because, whereas in the pressurised case the possible outcome of the dominant smaller releases is escalation to a BLEVE, in the refrigerated case the dominant small releases may escalate to a full bund fire, via failure of the bottom outlet. The consequences of a BLEVE are much more severe than those due to a full bund fire. The absolute risk values are significant, but not necessarily higher than criteria that have been suggested. For example, the first report of the Advisory Committee on Major Hazards (24) states that if "...in a particular plant a serious accident was unlikely to occur more often than once in 10,000 years (ie 10^{-4} per year) ... this might perhaps be regarded as just on the borderline of acceptability ...". Most of the accidents considered in this paper would, if they occurred, produce more than ten offsite casualties. Even if only a few were fatalities this would be unprecedented in the UK and would undoubtedly be considered to be a "serious accident". If this interpretation is reasonable, the risk from both installations on the urban site is close to this borderline. The individual risk values are lower than many everyday risks to which we are exposed. However, as the precise purpose of the installation has not been specified, the additional risks posed by other activities on the site are not included. For example, a road or rail loading facility for pressurised butane would be expected to considerably increase the overall risk, particularly if it were close enough to the main storage for interactions to be possible.

If we consider the pressurised installation on a remote site, ie with a population exclusion distance of 1 km, the maximum individual risk is found to be about an order of magnitude lower than for the urban site. This is partly because many of the smaller events cannot affect an individual 1 km away from the plant. Additionally, population at this range will only be affected by a BLEVE if they are outdoors. However, a considerable populated area is still within the hazard range from this type of event and so, although only one in six become casualties, the total number of people affected by any such accident is still large. Because ignition at source accidents can affect the population in this way, the total societal risk, dominated by these events, is very similar to the urban pressurised installation. Wind direction and weather conditions have little effect on the risks since the contribution of delayed ignition events is small.

The similarity in societal risk between the urban and remote sites for the pressurised installation is due to the particular case studied and the assumptions made concerning the location of population. The 1 km separation distance would achieve a greater risk reduction for smaller plants: if the largest possible fireball involved about 250 te LPG there would be no casualties beyond 1 km. However, in this example, very much larger fireballs are possible as the inventory selected is at the high end of the range covered by pressurised storage, to make the comparison with refrigerated storage meaningful. The population distribution assumptions were chosen partly for convenience in calculation and are obviously artificial. It is most unlikely that an urban density of 4000 per km^2 would be present in all populated areas around the site, particularly in the "remote" example. At first sight this might not appear to affect the risk relationship between the urban and remote sites, but other assumptions could have been made producing different results. For example, if the populated area were assumed to lie behind an infinitely long line parallel with the north site boundary, the maximum individual risk, for the individual at 100m and 1 km north of the storage, would be very similar to those calculated in this paper. However, the ratio of populated areas affected by a BLEVE in these two cases would be very different from the ratio of populated areas affected in the examples studied in the paper. As these events dominate the overall risk from the pressurised installation a much greater reduction in societal risk would be obtained by the 1 km exclusion distance. This illustrates that each individual case will have its own particular features and should therefore be considered separately.

A different pattern emerges when we compare the refrigerated installation on urban and remote sites. Although the largest possible pool fire can still affect the population on the remote site, the likelihood of this event is low and delayed ignition events, ie drifting vapour clouds, become significant contributors to the total risk. Whether an individual is affected by a drifting vapour cloud depends on wind direction and, in most cases, weather conditions, since all but the largest vapour clouds will only reach the population under inversion conditions. A constant density population distribution around the site has been assumed, together with an equal probability of wind direction for each 30° sector. Wind direction therefore has no effect on the societal risk in this example. Because only the largest and most

unlikely events can affect the most exposed individual, and then usually only under certain wind and weather conditions, the maximum individual risk for the refrigerated installation on a remote site is two orders of magnitude lower than for the same installation on an urban site. The societal risks are also very much lower. The absolute values of risk for the remotely sited refrigerated plant are low and would be considered by many not to justify pursuit of reduction.

Comparison of the two types of plant on remote sites reveals the risks to be much lower for the refrigerated plant. One particular reason for this is the different consequences of escalation of relatively small releases. A BLEVE can still affect population 1 km away from the pressurised plant, whereas a full bund fire cannot affect population 1 km away from the refrigerated plant. As would be expected, the benefits in terms of limiting offsite risk are considerable by the combination of a plant with inherent safety advantages, sited away from population.

This study highlights the point that the offsite risk from an installation storing liquefied flammable gas is a function of several factors. In addition to the likelihood of a release of flammable material, consideration of the different eventualities which may occur when a flammable release is ignited is important. As would be expected, siting of the plant is also important.

The authors conclude that, if there were a genuine choice between these installations, and all other things being equal - which of course they rarely are - the refrigerated plant would be clearly preferable, due to the significantly lower chance of an accident causing more than a hundred casualties on an urban site and significantly lower individual and societal risks on a remote type of site. If there were other factors affecting the choice, which are outside the scope of this paper, the estimated offsite risks should be considered in conjunction with these in an attempt to arrive at a balanced view of risks, costs and benefits.

The outline designs of the pressurised and refrigerated units for this paper were based on current codes of practice. Neither unit could be considered to meet only the minimum requirements of such codes but, because some features are regarded as optional in the codes, there is scope in each case for reduction of offsite risk, with associated cost penalties, by additional design features. For example, in the case of the pressurised storage spheres, the likelihood of a BLEVE may be reduced by installation of fixed water sprays (although their ability to protect against torch impingement is uncertain) or some other fire protection system. Because of the importance of BLEVES in the pressurised case a significant reduction in risk might be obtained by such means. A secondary containment could be considered for the refrigerated storage tank and a higher bund would reduce the risk of bund overtopping. The authors hope to consider the effect of such additional features on offsite risk in a future paper.

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SYMBOLS USED

F_{ts}	view factor
H_f	flame height
N	number of casualties
N_c	number of people within a particular casualty probability band
P_c	casualty probability
P_d	probability of a drifting cloud burning at edge of or over population
P_{dis}	probability of delayed ignition at source
P^1_d	probability of a drifting cloud undergoing delayed ignition at source
P_e	probability of an event which produces offsite casualties
P_E	probability of an explosion on ignition
$P_{FF/EX}$	probability of flash fire or explosion
P_{ii}	probability of immediate ignition
P_{ip}	probability of ignition at edge of, or over, population
P_{rel}	probability of a release of butane
$P_{Weather}$	probability of particular weather conditions (ie neutral or inversion)
P_{Wind}	probability of wind blowing into a particular 30^o sector
q_s	radiative heat flux from flame surface
q_t	radiative heat flux at target
R	cloud width
R_f	flame width
W_f	flame thickness
α_t	absorptivity of target to thermal radiation
δ	cloud height
τ	atmospheric transmissivity

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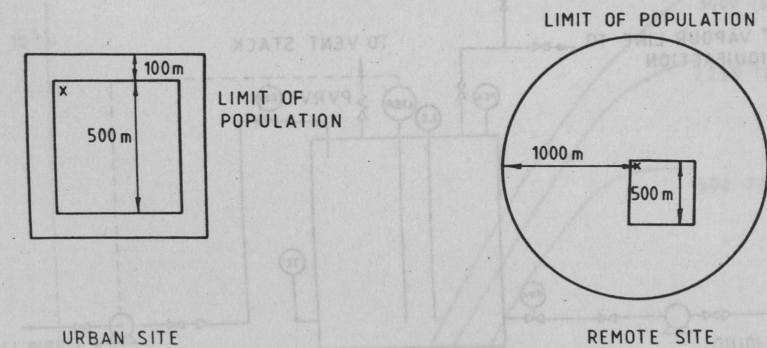

Figure 1a Location of Population around the Site.

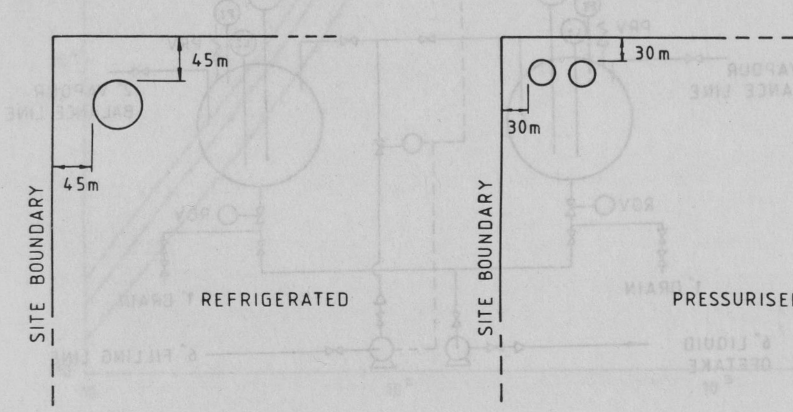

Figure 1b Position of Storage and Boundary Fence

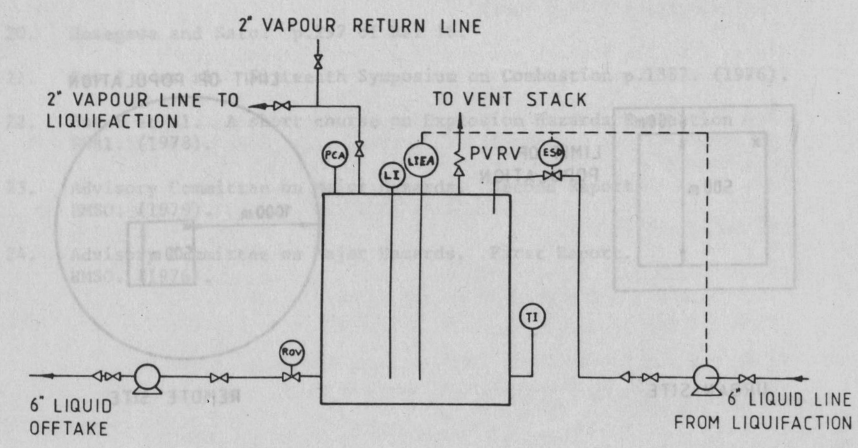

Figure 2a Outline for Refrigerated Storage of 3000Te Butane showing main Features

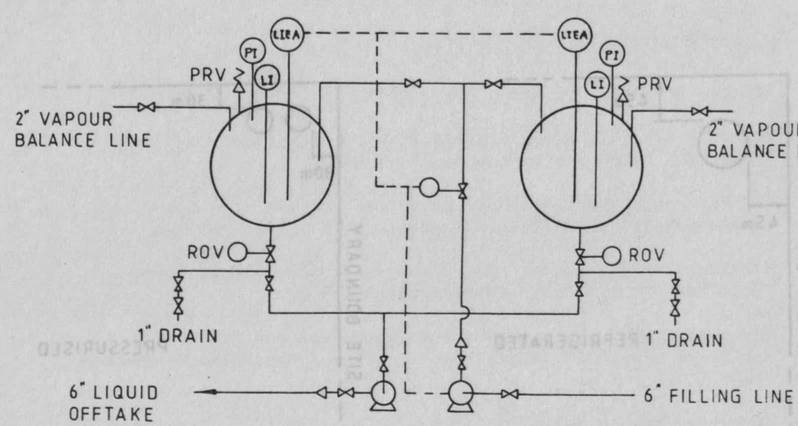

Figure 2b Outline for Pressurised Storage of 3000Te Butane in Two Spheres showing main Features

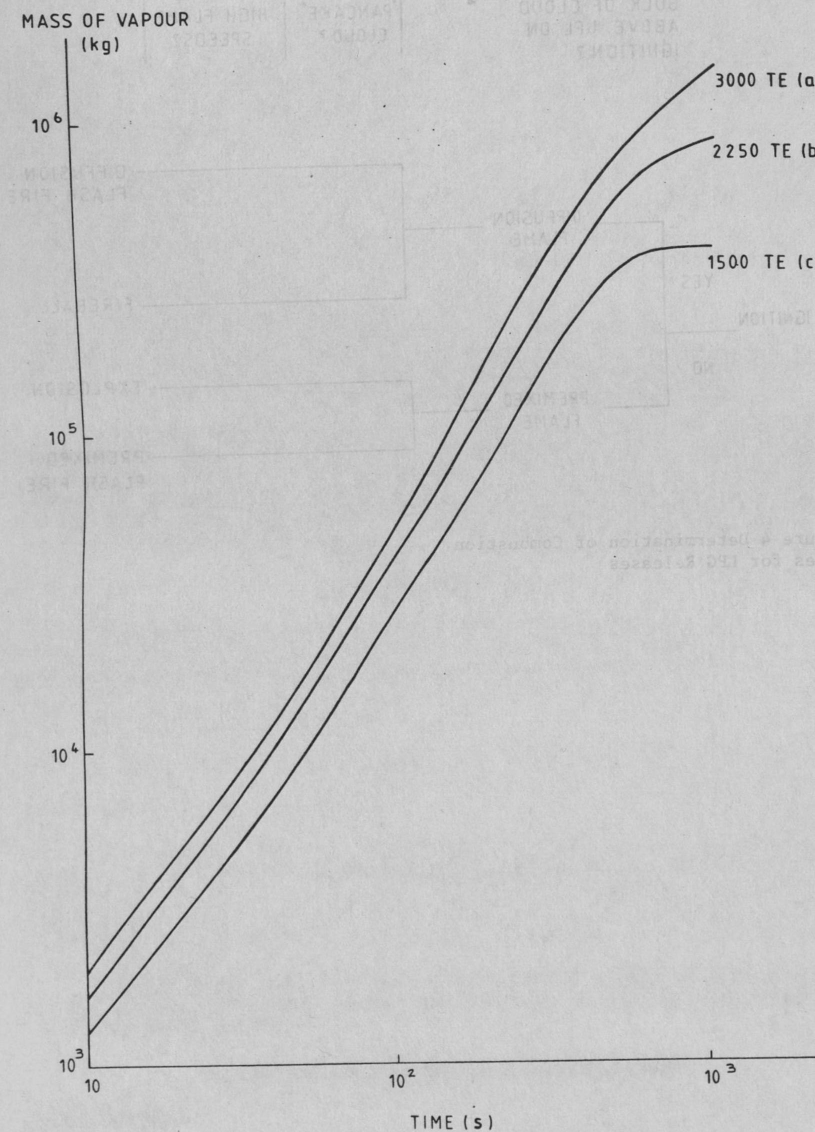

Figure 3 Curves Plotted from Spill Results for Instantaneous Releases of Refrigerated Butane

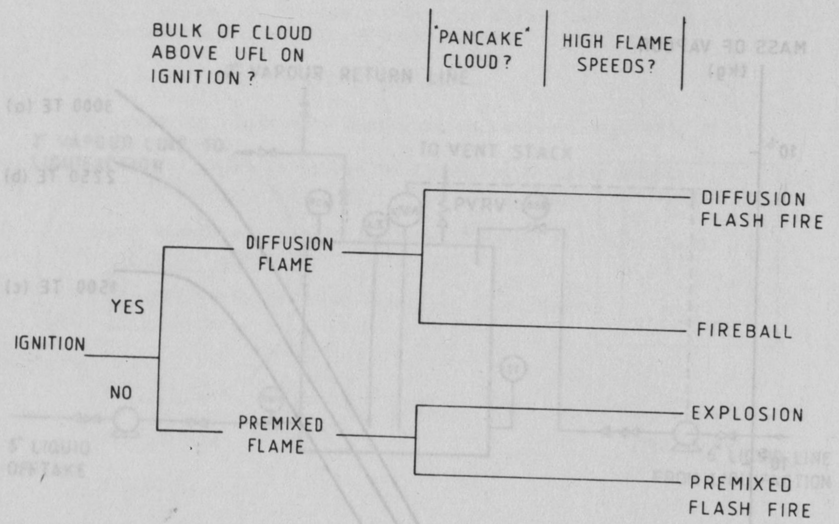

Figure 4 Determination of Combustion Modes for LPG Releases

the plot but within the site and outside the site.

Chemical plant design of which process design, layout design and engineering design form parts, takes place in three stages, (Mecklenburgh (11)). Stage one (variously called preliminary, conceptual, proposal, front end or definition) design occurs before design sanction. Stage 2 (called intermediate, secondary or sanction) design leads to the sanction of construction. Stage 3 design after sanction consists of detailing.

The main object of the stage one design is to provide sufficient information so that the feasibility, e.g. cost, economics, hazard, risk and environmental and social impact of the proposed project can be estimated with sufficient accuracy for approval in principle by the sponsor and for new sites, by the regulatory authorities. The sponsor then allocates funds for stage 2 design and if applicable, site purchase.

One purpose of stage 2 design is to provide detailed costs for the full sanction of the project by the sponsor. A second, equally important purpose is to give comprehensive hazard, environmental and social assessments to the regulatory authorities in order to obtain detailed planning permission.

After sanction the final detailed designs for construction are produced based on the stage 2 design plus any constraints imposed by sanction, contract or planning approval. This stage is most time consuming and any subsequent change to the layout can be very costly both in money and delay through extra design effort and reapplication for planning approval. Consequently hazard assessment should only be needed to be undertaken in stages 1 and 2.

RELEVANT HAZARDS

The proposed procedure considers the following four hazards:

a) Overpressure from unconfined vapour cloud explosions (UVCE)

b) Thermal radiation from fires

c) Toxicity effects of vapour clouds

d) Flammability of vapour clouds.

In the first three, the consequences lead to fatalities, injuries and damage. The fourth item is not strictly a hazard but a property, but it is convenient to treat it as a hazard. It leads to the first and second hazards and flammable limits are used, as a precaution to define electrical classification zones and the separation of sources of ignition from flammable leaks.

A fifth hazard that of chemical and physical attack is covered indirectly as items (b) and (c) above require the determination of the size and position of liquid pools and jets.

THE PROBLEMS OF DEVISING AN ASSESSMENT SCHEME

Ideal Approach

The probability that a loss of containment will cause a given amount of damage or fatalities to a particular target can be split into three separate probabilities, those of loss of containment, transmission and damage.