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EXPERIMENTS AND MODELLING:- AN OVERVIEW WITH PARTICULAR REFERENCE TO FIRE ENGULFMENT

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SUMMARY

The paper considers general modelling and experimental requirements before discussing the problems associated with losses from containment of pressurised liquefied gases. Computer models for assessing the consequences of fire on LPG type storage vessels are reviewed together with the experimental data currently available for model validation purposes.

1 INTRODUCTION

The quantities of gases stored and transported as liquids under their own vapour pressures ie. as pressurised liquefied gases, have increased considerably over the last two decades. In most industrialised countries this trend is likely to continue for many years yet, because liquefied gases are used by the chemical and petrochemical industries in vast quantities, as the raw materials for many products eg. feedstocks and fertilisers from chlorine, ammonia etc or as hydrocarbon fuels (LNG, LPG, Butane). The processes and products utilising liquefied gases in a typical industrialised country are chemical production (organic and inorganic), transportation (fuels), domestic and industrial heating, and electricity production.

There are three main categories of liquefied gases, 1) pressure storage ie. liquefied gas under pressure and at ambient temperature; 2) semi-refrigerated storage ie. liquefied gas under pressure at low temperature and 3) fully refrigerated storage ie. liquefied gas at atmospheric pressure and very low temperature. It is the first and second of these categories that are of primary concern because they are a greater hazard. Generally speaking pressurised liquefied gases in commercial use are either toxic or flammable, although some gases have both properties e.g. acrylonitrile. Further sub-divisions are the relatively small inventories of acutely toxic and persistent chemicals (carcinogens). The more commonly used of the liquefied gases are listed in Table 1, which is reproduced from Vilain[1].

It is because of their potentially harmful properties, together with the large inventories often stored, that many liquefied gases are deemed to be potential major industrial hazards. The traditional, mainly retrospective

TABLE 1

Boiling point and typical storage (pressure) of common chemicals

Paraffins	Methane	Ethane	Propane	Butane	Pentane	
B.P °C	- 164	- 88.6	- 42	- 0.5	36.1	
Storage	F.R.	-	8-10 b	3-4 b	A	
Olefins	Ethylene	Propylene	1 Butene	2 Butene (cis)	1 Pentene	
B.P °C	- 103.7	- 47.4	- 6.3	3.7	29.9	
Storage	80 b (piped)	P	P	P	A	
Industrial	Hydrogen	Oxygen	Nitrogen	Chlorine	Ammonia	Acetylene
B.P °C	- 259.1	- 209.8	- 218.4	- 34.6	- 33.3	- 84
Storage	F.R.	F.R.	F.R.	8-9 b	10-12 b	cylinders A
Others	Vinyl-chloride	Ethylene-chloride	Ethylene-oxide	1-2 Butadiene	Benzene	Acrylo-nitrile
B.P °C	- 13.4	83.5	13.5	10.85	80.1	77
Storage	P	A	1-2 b	-	A	A

F.R. = fully refrigerated
P = liquefied under pressure
A = ambient storage

safety approach of learning from experience, developing codes of practice, devising precautions and stipulating operating instructions have become unacceptable because of the scale of possible accidents. Thus, in parallel with the increasing inventories and accidents, methodologies have developed for assessing the hazards and risks posed. The use of fault tree analysis, hazard analysis, hazard and operability studies etc, have now become widespread in an attempt to anticipate possible hazards and where possible reduce the likelihood of their occurrence. As a consequence, without being complacent, it may be argued that accident controls have more or less kept pace with the growing use and the increased hazard potential of the substances involved. Nevertheless a number of major accidents involving releases of both flammable and toxic gases have occurred during the past two decades.

Two objectives of hazard assessments are, firstly to quantify the hazard and the risk of it occurring, and secondly to reduce the risk. The two are connected but are not identical. Much of the value of a hazard assessment lies in the discipline produced and in identifying the weaker links in the overall system. The hazard assessment of a particular process, storage or transport system examines the consequential events resulting from what are considered to be credible failures. An integral part of this assessment is the need to utilise models and modelling techniques to both assess and predict the hazards and their consequences. Thus a considerable amount of research effort, both nationally and internationally, is being devoted to developing suitable models and validating them against acceptable experimental data.

The paper discusses modelling and experimental requirements, the various modelling approaches currently used, and model validation in the light of available data. The consequences and physical processes involved in losses of containment of pressurised liquefied gases are discussed. Particular consideration is given to the fire attack on storage and transport vessels containing flammable pressurised liquefied gases as the majority of the papers presented at this conference relate to this aspect.

2 EXPERIMENTS AND MODELLING

2.1 Basic Philosophy

'Models' in the context of this paper are taken to mean systematic quantitative techniques used for predictive purposes, whether these be graphical techniques, analytically-derived equations, correlations of experimental data, or computer programmes. The proof of any model is in its ability to make reasonably accurate predictions within its acknowledged limitations. However, practical constraints may be imposed upon a model or modelling technique. For instance, if the model is one of a number which could be called upon during a hazard assessment, then the factors that assume importance are, ease of use (the user may not be totally familiar with the basis of the model), efficiency (in terms of computing requirements), the user's confidence in its physical basis and in its predictions. Other desirable features may be versatility, numerical stability, and the knowledge that it has been checked against acceptable experimental data.

Models for assessing what may happen for a clearly defined set of circumstances may differ considerably in their predictions. One reason being that each model makes various assumptions about the nature of the complex physical processes involved. Often the physics of the processes are not well understood and their description in the model involves a good deal of empirical input. This input often comes from experiments carried out on a much smaller scale than that of concern in the industrial context. Furthermore the appropriate scaling laws may not be well understood or cannot be completely satisfied on a different scale. In these circumstances one approach is to carry out 'large-scale' experiments in order to provide data to, 1) enable predictive models to be validated, 2) further the understanding of the physical processes and test model hypothesis and 3) provide information on scaling criteria so that better use can be made of laboratory or small scale tests.

The user may also need to know that the model is 'valid', ie. that the predictions of the values needed to assess a particular hazard agree with the results of representative experiments to an extent which is consistent with the uncertainty in the available data, and the accuracy required for the hazard assessment. The situation is by no means clear cut, and it is to be expected that competing models will differ in the degree of validity they have, according to the parameter that is being considered. For instance, a model may predict one property with acceptable accuracy but may not do so for others, or it may in achieving acceptable results for one parameter require unrealistic values to be used for others. Perfect agreement would not of course be a reasonable objective and acceptable tolerances or error bands need to be imposed from the outset.

Moffat[2] asks the question, "When a good theory and a good experiment differ, how much difference can be overlooked before one must conclude that a disagreement exists?" He concludes that the question cannot be answered until the uncertainty on both counts is properly documented. In controlled experiments it may be estimated and reduced by appropriate design. However in modelling the sources of error lie in the assumptions and simplifications used to arrive at a tractable model, in the empirical constants used, and with more complex models in errors associated with the numerical and computational procedures.

2.2 Model Validation

The majority of the physical processes of interest, in the context of this paper, are statistical in nature rather than deterministic, eg. the structure and nature of turbulent flows. Consequently any characterisation must resort to statistical principles. Ideally the mean of any property should be defined from ensemble averages, but in practice this is technically impractical on the large scale, as it requires many replicate runs of an experiment in order to assess the variability. However it may be possible on the small (laboratory) scale under carefully controlled conditions. This raises the question of what to accept as an alternative averaging procedure. The position is by no means clear but usually the parameters are assumed to be statistically stationary, and time-averaged quantities at a point are substituted.

It may be argued that the aim of model validations should be to determine whether predictions of a particular parameter fall within the observed error bands of that parameter with the frequency indicated, and if not whether the failure is attributable to sampling fluctuations or is due to the failure of the model hypothesis.

Models may be assessed in a number of ways such as by direct comparisons of model predictions with the equivalent parameters derived experimentally. There are no hard and fast rules and 'selected' trials or data sets are chosen for comparison. There may be good reasons for doing this ie. some trials within a series may not have produced a complete data set possibly because of instrumentation failure. Nevertheless, for an objective assessment of model performance one needs to be satisfied that there has been no judicious choice of data.

Other assessment methods are comparisons of non-dimensional quantities (arising from the framework of a model) with observations, or parametric sensitivity studies of models. Both of these may prove particularly useful for understanding the scaling properties of models and the examination of the validity of the modelling of the physical processes and process parameters. Finally the optimisation of empirical constants within a model by comparison with experimental data, although not strictly speaking model validation, can shed light on the way the models perform.

2.3 Experimental Requirements

Any experimental data set relating to events that are stochastic in nature must ideally be regarded as one of a number of replicate trials under the nominally identical conditions necessary to obtain ensemble averages. Usually a large number of replications (possibly 100) are required to obtain stable estimates assuming that identical conditions can be reached in the first place. In many situations, particularly where turbulent fluid flows are of importance, true replication cannot be achieved, but in addition there is a practical constraint of cost, especially with large scale trials. Often the test conditions for small scale laboratory tests, although not necessarily an exact simulation of the real event, can provide replicated conditions at a reasonable cost. Experimental trials are often planned within a framework of extending an already existing data base. Thus taken as a whole, the extant field and laboratory experiments provide a range of observations which may be appraised collectively, and as such should provide more information on aspects such as scaling criteria than is possible from an experiment conducted in isolation.

Any test data not only needs to be as comprehensive as possible within the constraint of a budget, but it must also provide 'core' data which can be used for testing as wide a range of models as possible. The test conditions must be clearly established and defined as precisly as is practical. The results provided should include estimates of random and systematic errors for individual sensors, combinations of sensors, the data collection system, and the processed information.

3 LOSS OF CONTAINMENT

Commercially, it is the ability to store, transport and process certain gases in liquid form which make them attractive. However from a safety viewpoint it is this which makes them so hazardous, since for a given volume of material stored, liquefied gases generate the largest vapour clouds on release. The manner of the release contributes significantly to the degree of hazard. The worst case is a pressurised liquefied gas release at ambient temperature as the sudden release to atmospheric pressure causes a proportion of the superheated liquid to flash evaporate rapidly to vapour. If the expansion is rapid enough the vapour may drive a blast wave into the surrounding air. Thus the primary aim of any hazard assessment must be to maintain the integrity of the storage system. However, the consequences of any loss of containment must automatically be considered, and steps taken to minimise them.

3.1 Partial and Total Losses

The consequences of any loss of containment, particularly with pressurised liquefied gases, are often classified in terms of whether a total or a partial failure occurs. The former implies sudden rupture of the vessel leading to the immediate release of the whole of the contents. A partial loss implies a jet-type of release, the nature of which is dependent upon the size and location of the failure. A relatively small leak from a vapour space may result in an all vapour release in the form of a high-velocity jet emission. Whilst a larger breach in the same region may result, at least initially, in a high-quality two-phase flashing jet, due to liquid carry over brought about by boiling and swelling of the contents as the pressure falls. A loss from the liquid region may result in either an all liquid jet which may subsequently flash evaporate, or the establishment of two-phase flashing flow through the breach itself.

The release of an initially saturated liquid from a pressure vessel, either as a result of a total or a partial failure, is subjected to a decaying pressure field. Consequently the liquid accelerates as well as flashing. The latter is a relatively rapid process because the heat required for the phase transition is available within the liquid itself. Hence, an adiabatically flashing liquid always results in a two-phase mixture at a lower temperature than the original (vessel) temperature. Consequently the process is governed by an interaction of hydrodynamic and thermodynamic phenomena, in which non-equilibrium effects predominate in the early stages of the process.

3.1.1 Modelling total losses

A liquid-vapour release following a total loss is usually termed a BLEVE (boiling-liquid-expanding-vapour-explosion). The overpressures generated are usually minimal, however tank or vessel fragments may be projected over large distances because a relatively high proportion of the energy released is imparted to the fragments.

Upon catastrophic failure the vessel's contents are assumed to be released in two stages. An initial rapid (adiabatic) depressurisation occurs during which the pressure-energy causes a fraction of the liquid to flash to vapour (flash fraction). A large cloud is thus formed comprised of both vapour and liquid droplets, some of which fall as rainout. The two phases may not necessarily be in thermal equilibrium nor moving at the same radial velocities. During the second stage air entrainment, turbulent mixing, and heat transfer effects predominate, resulting in further liquid evaporation and an increased size of vapour cloud.

Theoretical studies of the expansion processes are described in the literature(3-4). Generally speaking these assume that isentropic flash evaporation of the superheated fluid occurs initially with both thermal and velocity equilibrium existing between the vapour and liquid phases. Enhanced turbulent diffusion coefficients are often used to model the increased turbulent mixing which occurs during the momentum-dominated expansion phase of the cloud formation process.

Experimental studies are reported(5-6) in which scaling, cloud growth, energy partitioning and turbulent mixing effects have been examined. In the majority of these studies releases of fluids such as propylene, propane, butane and freons were made from spherical or cylindrical vessels under controlled conditions. Some experiments have included measurements of overpressures and combustion behaviour. The practical difficulties of scaling up from relatively small experimental releases to the industrial scale are recognised. However the costs of large scale trials are likely to remain prohibitive unless undertaken on a collaborative basis.

In some industrial accidents, unexpectedly high overpressures were reported, which it has been suggested(7) may be as a result of a high initial liquid superheat combined with rapid depressurisation. This may lead to the superheat limit locus being exceeded resulting in homogeneous nucleation and an increase in the intensity of the explosion. Although this is possible in theory, the experimental evidence available at present is not wholly supportive.

3.1.2 Modelling partial losses

The jet release resulting from a partial vessel failure may be either single or two-phase depending upon the inlet quality and the geometry of the breach. Mass flow rates, pressure losses, etc for single phase releases are obtained using existing well documented and validated modelling procedures for both liquids and gases. The storage pressures utilised in practice will result in sonic or choked flow limiting the mass efflux rate with all gaseous releases. If in these circumstances the exit pressure is greater than ambient, then further expansion occurs outside of the breach, and the resulting under-expanded jet may become supersonic locally. The structure and decay of under-expanded jets has been reviewed recently by Ramskill(8).

The dispersion of jet releases has been studied extensively. Two stages to the process are usually identified, firstly a high velocity jet or momentum-dominated phase, and secondly a plume dispersion phase when the jet velocity is comparable to the windspeed. During this latter phase, buoyancy and atmospheric turbulence control the mixing and dispersion processes. A number of recognised modelling procedures are currently used for assessing the dispersion, these include similarity or integral procedures. Complex 3-D turbulence field models have also enjoyed a limited amount of success. More recent developments have attempted to incorporate combustion effects into the turbulence modelling scheme.

All vapour jet releases, because of the rapid mixing are, in the case of flammables, soon diluted to concentrations well below their LFL. Thus when plume-type behaviour becomes predominant it is usually only the dispersion of toxic materials that is of importance. This may not be the case with two-phase jet releases, as fig 1 illustrates. This shows a release of liquid propane at 5 bar pressure in a calm stable atmosphere. Despite the initial jet momentum and air entrainment these have not proved sufficient to prevent buoyancy effects from dominating, and a large flammable heavy gas cloud has developed at ground level.

In contrast with single phase jet releases, the currently available knowledge of the dispersive properties of two-phase flashing jets is limited as a recent review by Appleton(9) has highlighted. Considerably more parameters influence the structure of the jet. For instance the geometry of the opening influences its composition because it governs the degree of flashing which occurs prior to release. Non-equilibrium conditions are considered to exert a significant influence on the spatial and temporal droplet size and velocity distributions in the liquid phase. The observed sudden expansion of the jet is assumed to produce a change in the turbulence levels and momentum exchange rates.

Current modelling methods have either applied the basic conservation equations globally under equilibrium conditions, or have applied the same principles to the two phases separately. The latter approach has been developed extensively in the nuclear industry for examining multi-phase blow-down phenomena in pipes, as reviewed by Wolf(10). He concludes that numerical codes offer considerable potential, but whilst computing costs remain high, attention is likely to focus upon devising more efficient and economical solution algorithms, together with better defined interphase transfers coefficients especially with regard to their realisation and range of applicability. Experimental work may also focus upon this area aided by advances in optical techniques.

3.2 Flammable and Toxic Releases

The direct risk to people and nearby plant structure from fire is burning by direct flame or by thermal radiation. The extent of any burning cloud following a total sudden release of a pressurised liquefied flammable gas is substantial, and as a consequence so is the fire or thermal radiation source. This is also true of a burning two-phase flashing jet release, where the observed flame lengths are considerably greater than those associated with an all vapour jet from the same size of orifice and with the same driving pressure. The surface emissive powers of burning jets or fireballs, because of their highly turbulent structure, are usually considerably greater than those from liquid hydrocarbon pool fires. Values in excess of 200kW/m^2 have been observed from burning jets of LPG.

Toxic releases can result in the production of large lethal clouds, which

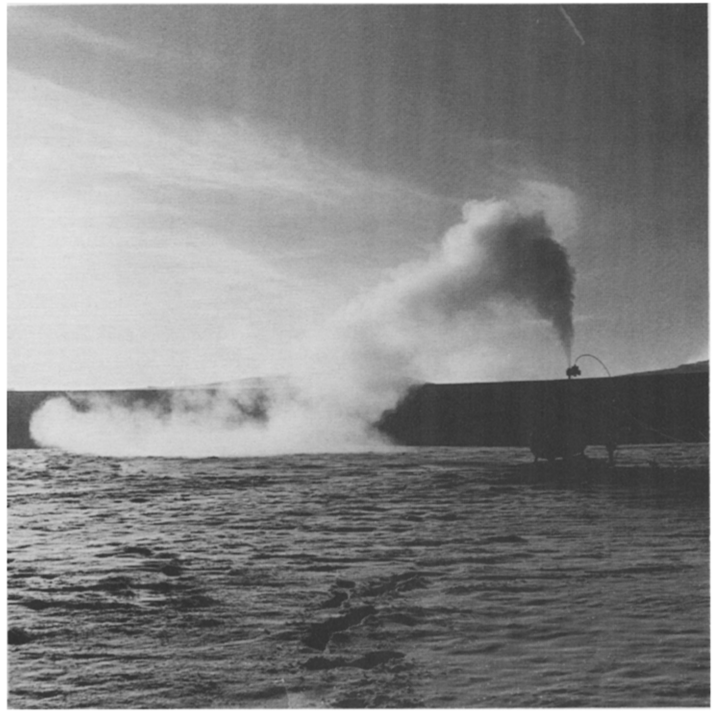

Fig. 1 - Two-phase jet release of propane (reproduced from HSE data)

may be potentially harmful for distances well beyond the local confines of the storage site. The nature of the hazard presented is dependent upon the conditions of exposure. Toxic releases, unlike flammable ones, are harmful only if direct exposure of the target occurs, however much greater dilution (to a few ppm) is required before the substance becomes harmless.

Toxic releases are almost invariably denser-than-air and their effective dilution and dispersion is very dependent upon the atmospheric conditions pertaining at the time of release. This may not of course be true of toxic releases which occur during a fire when the buoyancy within the fire plume can be expected to dominate the early stages at least of the dispersion process.

Toxic releases, initiated as a result of a total vessel failure, lead to the immediate formation of large vapour clouds, with relatively little dilution. On the other hand, jet releases from partial vessel failures have high initial momentum, which act to increase the rate of atmospheric entrainment and hence the degree of dilution achieved.

A considerable amount of effort has been expended over the past few years on improving our understanding of the dispersion processes of negatively buoyant and passive releases. Both experimental and theoretical studies are reported in the literature, as reviewed by Wheatley [11].

4 MODELLING FIRE ENGULFED STORAGE TANKS

Fire is the most likely event to initiate a vessel failure which leads to release of the contents. Although other initiators, such as impact, overpressure from an explosion, or earthquake damage must also be examined in storage and transport assessments. Fire attack on a pressure vessel creates an overpressure and eventual failure due to structural weakening, as all steels at sufficiently high temperatures, undergo a reduction of their yield and ultimate strengths. However, at sustained elevated temperatures steels also undergo creep, and creep strengths may become the limiting design factor.

Fire attack may be one of three modes or a combination of modes: 1) total or partial pool fire engulfment, usually the result of a 'large-liquid' leak, 2) jet flame impingement, resulting from the burning of a single or two-phase leakage under pressure or from the controlled flaring of discharges through pressure relief systems, 3) thermal radiation from nearby or off-site fire events. There are consequential effects with jet flare impingement such as increased ventilation of any additional pool fire attack, high thermal stressing, and distance effects, ie. noise and thermal radiation.

An assessment of the effects of the received heat upon the vessel and its contents requires knowledge of, the modes of heat transfer, any thermal stratification which occurs within the contents, and the bulk or subcooled

TABLE 2 Currently available models for predicting the consequences of fire attack

Model Title	Date	Originating Body (Author)	Modes of fire attack modelled	Vessel Contents modelled	Vessel Type	Modes of Protection	Comments
CALSPAN		Transport Canada	Total pool fire	Pressurised liquified gases	Horizontal cylinder	Uninsulated	Basic code in public domain
ENGULF I	1984	SRD/HSE (Ramskill)	Total pool fire	Liquified gases multi-comp.	Any	Uninsulated & insulated. Water spray protected	A cuboid based model with three nodal points in the shell.
ENGULF II	1987	SRD/HSE (Ramskill	Total & Partial pool fires jet flares	Liquified gases multi-comp. gases	Horizontal cylinder. Vert cyl. & sphere to follow	Uninsulated & insulated	Later version of above in cylindrical coords. Enhanced fire modelling.
HEAT-UP	1987	SHELL RESEARCH (Beijnon)	Total pool fire engulfment	Pressurised gases	Horizontal cylinder	Uninsulated & insulated	2-D computer code for horizontal cylindrical propane tanks. Pressure relief valve operation is modelled accurately.
TNKCAR	1985	Davis Engineering (Birk)	Engulfing & 2-D torch fire	Propane n-butane n-pentane propylene	Horizontal cylinder various orientations	Uninsulated insulated radiation shielding Explosafe	Computer code predicts wall temps, internal press. liquid level & time to failure.
-	1987	Birk	As above	As above	As above	As above	Later modular version of TNKCAR
-	1984	UNB (Venart)	Total pool fire engulfment	Pressurised liquified gases	Horizontal cylinders	Uninsulated & Internal protection inc. Explosafe.	First version based on CALSPAN modified to include valve interaction with heat transfer modes.
-	1987	UNB (Sousa)	Total pool fire engulfment	Pressurised liquified gases	Horizontal cylinders	Uninsulated & internally protected	Current UNB Code
SAFIRE	1986	DIERS	Total time engulfment	Pressurised liquified gases	Any	Uninsulated	Wide ranging computer code for relief vent sizing which also includes external heat source.
-	1974	AAR	Total pool fire engulfment	Propane	-	-	No further details
-	1984	Nylund	Jet & Total fire engulfment	Process vessels gases only	-	Uninsulated	Code with failure routine for gas filled vessels only

boiling once the pressure relief system has operated. Interactions between the vent operation and the thermodynamic and hydrodynamic states of the fluid contents cannot be ignored, as the establishment of two-phase flow within a vent system has a significant influence on its overall performance and relief capacity.

The currently available models known to the author, and which assess the thermal response of both the vessel and its contents when subjected to fire attack, are listed in Table 2. All of the models are presented as computer packages, some of which are 'menu-driven'. Many will operate on micro's as well as mini and mainframe computers, although the run times may be prohibitive especially when repeat runs forming part of an overall assessment are contemplated.

4.1 Engulfing Fire

Most of the models listed in Table 2 cater specifically for total pool fire engulfment, some however can be modified relatively easily to model partial engulfment or radiant heating. In a pool fire models assume that the tank is engulfed to varying degrees by flame and hot combustion products. Thus the tank receives both radiant heat from the flames and convective heat from the hot gases. The absolute values and percentages of these two components depends in practice upon a number of parameters such as, 1) the nature and type of fuel, 2) its combustion characteristics, 3) the local meterological conditions, 4) the size and extent of the fire, 5) optical thickness of the flame, 6) the size of the tank, and 7) the thermal properties of the tank. Thermal data pertaining to various types and sizes of pool fires are available in the literature as reviewed by Mudan[12]. Modelling methods for specifying the fire flux require the average heat flux received by the tank to be specified over the area of engulfment. This may take the form of a direct heat flux specification or as a radiative component requiring a representative flame temperature and a surface absorptivity to be specified. Clearly such approaches are not an accurate representation of the complex interactions which govern a true fire. However, they are considered to provide a sufficient degree of realism. They enable the user to exercise an engineering judgement of what the fire conditions are in any particular situation. Spatial and temporal heat flux variations (which characterise a typical fire) are ignored in view of the thermal capacity of the tank and its contents. An enhancement used by Sousa et al[13] allows circumferential radiative and convective heat flux component variations to be specified.

Hydrocarbon pool fires are usually quoted as having average heat outputs in the region of 100-120 kW/m^2, the lower value is used in most codes of practice as the basis for sizing pressure relief valves to cope with a fire attack (no account being taken of non-uniform heating effects, nor of the maximum wall temperatures likely to be attained).

The burning jet which results from the ignited release of a vapour or vapour/liquid at pressure, may have a higher heat flux output than a pool fire due to increased turbulence and mixing. Should such a jet engulf a tank then the consequences may be more severe than those of pool fire engulfment, because of the localised nature of the fire attack. A similar characterisation is required from a modelling view point. The total heat flux is again considered to be comprised of radiative and convective components. However the energy partitioning may differ, and may not be constant. The heat flux distribution under the 'wall-jet' is non-uniform and the hot gases can reach zones of the tank well away from the direct impingement zone. The physical modelling of this situation is highly complex even if steady-state conditions are assumed to exist. The assumptions of one and two-dimensional heat conduction through the tank walls are not valid and a three-dimensional solution must be sought, usually based on finite difference or finite element solution procedures. Alternatively if a uniform heat flux is assumed over the heated area then a network analysis approach may provide representative results, as suggested by Ramskill[14].

The received radiative heat flux from a distance source is usually treated as an area or point source of constant flux, which is calculated by well developed methods. Atmospheric transmissivity can produce heat flux variations but these can also be estimated and accounted for. The surface absorptivity of the receiver may also be considerably less than unity, the value usually assumed for flame engulfment. Flames which are selective emitters may require a more rigorous analysis in order to obtain a representative heat flux. In some instances the target may be close to a boundary consequently the respective view factors of the source to target and vice-versa become significant when assessing the radiative heat exchange.

4.2 Wall Heat Conduction

Most of the current models assess the heat conduction through and within the vessel walls by solving the 2-D heat conduction equations in the radial and circumferential directions, using finite difference solution procedures. Although an alternative 1-D solution procedure with single nodal points in the liquid and vapour walls is used by Ramskill[14] for analysing total fire engulfments. In practice considerable temperature variations, especially in the vapour space tank walls, are to be expected and have been observed. These are not of course only dependent upon the nature of the fire, as compositional changes in the internal fluid boundary layer, modes of heat transfer, and operation of the PRV etc., can all create feedback effects which will influence the tank wall conduction.

4.3 Heat Transfer to Contents

As the tank liquid and vapour walls become fire engulfed, heat is transferred by convection and radiation to the liquid and vapour contents of the tank. The modes of heat transfer to the liquid are, depending on the bulk liquid and inner wall temperatures, either convective, subcooled/saturated nucleate boiling or film boiling.

Initially heat is conducted into the liquid, but after a short time, the buoyancy forces predominate and convection becomes the dominant mode of heat transfer. Both convective heating and nucleate boiling create a buoyancy-driven flow in the region of the walls, which can form thermally stratified layers in both the liquid and vapour regions. Current modelling procedures utilise empirically based free convective heat transfer correlations to represent these regimes. Once saturated or subcooled nucleate boiling is predicted then alternative empirical heat transfer coefficients are employed such as those proposed by Rosenhow[15]. Some correlations require knowledge of various fluid properties, which are themselves dependent on the thermodynamic state of the fluid. Thus either analytical property routines or a data base must be referred to at each time step of the solution procedure in order to calculate the appropriate heat transfer coefficients.

In practice the heat transfer coefficients are also dependent upon other parameters, such as the type of surface and its finish, its inclination and curvature. The geometrical scale, the internal pressure, and the presence of dissolved gases are also known to influence local heat transfer values, Butterworth[16]. These factors are not accounted for specifically in the heat transfer relationships normally used but there may be an implicit dependence. Models which allow heat transfer coefficients to vary around the vessel walls in a specified manner (often in relation to the wall temperature distribution) have an implied dependence.

Some models allow for the possibility that stable film boiling may exist, by using an appropriate heat transfer correlation and increased wall temperature. Film boiling of liquid propane is considered unlikely during the normal heating and boiling cycles associated with typical hydrocarbon pool fires heat fluxes of around 100 kW/m^2. This is particularly true if subcooling is present, as this increases the critical heat flux necessary to trigger film boiling thus taking it further away from normal pool boiling fluxes. However it has been suggested by Venart[17] that stable film boiling could result from the sudden flashing and frothing accompanying the opening of the PRV, because the increased vapour likely to be present in the near wall region may allow wall burn-out to occur.

Radiative heating of both liquid and vapour by heat transmitted through the hot vapour walls is included in the majority of the modelling procedures. Radiative heating of the liquid results from that proportion of the radiation flux which is transmitted through the vapour. It is usually considered to form the major proportion of the radiative heat transfer, because of the transparent nature of the vapour.

4.4 PRV Operation and Bulk Boiling

Evaporation from the liquid/vapour interfacial layer governs the internal pressure within a vessel, so that PRV operation may occur before bulk boiling has been achieved. However the pressure drop following PRV opening may be sufficient to induce liquid flashing due to superheating. This can result in a two-phase swelling of the liquid region as vapour bubbles rise through the liquid. In vessels which are nearly full initially the liquid swelling could have a considerable influence on the quality of the fluid entering the vent system. A commonly used assumption is that a homogeneous vapour/liquid mixture enters the vent. Experimental evidence from Sallet[18] suggests that, for normal venting operations, liquid carry-over does occur and gives a high-quality flow into the vent. This becomes all vapour as venting progresses and the liquid level falls. Current models assume (as do the current codes for relief valve sizing) that only all vapour choked flow takes place through the vent. In some models ie. Beijnon,[19] this can be treated as a superheated vapour rather than one at the equilibrium temperature (as is current vent sizing practice).

4.5 Mass and Energy Conservation

As a quantity of mass is lost from the vapour space through the vent system a similar amount is evaporated off from the liquid region. In all models this is calculated from the conservation equations for mass and energy, which are coupled together and solved numerically. Different solution procedures are used depending upon the complexity of the sets of equations to be solved. Saturation conditions are assumed to exist throughout the liquid region during boil-off, and an appropriate saturation curve defined to facilitate the solution procedure. This avoids numerical instabilities and gross errors particularly when coarse time steps are used. None of the solution procedures can be solved graphically or by hand calculations.

The computer programmes predict the thermal response of the vessel and its contents as a function of time, particularly wall temperatures, time to PRV opening, internal pressure and liquid level. In some cases failure criteria are activated, which predict the time to vessel failure, these are based upon the reduced mechanical properties of the vessel walls at elevated temperatures.

4.6 Tank Protection Systems

There are several methods in current use for protecting LPG storage vessels from the worst effects of fires. These include water spray protection, covering the tanks with thermal insulation and burying or mounding of the tanks. All three methods reduce the heat flux into the contents of the tank and maintain the tank walls at relatively safe temperatures particularly in the vapour space region. An efficient insulation may reduce the heat flux by a factor of 10 or more. Water spray protection, when applied uniformly at the currently recommended rates, can be expected to maintain wall temperatures at around 100°C.

The presence of thermal insulation can be incorporated into modelling procedures as an additional thermal resistance surrounding the tank. A procedure to model water spray protection is included in the computer codes described by Ramskill(14). The water spray protection is represented as an evaporating layer of water upon the tank surface. A uniform coverage over the whole of the tank is implied. This may be difficult to achieve in practice, because of wind effects, the need to ensure that all the spray nozzles are working properly, and structural features unique to a particular installation.

4.7 Range of Applications

The utility of a computer model is enhanced if it can be used relatively easily for a range of fluids. This is possible in most cases as the physics of the models are general, and apply to most fluids, hydrocarbon or otherwise. A range of fluid property routines are therefore incorporated into some codes, and in some cases the heat transfer correlations are also modified. A further enhancement included in some codes(14) is the ability to predict the response of vessels containing either multi-component fluids (ie. petrol) or permanent gases. A model to predict the response of vessels filled only with permanent gases is given by Nylund(20).

Most codes have been designed primarily to predict the behaviour of cylindrical vessels mounted horizontally or nearly so, yet many installations contain spherical vessels or cylindrical ones mounted vertically. Models may not be readily applicable to these alternative designs, as the geometrically dependent behaviour is not necessarily the same. However, the thermodynamic

TABLE 3 Recent fire engulfment experiments

Responsible Body/Author	Date	Tank Size/ Scale	Contents	Environment	Measurements	Comments
Bray	1964	5T	Water	Outdoors	OWT (V/L) BFT	Water spray protection test. Kerosene/oil fire.
AAR-RPI	1973	1/5 scale	Propane	Outdoors	-	Unprotected tanks
AAR-RPI/ABR Anderson	1973	Full scale 64T	Propane	Outdoors	OWT (V/L) IWT (V/L] BFT, P, WHF FHF, FT, FD	Unprotected railcar. Tested to destruction. JP-4 fuel.
Transport Canada Appleyard	1980	1/5th scale	Propane	Outdoors	OWT (V/L) BFT, P FT	Unprotected and protected (Explosafe) JP-4 pool fire.
HSE/Shell Cutler Williams	1980/81	1/4T	Water Propane	Outdoors	OWT (V/L) BFT, P FT	Protected tanks to test Insulations. Numerous tests.
HSE/Shell Cutler Moodie	1981/82	1/4T & 1T	Water Propane	Outdoors	OWT (V/L) BFT, FT, P	Full kerosene fire engulfment 5-tests Unprotected.
Droste	1983	2½T	Propane	-	OWT (V/L) P, FT	3-tests to destruction. Pool fires.
DIERS Fauske	1983	Lab Tests	-	-	-	-
Venart	1983-86	40 l	Freon's	Indoor Laboratory tests	BFT, P LC, WHF	Test rig electrically heated. Examined thermal response of vessel and contents.
HSE Billinge	1985	1/4T	Propane	Outdoors	OWT (V/L) BFT, P FT	Water spray protected tanks. Numerous tests.
Davis Eng	1985	1/5th scale $0.5m^3$	Water	Indoors	OWT (V/L) BFT, FD, TR WHF, FT	Pool fire test to assess flare effects. Radiation feedback.
Nylund	1985	3.0m Dia.	Gases	Outdoors	P, FT	-
HSE/Shell/ BGC Moodie Cowley	1985/86	5T	Propane	Outdoors	OWT (V/L) FWT (V/L) BFT, P, LC WHF, FHF, FD, TR, FT	Full kerosene fire engulfment 5-tests different fills. Unprotected.

OWT (V/L) Outer wall temp
IWT (V/L) Inner wall temp
BFT Bulk fluid temp
P Pressure
LC Tank weighed by load cells
FT Fire temperature

WHF Wall heat flux
FHF Fire heat flux
FD Flare data
TR Thermal radiation
V-Vapour L-Liquid

and physical processes are similar, as are the overall thermodynamic responses. The first of the codes attributed to Ramskill[14] utilises a 'volume equivalent cube' to represent different shapes of vessels. The DIERS developed model SAFIRE, the venting aspects of which are described by Forest[21], also applies to different shapes of vessels.

5 LPG STORAGE - FIRE ENGULFMENT EXPERIMENTS

To the best of the author's knowledge the published experimental work carried out over the last few years is as listed in Table 3. Only experiments directly related to simulating in-total the fire engulfment of LPG type containers are included, irrespective of scale. Many other fire engulfment experiments have been undertaken before the period considered. Some experiments go back to 1925 and are the basis of the pressure relief valve sizing methodologies utilised in the main codes of practice.

The largest fire engulfment test so far reported appears to be that described by Anderson et al[22], in which a 64 tonne rail car was fire engulfed. Vessel wall temperatures for both inner and outer surfaces were recorded, together with the bulk liquid and vapour temperatures, and the average heat flux from both the fire and the PRV flare. Measurements were also made of the liquid level in the tank and the thermal radiation from the PRV flare. The vessel failed catastrophically some 24.5 minutes into the test, with an estimated 40% of the LPG still remaining in the tank. Fragments from the vessel were reported at considerable distances from the test site. The maximum wall temperature near the point where the vessel started to fail was of the order of 650°C and the internal pressure was 24.1 bar. A series of 1/5th scale trials of this rail car test are also reported in the literature[23].

Fire tests on smaller capacity vessels (2½ tonnes) have been reported by the Federal Institute for Material testing, Berlin[24]. Three fire tests were completed for LPG, stored in accordance with the appropriate DIN standard, and again vessel skin temperature variations with time were recorded. In all these tests tank failures occurred within 7 to 12 minutes from the beginning of the fires, depending upon the initial temperature of the LPG. Recent studies by the same organisation include fire tests on water spray protected and insulated tanks.

Extensive laboratory simulations have been undertaken by Venart et al[17]. An electrically heated 380 mm diameter, 40 l capacity cylindrical pressure vessel was used, it was fitted with observation windows at both ends and contained Freon 11 or Freon 12 to simulate the LPG loading. It was extensively instrumented so that various aspects of the thermal response could be studied and compared with theoretical predictions.

Although not pressurised liquefied gas storage, Nylund[20] has made theoretical and experimental studies of the behaviour of pressurised gas process vessels subject to both total and partial fire engulfment. His predictions of vessel failures within a relatively short time after the beginning of the fire were confirmed experimentally.

The work undertaken by HSE[25-28] covers a range of tank sizes up to 5 tonnes capacity. Kerosene pool fires were used in all of the tests to provide realistic total fire engulfment. The tests were conducted at an open moorland site. Uninsulated tanks of 1/4t, 1t and 5t capacity were tested. 1/4t tanks were used to assess the effectiveness of various types of insulation materials such as mineral wool blankets and epoxy-based intumescent coatings. A 1/4t tank was also used to assess the efficiency of water spray protection systems. Vessel wall temperatures were measured for both the vapour and liquid wall regions, together with the bulk liquid and vapour temperatures, and the internal pressure. The 5 tonne tests were more extensively instrumented than the smaller capacity tanks, this enabled other parameters such as the heat flux and the internal vessel stratification to be measured. The discharge rate through the pressure relief system was also obtained from the weight loss recorded from load cells (1t and 5t tests only). Vent stack exit velocity measurements were made during the 5t tests. The radiation emitted by the flare was also characterised, from radiometer data and photographic records.

Davis Engineering[29] report an indoor fire test performed on a scale model of a rail tank-car, to study the influence of a burning flare of LPG on the tank and engulfing fire. The test used a $^1/_5$th scale water-filled tank with JP-4 as the fire fuel. The instrumentation measured tank wall temperatures, wall heat fluxes, bulk temperature, fire temperatures, heat flux to remote targets, and entrained air dynamic pressures. The results indicated that in the absence of cross winds effects, the burning flare had little or no effect on the tank engulfed in a sooty fire. However the overall fire size was increased.

A series of outdoor $^1/_5$th scale tests are also reported by Appleyard[30]. Fire engulfment trials were conducted with unprotected tanks (Enigma Series) and with Explosafe protected tanks (Nova Series). The main parameters measured were the internal pressure, wall temperatures, and the liquid level.

Bray[31] undertook a series of fire engulfment trials, on a water filled vessel some twenty years ago. The purpose was to ascertain the water spray rate necessary to prevent excessive skin temperatures. The test tank was extensively instrumented with thermocouples. A kerosene/oil spray burner was used to provide the source of heat. The results of Bray's work have provided a design basis for water spray protection systems in the UK.

The DIERS project(32) was concerned mainly with the sizing of vent systems for vessels containing a range of substances both reacting and non-reacting. Included are design methods for sizing relief valves to cope with fire engulfment(21). It is understood that some laboratory scale experiments were carried out for validation purposes, but these have not yet been reported.

5.1 Comments on Test Data

Collectively the experimental results currently available provide a comprehensive data set, ranging from laboratory simulations, through to realistic pool fire engulfment trials on propane filled tanks from 1/4t to 64t capacity. Additional data is available from fire tests with insulated tanks, flares, water spray protected tanks, and gas filled pressure vessels.

5.1.1 Flame and wall temperatures

The influence of prevailing meteorological conditions was apparent in many of the pool fire engulfment trials, as considerable spatial and temporal flame temperature variations were observed at different locations within the fire zones. Although this to some extent reflects the highly turbulent nature of the flame and combustion processes, it meant that there were considerable variations in the observed tank vapour wall temperatures, both across the tanks and from end to end. Behaviour of this nature presents difficulties when making and interpretating model predictions, especially failure predictions, because of the 1-D or 2-D assumptions contained in the models. A similar degree of variability was not usually observed between liquid wall temperature measurements, presumably because of the thermal mass of the liquid.

Wall temperature measurements for unprotected pool fire engulfed LPG tanks, at the time of failure or when it was thought imminent, showed that the vapour region walls reached peak temperatures of around 600^{o}C. The actual values are dependent upon the internal pressure and the strength of the vessel. This is illustrated in Table 4, which lists the maximum wall temperatures and the corresponding pressures. Also given in Table 4 are the times to PRV opening, percentage fills, initial propane loadings, and the fire heat fluxes. The interdependence between these parameters is complex, but generally speaking for a given heat flux, the smaller the vessel and the lower the percentage fill, then the shorter the time to failure or potential failure. The times to initial PRV opening appear to be both specific heat flow rate and test dependent, although they are similar for all the reported

TABLE 4

Summary of experimental results - unprotected tanks

Originator(s)	Nominal Tank Size & Percentage Fill	Initial Quantity of LPG (litre)	Maximum wall Temp (°C)	Pressure at max. Temp (bar g)	Time to PRV first opening (secs)	Calorimeter Heat Flux (kW/m²)
HSE	1/4t, 40%	185	600	35	190 (1)	-
	1t, 20%	308	570	7	297	-
	1t, 40%	789	620	8.8	262	-
	1t, 80%	1,635	680	6.3	226	-
	5t, 20%	2,250	635	11	373	99
	5t. 40%	3,676	657	10	415	101
	5t, 60%	5,900	610	11	401	-
	5t, 80%	7,644	572	11	312	96
Anderson	64t, 95%	121,500	650	25	160	104
Droste	2½t, 50%	2,820	460	245	340	-
	2½t, 50%	2,820	420	573	100	-
	2½t, 50%	2,820	-	-	150	-
AAR	13t	-	-	-	-	-
Davis Engineering	0.51m³	(2) 500	660	-	-	90
Appleyard (Enigma)	.98m³	800	570	13	120	-
Bray	21.9m³, 90%	(2) 19,700	-	-	-	-

(1) Includes time for fire to establish itself
(2) Water only

pool fire tests on unprotected tanks.

5.1.2 Pressure relief

All of the tests were undertaken with pressure relief systems fitted, usually in accordance with a specified code of practice. The internal pressures rose relatively quickly once the fires had started. The initial opening was often followed by a sharp drop in pressure before rising again to maintain a pressure near to the set pressure. The level to which the pressure subsequently rose depended on the fill level and whether two-phase flow was occurring in the vent. In some tests[24] the relief valve capacity seemed inadequate and the internal pressure rose well above the set pressure before failure occurred.

5.1.3 Bulk fluid behaviour

The experimental results confirm that the internal pressure was governed principally by conditions at the liquid interfacial layer. In particular the evidence from small scale laboratory trials[17] and the large tank car fire trial[22] shows that thermal stratification exists in the liquid regions at least up to the onset of bulk boiling. Liquid stratification can be important when calculating the times to initial PRV opening, the liquid behaviour following PRV opening, or the maximum levels of fill which can be tolerated.

Considerable thermal stratification was reported to exist within the vapour space for all tests where measurements were made. Similar patterns were observed in most cases with the temperatures and the degrees of stratification rising initially until the PRV's first opened. They then fell momentarily towards saturation, presumably as frothing or bulk boiling was initiated, before rising again as venting progressed. The resulting superheat levels can be expected to decrease maximum vent discharge rates if all vapour venting is taking place, which if not accounted for may lead to overprediction of mass discharge rates. In practice there is some compensation if droplet carry over or frothing occurs, as these result in a two-phase mixture entering the vent system. This has been observed in small scale experiments reported by Venart[17].

In some tests, bulk liquid, boundary layer temperatures and wall heat fluxes were measured. The majority of this data provides support for the heat transfer modelling procedures discussed previously. The dominant mode of convective heat transfer is that of nucleate boiling. Although the differences between wall temperatures and the saturation temperature suggest that in many instances considerable vapour generation was occurring in the near wall region. High vapour containing boundary layer flows have been observed in the laboratory trials reported by Venart[17].

Modelling proceedures usually assume that saturated bulk boiling occurs during venting. Whilst this was confirmed by observation from many tests there have been some exceptions. In particular during the 5 tonne HSE/SHELL/BGC tests liquid superheats in excess of 20^{o} were observed. At present this phenomena is attributed to a mixture of saturated liquid and superheated vapour. The latter being entrained from the vapour region or as a result of sloshing during venting. Although such behaviour may be peculiar to one set of tests, it cannot be easily dismissed in modelling terms, as it may have implications for future model developments and their applicability.

5.2 Scaling and Averaging

The currently available test data from pool fire engulfment trials provides a range in scale (based on tank internal diameter) of about 1:8 (0.38m:3.05m) for horizontal cylindrical vessels. The data allows those aspects to be examined which are considered particularly sensitive to scaling, such as fluid properties, boundary layer development, wall to liquid heat transfer coefficients, and possibly thermal stratification. The scaling criteria can be established where possible and compared with theoretical predictions. The laboratory and field data may be used to test the validity of the scaling criteria through parametric sensitivity studies, thus allowing predictions to larger scales to be made with reasonable confidence. As a consequence the range of model applicability may be extended upwards to include the largest sizes of storage tanks.

There are three components to the overall heat transfer process; heat from the fire, conduction through the walls, and natural convection (both liquid and vapour). In all three, appropriate scaling laws are derived by non-dimensionalising the governing equations.

There is a considerable amount of appropriate data in the literature which can be utilised to test these scaling laws. Free convective flows, in particular, have been comprehensively studied and their scaling criteria are well established. Flow pattern predictions for free convective flows in partially filled horizontal cylinders have been obtained using hydrodynamic computer codes as reported for instance by Hadjisophocleous[33].

The questions of variability between data sets and averaging principles have not been fully examined. Full scale statistically meaningful replicate data sets do not exist nor are they likely to in view of the costs involved. What evidence there is suggests that atmospheric turbulence variations are having a significant influence on the heat flux profiles to the tank and its thermal response. However, the influence may go deeper and effect both the extent and stability of the convective flows in the liquid region. Precise laboratory simulations of field tests may help to clarify some of these influences, particularly the consequences of asymmetric heating, and the most appropriate averaging procedures to be adopted. They may also help to verify scaling criteria.

The nature of the flow patterns which exist within the vessel during field tests have not been examined to anything like the extent that they have in the laboratory. There are considerable practical difficulties viewing inside a tank during a fire engulfment test, and of measuring velocities and phase compositions. Nevertheless the problem needs to be addressed in view of the potential benefits to be gained from such information.

5.3 Future Developments

Experimental results suggest that thermal stratification in the vessel, and two-phase flow effects in the vessel and vent system following PRV actuation, have a significant effect on its thermal response which cannot always be ignored for modelling purposes.

The 'exactness' of both average wall temperature predictions and other fire dependent parameters may need to be reappraised in view of the degree of variability noted during and between 'similar' tests.

Future model developments can be expected to address further the problems of different modes of fire attack, such as partial pool fire engulfment and jet flare impingement. Modelling the latter aspect may require comprehensive three-dimensional models in view of the nature of jet flares and the number of different modes of impingement. Suitable experimental data with which to validate such models is not available.

The majority of current models are intended specifically for horizontal cylindrical vessels, yet many installations are either spherical or vertical cylindrical ones. Models are costly to develop and any enhanced versatility in this area is desirable commercially. Further model development is therefore likely, as also is experimental validation in view of the current lack of data for other than cylindrical vessels. The extension of models to handle multi-component fluids and gases rather than single component fluids is also likely to receive further attention. A number of models have already been developed, but experimental validation is sought.

6 CONCLUSIONS

Considerable progress has been made in recent years on analysis techniques, model development and experimental verification in connection with the assessment of major hazards.

The development of suitable models to predict the consequences of one aspect, namely fire attack on transport and storage vessels containing pressurised liquefied gases has not lagged behind, nor have the necessary experimental validation exercises.

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