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Review

State of the art review of pressure liquefied gas container failure modes and associated projectile hazards

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Abstract

The purpose of this study was to investigate the state of knowledge relating to the failure of pressure liquefied gas (PLG) transport and storage vessels. A literature search and review has been carried out to assess the state of knowledge with regard to PLG vessel failure modes and mechanisms, release severity, projectile hazards, and blast effects. Specific parameters of interest were the effect of vessel initial conditions (fill level, initial temperature, etc.) on rupture severity, and our ability to predict the occurrence of the boiling liquid expanding vapour explosion (BLEVE). This literature review revealed there are several areas where our knowledge is weak and some where there is a definite lack of knowledge. Areas where knowledge is weak include: the effects of blast on structures and the understanding of the failure modes of PLG containers. Areas where knowledge is lacking include: projectile modelling for PLG vessel failures and the effects of fill level on the severity of an explosion or the likelihood of a BLEVE.

Introduction

Pressure liquefied gases (PLG's) are substances, such as propane and chlorine, that under atmospheric conditions are gases but for transportation and storage are liquefied by pressurization. They are stored and transported in many industries. Pressure liquefied gas containers of specific interest in this study include rail tank cars, highway tank trucks and large stationary storage vessels.

If for some reason a PLG containment vessel is punctured, the resulting drop in pressure can result in a very large release of energy. This released energy can cause significant damage to surrounding structures and personnel. The degree of severity of a PLG release depends on a number of factors such as:

- the mass of the substance being released
- size of the puncture (i.e. how quickly is the substance released)
- properties of the substance at the time of release
- flammability or toxicity of the released contents

Some modes of failure are not severe, while others can be devastating. The

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most severe form of release has a special name — boiling liquid expanding vapour explosion (BLEVE). The BLEVE is usually associated with a large explosive release of a PLG. The explosive part of the release is caused by a very rapid phase change from liquid to vapour. A BLEVE does not necessarily involve a fire ball.

Figure 1 shows a chain of events from the beginning of an accident through to its consequences. The entire event consists generally of three phases: the accident phase, the release phase and finally the hazard phase. Over the years there have been many studies that have looked at all three phases. However, because of obvious practical needs, most of the work has focused on the accident phase with the objective of reducing the number and severity of accidents. For example, in North America, work by the AAR (American Association of Railroads), FRA (Federal Railroad Administration), DOT (Department of Transport) and TC (Transport Canada) has addressed the accident phase and as a result the number of severe accidents has been reduced significantly. However, accidents can and do occur and therefore there is a continuing need to understand the release and hazard phases of a given accident.

The objective of the present study was to look at work that has been carried out in recent years and to identify areas that need attention. Specific questions of interest here include:

(i) What determines if a release causes a BLEVE or a slow boil off?
(ii) What determines the size and the number of missiles or projectiles that are created and what are their properties?
(iii) What are the associated blast effects from any resulting release or explosion?

Fire fighters need to know the projectile hazards generated by the explosions of PLG containers to protect citizens and themselves. Storage facility designers need to know how to stop the spread of accidental release from container to container and to minimize the damage to surrounding plant buildings and

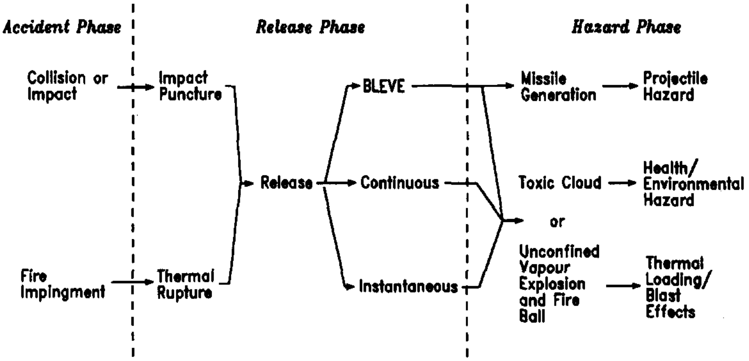

Fig. 1. Chain of events for a pressure liquefied gas container accident.

emergency water supplies. City planners need to know the projectile and the blast wave hazards on private buildings so new storage, loading or processing plants are located safely within cities. Clearly if the risk of loss of life and property is to be reduced an understanding of the release and hazard phases are required.

Discussion of reviewed works

The following pages present an overview of some of the material that has been found in the open literature. The material is summarized in tabular form for easy reference. Readers that are interested in additional detail should obtain the original publications. The material has been organized into the following categories:

(i) Fire impingement tests
(ii) Fire impingement modelling
(iii) BLEVE theories
(iv) Modelling of projectiles
(v) Blast and missile effects
(vi) Case studies

A significant amount of time has been focused on fire impingement of PLG containers because severe accidents and BLEVE's are usually associated with thermal ruptures (i.e. ruptures caused by fire impingement). The authors believe that a better understanding of BLEVE's and associated consequences will probably come from a better understanding of thermal ruptures.

Fire impingement experiments (see Table 1)

In 1971 two U.S. agencies (AAR and FRA) joined together to form the Rail Tank Car Safety Research and Test Project (RTCSRTP) [1–4]. The objective of the work was to improve the safety of the transport of liquefied gases by rail. This agency conducted fire tests in 1973, and 1975. The recommendations resulting from the RTCSRTP (thermal insulation, head shields, shelf couplers) resulted in a significant reduction in the number of serious accidents in the rail transport of PLG's in North America.

A series of 1/5 scale (rail tank car) fire tests were conducted in Canada by TC [5] to evaluate a new concept in thermal protection. These tests provided a large amount of high quality data on fire impingement of tanks.

Tests into insulation performance in an engulfing fire environment were performed by the HSE (U.K. Health and Safety Executive) [6–8]. In these tests various sizes of tanks were tested with and without insulation. The results confirmed that insulated vessels survived fires longer than uninsulated ones. The HSE [9] and the BAM (Federal Institute for Materials Research and Testing) conducted tests to evaluate the use of water spraying systems (WSS)

TABLE 1

Fire impingement tests

Title/date	Author(s) [ref]	Sponsor	Focus	Findings	Recommended further work	Comments
Phase II report on analysis of 1/5 scale fire tests/1973	L.J. Manda [1]	Association of American Railroads	- 7 1:5 Scale rail tank car fire tests were conducted to evaluate test procedures and thermal shielding	- Pressurization rates before discharge of pressure relief valve (PRV) can provide an indication of the effective heat flux to the lading - Any of the insulation systems tested can reduce the unit heat flux by a factor of 5 or 6 for durations of longer than 40 min		- 2 Tests were conducted with water to evaluate test procedures - 2 Tests were conducted on uninsulated tanks - 3 Tanks were conducted on tanks insulated with 3 different types of insulation - Suggested that test results should not be extrapolated to full scale - Water tests gave no useful data
Comparison of thermally coated and uninsulated rail tank cars filled with LPG subjected to a fire environment/1974	W. Townsend C. Anderson J. Zook G. Cowgill [2]	Federal Railroad Administration	- Fire test of two full scale rail tank cars (insulated and uninsulated)	- The rate of temperature increase in the insulated car was lower that for the uninsulated car - The rate of vaporization in the insulated car was lower than the uninsulated car - The insulated car will survive longer		- Report has mass and distance information for the major fragments - A lower temperature means higher rupture pressure - Lower vaporization rate means a lower pressure
Fragmentation and metallurgical analysis of tank CAR RAX 201/ 1974	C. Anderson E.B. Norris [3]	Federal Railroad Administration	- Analysis of the failure of an uninsulated tank car due to fire engulfment	- The longer the car is subjected to high temperatures the lower the pressure that is required to rupture the vessel - Failure was due to stress rupture - Failure initiated in an axial direction		- Failure occurred at an area where a thermocouple was mounted (tests showed failure was imminent in other places) - Car ruptured after 24.5 min

A metallurgical investigation of a full-scale insulated rail tank car fitted with LPG subjected to a fire environment/1975	J.G. Early C.G. Interrante [4]	Federal Railroad Administration	- Analysis of the failure of an insulated tank car after rupture due to fire engulfment	- Rupture initiated in an axial direction due to thinning then the Explosion occurred and the crack propagated circumferentially generating fragments		- Tank car was approximately 100% full - Tank failed after 94 min - Tank ruptured into 4 major fragments - Two ejected from pit two remained in pit
Testing and evaluation of the Explosafe system as a method of controlling the BLEVE/1980	R.D. Appleyard [5]	Transportation Development Centre	- Describes the investigation of the effectiveness of Explosafe in preventing the failure of pressure vessels	- All of the three 1/5 scale rail tank cars that were protected with Explosafe successfully survived an engulfing fire - One of the tanks with explosafe came very close to failure as indicated by vessel deformation	- Full scale rail tank car tests should be conducted	- Tests were conducted on a 1/5 scale rail tank car - Tanks filled to 85% with propane - 2 Tests of unprotected tanks and 4 tests with 3 different configurations of Explosafe - Both unprotected tanks ruptured and no protected tanks ruptured although one system of Explosafe was close to failure - Unprotected tanks failed after 9.5 min and 8 min - Neither rupture generated fragments
Fire engulfment with LPG tanks with a range of fire protection methods/1983	A.F. Roberts D.P. Cutler K. Billinge [6]	Health and Safety executive	- Fire test of 1 uninsulated and 2 insulated storage vessels	- After 75 min in the majority of the tests the temperature difference between upper and lower wall was small - Indicates propane was not wetting the lower wall but was supported by vapour layer		- Calibration trials using water showed that the fire conditions could be reproduced - Tanks not taken to rupture

TABLE 1 (continued)

Title/date	Author(s) [ref]	Sponsor	Focus	Findings	Recommended further work	Comments
Experimental determination of the heat transfer in the vapour space of a partially filled horizontal cylinder/1984	G. Qureshi [11]	Transportation Development Centre	- Model of effects on vapour space of fire engulfment	- An open pressure relief valve enhances the heat transfer from the wall to the vapour		
Failure mechanisms of propane tanks under thermal stresses including fire engulfment/ 1984	D. Schulz-Forberg B. Droste H. Charlett [12]	Federal Institute for Materials Research and Testing (BAM)	- Fire test of 3 LPG storage vessels - The initial temperature and pressure were varied	- The higher the initial temperature and pressure the shorter the time to rupture	- Further tests and theoretical work needed	- Tests conducted with 50% fill on uninsulated storage vessels - Postulates that less fill will mean less time to rupture
An experimental investigation of a cylindrical vessel engulfed in fire with a burning relief valve flare present/1985	A.M. Birk [13]	Transportation Development Centre	- Tests of a cylindrical vessel exposed to fire engulfment plus a PRV flare and only a PRV flare were conducted	- Heat flux from a PRV flare alone is small (3–6% compared to the heat flux due to fire engulfment) - The additional effect from a PRV flare to a tank already engulfed in fire is negligible - The flare effects the pool fire geometry and may increase the radiant heat to remote objects		- Tests conducted indoors - The PRV flare only test consisted of water as lading and 6.5 min flare burn - Flare 6 to 7 m long - The PRV flare and engulfment tests consisted of water as lading and pool fire of JP4 jet fuel (14.5 min) with 2 flare burnings of 3 and 2 min
The fire engulfment of LPG storage tanks/1985	K. Moodie K. Billinge D.P. Cutler [7]	Health and Safety Executive	- Fire tests of 2 uninsulated 1/4 tonne and 3 one tonne tanks - Measure	- Temperature of walls adjacent to vapour space rose linearly - Temperature of wall adjacent of liquid space	- Require further information on the boiling behaviour of the liquid - Require further	- All PRV's that failed (all but one of them open) failed due to fire damage to the valve seats and springs - 1/4 tonne tests conducted

			temperature, pressure and PRV discharge rates	rose to a plateau (boiling point) then only rose further when the liquid level dropped - Rupture of one 1/4 tonne tank was in the axial direction - Some PRV's failed open near the end of the tests and may have prevented the failure of the other tanks	information on the quality and mass flow rates of propane through the PRV	a 40% fill - Pieces from the 1/4 tonne test that failed were hurled up to 120 m but most stayed within 20 m - 1 Tonne tests were conducted a 20, 40 and 80% fill levels
Tank car thermal response analysis: executive summary: Vol. 1/1985	J.E.S. Venart [14]	Transportation Development Centre	- Report summarizes the work done to date with Explosafe	- Internal pressure for the lading is determined by liquid surface temperature and low boiling point impurities - Explosafe layers, 25 mm and 50 mm thick, showed little or no advantage	- Work is needed to determine the effects of PRV operation, heat flux, lading fill and orifice diameter on pressure relief and thermal hydraulics - Work is needed to determine the effectiveness of the use of high heat flow interior surfaces for internal vapour space cooling	- Lab simulations of fire conditions conducted with and without Explosafe varying heat flux, PRV orifice diameter and fill level - Conducted studies of the stratification and boundary layer of fluid in a cylinder heated with and without Explosafe - Boiling and liquid swelling was investigated with and with out Explosafe
The use of water sprays to protect fire engulfed LPG storage tanks/1986	K. Billinge K. Moodie H. Beckett [9]	Health and Safety Executive	- Series of 7 tests on 1/4 tonne tanks engulfed in fire protected by a water spray system were conducted	- Currently recommended spray rates are sufficient to prevent failure - PRV opened after spraying began (1-3 min) - Temperature of vapour space walls rose linearly - Temperature of liquid space walls rose to a plateau then when liquid level dropped due to PRV operation the temperature		- Tanks 40% full - PRV's on lowest water rates failed safe (i.e. open) because of burnt valve seats - In tests with higher water spray rates PRV's operated correctly - Seventh test vessel ruptured (no fragments generated)

TABLE 1 (continued)

Title/date	Author(s) [ref]	Sponsor	Focus	Findings	Recommended further work	Comments
				rose linearly - Water spray reduced flame temperature and lengthened time to PRV opening - PRV discharge rate was larger for water spray protected tanks than for the unprotected tanks (lower temperature) - Insulation is more effective that water sprays		
Investigation of water spraying systems for LPG storage tanks by full scale fire tests/ 1988	W. Schoen B. Droste [10]	Federal Institute for Materials Research and Testing (BAM), Berlin	- Reports on 10 fire tests of 4.85 m^3 LPG storage tanks protected by a conventional WSS - And 5 protected with a modified WSS	- Conventional WSS with 1000 l/m^2 h could not have protected the tank against rupture - Improved WSS with 400 l/m^2 h could protect the tank against rupture - Some thermal insulation or other protective measure needs to be added to the conventional WSS for it to be effective - A tank protected by the improved WSS can survive a fire for over 90 min		- Used 20% fill for the conventional WSS tests - Used 20 and 80% fill for the improved WSS tests - Tanks not taken to rupture - Thermal insulation alone is enough to protect the tank for 90 min
Fire Engulfment Tests on a 5 tonne PLG tank/1988	K. Moodie L.T. Cowley R.B. Denny L.M. Small I. Williams [8]	Health and Safety Executive and Shell Research	- Fire test of 1 uninsulated tank car 5 times	- Time to rupture is shorter for lower fill levels		- Tank not taken to rupture - Same car used each time with new PRV's

TABLE 2

Fire impingement modelling (for modelling work from 1975 to 1987 see Table 3)

Title/date	Author(s) [ref.]	Sponsor	Focus	Findings	Recommended further work	Comments
Effects of fire on LPG tank cars/ 1971	L.J. Manda [15]	Association of American Railroads	- Theoretical evaluation of the effects of fire on a tank car	- A rail tank car's survivability can be increased by raising the pressure relief valve setting - Fill level should be as high as possible to decrease the time until the tank liquid full	- Experiments should be conducted to determine the effects of temperature and density stratification on pressure	- Later work questioned findings - Very brief not much data
Development of a computer program for modelling the heat effects on a railroad tank car/ 1973	K.W. Graves [16]	Federal Railroad Administration	- Preliminary attempt to model the effect of fire engulfment		- More accurate model for energy transfer in vapour space required - Modification needed to account for liquid being in a non-equilibrium state - Needs to include the ability to simulate a tank car on an angle	- Provides a basis for future work - Attempts to predict failure of a rail tank car containing a PLG
Modelling techniques and small-scale experiments/1988	J.E.S. Venart [17]	University of New Brunswick Department of Mechanical Engineering	- Validation of PLGS-1 and 2 models for predicting response of PLG vessels engulfed in flame	- PLGS-1 underpredicts the initial pressure rise and does not predict the correct number of PRV cycles - PLGS-1 overpredicts the wall temperature in the vapour space but predicts bulk temperatures well - PLGS-2 predicts 2 eddy regions due to the rising of	- Improvements to the void development and flashing models to better predict 2 phase swell - Valve model must be improved to handle 2 phase flow, vapour flow or liquid flow - Extension of the code to handle 3-D and non-uniform heating	

TABLE 2 (continued)

Title/date	Author(s) [ref.]	Sponsor	Focus	Findings	Recommended further work	Comments
				heated vapour and liquid along the tank walls - PLGS-2 predicts as tank fill level increases the rate of initial pressure rise decreases except for very high fill levels (~98%) which will have the highest initial rate of pressure rise		
Thermal response analysis of LPG tanks exposed to fire/1988	N.U. Audemir U.K. Magapu A.C.N. Sousa J.E.S. Venart [18]	University of New Brunswick, Department of Mechanical Engineering	- Development of a numerical model for LPG tanks engulfed in flames - Experiments conducted to validate it	- Model's pressure relief valve discharge times, internal pressure and temperature are in good agreement with the test results	- Detailed analysis is required to determine the relationship between discharge coefficient and void fraction overpressure	- Uses two dimensional analysis - Assumes plane of symmetry down centre of tank
Experiments and modelling: An overview with particular reference to fire engulfment/1988	K. Moodie [19]	Health and Safety Executive	- Reviews literature on modelling and the experiments that exist to validate them	- For a given heat flux the smaller the tank and the lower the fill level the shorter the time to rupture - Improvements in modelling of pressure liquified gas have been made recently	- Models need to be developed to model partial engulfment and jet fire impingement (this will probably required 3-D modelling) - Experiments with jet fires and partial engulfment need to be done	- Lack data for non-cylindrical vessels

Assessment of mathematical models for fire and explosion hazards of liquified petroleum gases/ 1988	W.P. Crocker S.H. Napier [20]	University of Toronto, Department of Chemical Engineering and Applied Chemistry	- Reviews mathematical models for fire engulfment	- One model for quiescent conditions jet fire is seen as adequate to predict thermal hazard - For windy conditions the solid flame model using equivalent cylinder is the best - BLEVE fire balls seem to behave differently from other fire balls so the stationary ground level model should be used since it gives the most pessimistic results	- Rising fire ball models require further development - BLEVE blast model needs a more detailed aerodynamic model for explosive yield	- For jet fires in quiescent conditions there is a lack of agreement on view factors (one term of the equation) - TNT was used to express yield equivalent (there is some uncertainty over what the equivalence should be)

TABLE 3

Programs for fire impingement modelling (from Moodie [19] revised by the authors)

Model title	Date	Originating body (Author, [ref.])	Modes of fire attack modelled	Vessel contents modelled	Vessel type	Modes of protection	Comments
-	1975	FRA (Graves, [16])	Engulfing fire	Pressurised liquefied gases	Horizontal cylinder	Uninsulated	Basic code in public domain
TNKCAR	1983	Queen's (Birk, [21])	Engulfing fire	Propane	Horizontal cylinder	Uninsulated, insulated, radiation shielding, Explosafe, fusible plugs	Finite difference heat conduction three node thermodynamic model
ENGULF I	1984	HSE/SRD (Ramskill, [22])	Engulfing fire	Liquefied gases multi-comp. gasses	Any	Uninsulated, insulated, water spray	A cuboid based model with three nodal points in the shell
-	1984	UNB (Venart, [23])	Engulfing fire	Pressurised liquefied gases	Horizontal cylinder	Uninsulated, internal protection inc. Explosafe	First version based on CALSPAN modified to include valve interaction with heat transfer modes
TNKCAR	1985	TDC (Birk/Davis, [13])	Engulfing fire and 2-D torch fire	Propane, n-butane, n-pentane and propylene	Long cylinder various orientations (roll and pitch)	Uninsulated, insulated, radiation shielding, Explosafe, fusible plugs	Computer code predicts wall and lading temperature, internal pressure, liquid level and time to failure
SAFIRE	1986	DIERS ([24])	Engulfing fire	Pressurised liquefied gases	Any	Uninsulated	Wide ranging computer code for relief vent sizing which also includes external heat source

ENGULF II	1987	HSE/SRD (Ramskill, [25]	Partial and full engulfing fire and jet flares	Liquefied gases multi-comp. gases	Horizontal and vertical cylinder	Uninsulated, insulated	Later version of ENGULF I in cylindrical coords, enhanced fire modelling
HEAT-UP	1987	SHELL RESEARCH (Beiynon, [26])	Engulfing fire	Pressurised liquefied gases	Horizontal cylinder	Uninsulated, insulated	2-D computer code for horizontal cylindrical propane tanks, pressure relief valve operation is modelled accurately
PLGS-1	1987	UNB (Sousa, [27])	Engulfing fire	Pressurised liquefied gases	Horizontal cylinder	Uninsulated	Current UNB code

to protect PLG storage sites. They concluded that WSS do protect PLG vessels from the effects of fire but insulation does as good a job for less money.

The data available from these various studies has proven to be very useful for the development and validation of a number of computer models.

Thermal computer modelling (see Tables 2 and 3)

Table 2 contains highlights of early and recent thermal computer model development work. Table 3 outlines the computer models currently available for analysis of fire impingement on PLG containers.

The models typically assume full engulfing fire situations although some can account for torch type fires or partially engulfing fires. These thermal models vary in complexity from thermal network type models known as zone models, to the more complex field models which solve the full 2-D or 3-D continuity, momentum and energy equations. Both types of models have shown good agreement with fire test data.

Thermal modelling is of interest because these models can predict the time of thermal rupture, the tank fill, and the properties of the PLG contents at the instant of failure. It is expected that all of these play a role in the severity of a release. It is therefore reasonable to assume that models like these will be useful in the analysis of consequences such as BLEVE's, blast and projectiles.

BLEVE Theories (see Table 4)

Theories explaining the BLEVE are relatively new and very little data is available to fully support them. Reid [28] suggested that BLEVE's are superheat explosions and therefore can be predicted by considering the superheat limit for a given PLG. Subsequent work by Jones [29], Martinsen et al. [30], McDevitt et al. [31], Davenport [32] and Dunn [33] also support the superheat limit explanation.

Other theories have been put forward for the causes of BLEVE's and this is an area of current research activity. The objectives of much of the work is to develop techniques for predicting when a BLEVE will occur. A long term objective is to suppress or eliminate the occurrence of BLEVE's.

Projectile modelling (see Table 5)

Much effort has been put into developing models to predict the behaviour of projectiles generated from pressurized container failure. Most of this work has been in developing models for the projectiles from pressurized gases. Work has been sponsored by Lockheed Propulsion Company [35], the AAR [36], the Insurance Technical Bureau [37], Central Electric [38], the UKAEA [39,40], the Health and Safety Executive [41], the Michigan Technological University [42], Southwest Research Institute (SRI) [43,44] and Berkeley Nuclear Laboratories [45–47].

No fully validated model exists to predict the hazards from PLG container

TABLE 4

BLEVE theory

Title/date	Author(s) [ref.]	Sponsor	Focus	Findings	Recommended further work	Comments
Possible mechanism for pressurized liquid tank explosions or BLEVE's/1979	R.C. Reid [28]	Department of Chemical Engineering, Massachusetts Institute of Technology	- Provides a theory for the mechanism of BLEVE's		- Well conceived experiments are needed to prove or disprove this theory	- The Super Heat Limit theory - States that there is a limit to the degree of superheat that is attainable in a liquid - If a gas that is pressure liquified is suddenly depressurized then the super heat limit may be reached and sudden homogeneous boiling will occur (the BLEVE)
The BLEVE Parts I and II/1979	W.L. Walls [34]	National Fire Protection Association	- Offers an explanation of BLEVE's	- Not all of the liquid portion of a container will flash to a vapour in a BLEVE	- Need more data	- Theory is as above the Super Heat Limit theory
Vapour explosions resulting from rapid depressurization of initial temperature/1984	M.R.O. Jones [29]	BP Research Centre	- Presents a theoretical explanation of the effect of rapid depressurization of a liquid stored at its vapour pressure	- Homogeneous boiling leads to a more explosive event than heterogeneous, although explosive boiling can occur heterogeneously		- Super Heat Limit theory has some backing in experiments - Experiments do show that not all the liquid flashes - Disagreement over whether a BLEVE is any PLG explosion or only the very violent
BLEVE's: Their causes and effects and prevention/1986	W.E. Martinsen D.W. Johnson W.F. Terrel [30]	Energy Analysis Inc.	- Offers an explanation of BLEVE's			- Super Heat Limit theory - Uncertainties surround fire ball size

TABLE 4 (continued)

Title/date	Author(s) [ref.]	Sponsor	Focus	Findings	Recommended further work	Comments
What is a BLEVE?/1987	C.A. McDevitt F.R. Steward J.E. S. Venart [31]	University of New Brunswick, Mechanical Engineering Department	- Offers two explanations of BLEVE's	- BLEVE is often misused instead of the word explosion even though they are different things (i.e. heterogeneous vaporization is an explosion and homogeneous vaporization is a special kind of	- Since accident reports have inadequate information experiments are needed to determine which mechanism is responsible of BLEVE's	- Super Heat Limit theory - Offers a second theory as well, this theory is that homogeneous boiling occurs at the rupture location only as the liquid sucked out of the breach meets the atmosphere
Hazards and protection of pressure storage and transportation of LP-gas/1988	J.A. Davenport [32]	Industrial Risk Insurers	- Offers explanation of BLEVE's	- BLEVE's occur more frequently and faster when fire impinges on the vapour space than when fire impinges on the liquid space		- Theory is as above the Super Heat Limit theory
BLEVE: The propane cylinder/1988	V. Dunn [33]	New York Fire Department	- Offers explanation of BLEVE's - Gives information about time to BLEVE	- Due to weakening of the metal from high temperatures BLEVE's can occur even if the pressure relief system operates properly		- Theory is as above the Super Heat Limit theory

TABLE 5

Modelling of projectiles

Title/date	Author(s) [ref.]	Sponsor	Focus	Findings	Recommended further work	Comments
Velocities of fragments from bursting gas reservoirs/1971	D.E. Taylor C.F. Price [35]	Lockheed Propulsion Company Redlands CA	- Improves an old model for bursting of a gas pressurized sphere in a vacuum	- Old model had serious flaws - New one is much more accurate		- Only for a specific failure mode and conditions (i.e. a sphere that ruptures into two halves in a vacuum)
Analysis of tank car tub rocketing in accidents/1972	R.H. Prause J.W. Sullivan R.J. Eiber [36]	Association of American Railroads	- Preliminary model of tank car tub rocketing	- Distance travelled by tub is a function of the temperature and pressure of the lading, length of the tub, launch angle and the outage of the tank at the time of rupture - Tank diameter and lading type were not factors - The worst combinations of variables gave a distance travelled of 1220 to 3350 m - The range of rocketing decreased rapidly with the level of the lading in the tank - The ranges calculated are maximum upper bounds		- Tub rocketing model was developed based on isentropic expansion of the lading - Calculations assumed that 100% of the energy released goes into rocketing - Report speculated that short tubs will be less likely to travel in a straight line - Model validation is difficult since accurate data is hard to come by in accident reports
Initial velocities attained by plant generated missiles/1980	G. Munday [37]	Insurance Technical Bureau	- Provides a model for projectile hazards	- Model states an initial acceleration should be supplied for fragments projected by fluid jets and no initial acceleration should be provided for other fragments	- Experiments are needed to validate this model - Computer programs need to be written to handle this modelling approach	- No attempt should be made to present results for this model because each rupture case should be considered separately

TABLE 5 (continued)

Title/date	Author(s) [ref.]	Sponsor	Focus	Findings	Recommended further work	Comments
				- Stored energy methods are not a good model to use unless an upper limit is desired		
Assessment of missiles generated by pressure component failure and its application to recent gas cooled nuclear plant design/1980	J. Tulacz R.E. Smith [38]	Central Electric	- Derives several models to predict the distance fragments are hurled and the penetration damage they cause	- To evaluate the protection given by a barrier from the failure of a pressure vessel the penetration models should be used with a mode of failure with one missile occurring - Model should be used to give an upper bound to the distance a missile will be projected for missiles of types (a) and (b) (type (a) is a flat round section of a vessel, type (b) is a valve from the vessel and type (c) is a rocketing tub)	- Experiments are needed to validate an acceptable velocity model for type (c) missiles - Work is needed to see how the penetration model relates to the case of irregularly shaped (i.e. natural) missiles - Work is also needed in the area of penetration of mild steels	- Report identifies three different types of missiles to analyze - Provides an equation for the velocity of missile types (a) and (b) - Offers two unvalidated methods to estimate the velocity of a missile for type (c) - Provides equations to predict missile penetration and scabbing thickness on a reinforced concrete wall with cylindrical missiles - Provides an unvalidated way of relating natural missiles to cylindrical missiles
The velocity of missiles generated by the disintegration of gas pressurized vessels and pipes/ 1984	M.R. Baum [45]	Berkeley Nuclear Laboratories	- Provides a model for the velocity of fragments generated by the disintegration of a gas pressurized container that is validated	- Old model overpredicts velocities by a factor of 2 for failure at design pressures - Old model underpredicts velocities for failure by overpressure		- Uses experimental work to validate the new model and refute the old - The new model is also found to be a good one for the failure of pressure pipes as well

Large missiles generated by the rupture of gas pressurized vessels: A summary of current data from experiments at CEGB, Berkeley Nuclear Laboratories/1984	M.R. Baum [46]	Berkeley Nuclear Laboratories	- Discusses experimental work and preliminary models for three types of missiles	- Experimental data already gathered suggest that the existing models are inadequate (i.e. to conservative) for large missiles - Brittle failures result in many small fragments: here none have a large kinetic energy - Ductile failures result in few large (1 or 2) fragments which have a large kinetic energy	- Model development is necessary to help predict the results of catastrophic failure of pressure vessels - Energy is lost to leakage around fragments and models need to tank this into account	
Blast and fragments from bursting pressure vessels/1984	W.E. Baker [43]	Southwest Research Institute, San Antonio, Texas	- Survey of prediction methods for blast and fragment characteristics of bursting pressure vessels	- Describes the state of the art for predicting the blast and fragment characteristics for explosions involving flash evaporating liquids as fair to poor - Describes the state of the art for predicting the blast and fragment characteristics for explosions involving compressed liquids as zero to poor	- Experimental work is needed to form a basis for understanding blast and fragment characteristics for both flash evaporating and compressed liquids	- Provides a graph to predict the maximum fragment range for gas pressurized vessel ruptures - Provides a graph to predict the blast from gas pressurized vessel ruptures
Post test assessment of blast and fragment effects of explosive failure of a large steel containment shell model during pneumatic testing/1984	W.E. Baker [44]	Southwest Research Institute, San Antonio, Texas	- Describes the test results of a steel containment vessel that was ruptured explosively and compares it to the predictions made based on a model	- Failure initiated axially near a welded joint with end stiffener then branched circumferentially - Predicted projectile distances hurled were to low - Revised calculations (using the same model with actual fragment	- Work is needed to improve the modelling of projectile distance hurled	- Experiment consisted of pressurizing a vertical cylinder to 195 psig that was designed for 40 psig - Head separated into 2 pieces which was not predicted - Gives a table of mass and distance hurled for fragments

TABLE 5 (continued)

Title/date	Author(s) [ref.]	Sponsor	Focus	Findings	Recommended further work	Comments
				geometry) were 2 to 4 times to great		
Fragment hazards from failure of pressurized liquified gas vessels/1985	P.L. Holden A.B. Reeves [40]	United Kingdom Atomic Energy Authority, Safety and Reliability Executive	- Analyses fragment throw range frequency for accidents involving pressure liquified gases	- Models for pressure liquefied gases are not developed enough - 80% of fire events that rupture resulting in missiles - BLEVE events usually project 4 or less missiles - Non fire events usually project more than 4 missiles - 80% of fragments from LPG accidents travel less than 200 m - Spheres produce more missiles that cylinders (average 8.3 vs. 4) - End tubs travel further than other fragments - Smaller vessels project missiles further Missiles tend to export fire with them	- Experiments are needed to investigate the effect of vessel size on missile range - Work is needed to develop a model specifically for fragments from pressure liquified vessel failure	- Some confusion over use of the term BLEVE - Evacuation ranges are based on missile distances recommended in a 1972 report since 1972 civilians and fire fighters have been killed by missiles
Disruptive failure of pressure vessels: preliminary design guidelines for fragments velocity and extent of the hazard zone/1988	M.R. Baum [47]	Berkeley Nuclear Laboratories	- Provides a model for the upper limits of projectile hazards for a variety of vessel geometries and contents	- Most models for pressurized gas container failure are validated - Can be used to indicate an upper limit of the ranges and velocities of projectiles from those modes of failure considered		

				- Models for pressurized liquefied gas container failure are not validated		
Missile effects resulting from a sudden loss of containment/1988	K. Moodie [41]	Health and Safety Executive, Explosion and Flame Laboratory	- Review of modelling and experimental work for assessing missile effects resulting from catastrophic release	- Validated models exist to predict the missile effects from pressurized gas vessels and pipelines - Modification of the above to model missile effects from pressure liquefied gas vessel missiles are not verified - Conservative estimates do exist for missile throw distance from pressure liquefied gas vessels	- Need more data to help validate pressure liquefied gas vessel missile generation	- Paper discusses the methodology of various projectile modelling techniques
Dynamic launch process of preformed fragments/1988	D.E. O'Donoghue W.W. Prededon C.E. Anderson [42]	Michigan Technological University and Southwest Research Institute	- Provides a model for determining the stresses in cylinder under explosive forces	- Shock in circumferential direction causes expansion of vessel - Larger expansion ratios mean larger forces since gasses are contained longer		- Requires experimental measurement of expansion ratio - Expansion ratio is the ratio of initial diameter to the diameter at the time when gas begins to leak between the fragments (between 1.6–2.1) - Acquired a value for expansion ratio from other experiments and their own - Model is validated with these experiments

TABLE 6

Blast and missile effects on structures modelling

Title/date	Author(s) [ref.]	Sponsor	Focus	Findings	Recommended further work	Comments
Methods for prediction of damage to structure from accidental explosions/1978	W.E. Baker P.S. Westin P.A. Cox [51]	Southwest Research Institute	- Blast effects on structures - Differences in pressure waves between TNT and other types of explosions	- Outlines the design criteria (qualitatively) for buildings suited to withstand accidental explosions based on the models introduced		- Once the blast loads are known damage can be quickly estimated by simple models or more exactly from complex computer modes - P–I curve is discussed - Brigg's differential equation method is discussed (results are similar) - Computer models rely on finite element methods
Generation of missiles and destructive shock fronts and their consequences/1980	W.H.L. Porter [39]	United Kingdom Atomic Energy Authority	- General review of the effects of accidental explosions			- Provides equations for the penetration of missiles into metal and concrete - Provides equations to determine the blast impulse and shock wave from explosions
An experimental and theoretical study of blast effects on simple structure (cantilevers)/1983	D.K. Pritchard [52]	Health and Safety Executive, Explosion and Flame Laboratory	- Outlines the results from experiments involving cantilever beams in vapour cloud explosions	- The preliminary comparisons for elastic deformation showed the experimental procedure works - Fair agreement between test results and elastic plastic theory were obtained	- Information needed on the dynamic material properties of metals - Information needed on the aerodynamic characteristics of structures as they deform - Further experiments	- Used a 69 m long by 1.2 m diameter cylinder closed at one end as a test tunnel - Methane air mixtures were detonated at the closed end generating peak overpressures and rise times which were

					should be carried out to provide more data on a wider variety of loadings and dimensions	representative of vapour cloud explosions - Aluminum and mild steel rectangular, mild steel tubular cantilevers were tested - Equations of deformation were then developed based on the results and elastic plastic theory
The effect of external blast on cylindrical structures/1985	D.M. Brown P.F. Nolan [48]	Polytechnic of the South Bank, Department of Chemical Engineering	- Scale cylindrical storage vessels were subjected to simulated vapour explosions and the deformation effects were measured	- The drag loading phase of the pressure wave caused the damage - The model developed showed good agreement with the experiments and an actual accident - Increased aspect (*L*/*D*) ratios meant greater damage - Stiffening rings increased resistance to damage - Wind spoilers decreased resistance to damage		- 1:40 scale models were used - Test carried out in the same test tunnel as the Pritchard [52] experiment - 260 Explosion tests were carried out
Empirical equations for the perforation of mild steel plates/1985	A.J. Neilson [49]	United Kingdom Atomic Energy Authority	- Penetration experiments for flat ended cylinders into mild steel plates - Results analyzed dimensionlessly	- Equations derived from experiments for missiles with *L*/*D* ratios of >13 give a good correlation to the tests - For short missiles (*L*/*D* ratios <13) not enough data exists for confidence in the derived equation - Missiles with *L*/*D* ratios >13 showed no dependence on length	- Additional data for short missiles is required	- Non-deforming cylinders were projected at plates to find the maximum energy not giving perforation and the minimum energy giving perforation - Results from other experimental studies are discussed

TABLE 6 (continued)

Title/date	Author(s) [ref.]	Sponsor	Focus	Findings	Recommended further work	Comments
The effects of missile impact on thin metal structures/1986	J. Jowett [50]	United Kingdom Atomic Energy Authority	- Review of previous work on projectile penetration is used to develop a model to for predict penetration of mild steel plates by flat ended cylinders and pointed nosed missiles	- Pointed missile model agrees well with published data - Short missile model agrees well with published data - Non-perforating impacts can be predicted analytically but perforating impacts can not	- Work is needed to determine the influence of target welds, the effect of non-normal impacts and the behaviour of thin curved shell targets	- Hard missiles are considered with speeds of 25 to 300 m/s and targets with width/$D > 2$ and thickness/$D > 10$ - Provides equation of penetration for flat head short and long missiles (long is $L/D > 10$) - No perforation model exists for round nosed missiles - Provides an equation for pointed nosed missile penetration
The blast effect of explosions/1986	N.F. Scilly W.G. High [53]	Heath and Safety Executive	- Discussion of several methods for estimating blast damage and their draw backs	- To predict the effects of explosions on structures either P–I, R–W curves or the impulse/critical method should be used - The table method should only be used as a last resort when data is not available		- Smaller explosions need larger overpressures to do the same amount of damage as larger explosions because of the shorter blast wave duration - Outlines several methods of determining the blast effects on structures: Tables relating overpressure to damage, P–I curves (pressure–impulse), R–W curves (stand off distance–explosive yield) and an alternative method based on observations of explosions

ruptures. Some validation of theory has been carried out by researchers studying actual plant accidents as these are the only source of large scale data. Other data is usually generated in small scale tests under idealized conditions.

The UKAEA (Holden and Reeves [40]) analyzed data gathered in an accident survey. This analysis revealed several interesting facts:

- 80% of fire events that cause ruptures result in missiles;
- BLEVE events usually produce four or less missiles and non fire events usually produce more than four;
- 80% of fragments from LPG accidents travel less than 200 m;
- spheres produce more missiles than cylinders, spheres average 8.3 and cylinders average < 4;
- end tubs travel further than other types of fragments;
- smaller vessels project fragments further than larger ones; and
- missiles tend to export fire with them.

Blast and missile effects on structures (see Table 6)

The bulk of recent work on modelling the effects of explosions on structures has been done in the United Kingdom by the UKAEA (U.K. Atomic Energy Authority), the HSE, the Explosion and Flame Laboratory of the HSE and the Polytechnic of the South Bank. The SRI in the United States has also been involved in researching explosion effects.

The prediction of the blast effects on structures has progressed from the qualitative blast damage tables of the past to more vessel specific knowledge such as the one fortieth scale cylinder blast tunnel experiments conducted by Brown and Nolan [48]. These tests help further our understanding of the effects of PLG container explosions on neighbouring cylinders. The tests lead to a model for blast effects on cylinders; however this model is based only on small scale studies.

Penetration of missiles has also been studied in the United Kingdom [49,50]. This work has established some equations for predicting penetration of both pointed and flat headed missiles into concrete and steel.

Case studies (see Table 7)

A variety of case studies have been compiled into Table 6. The RTCSRTP of the AAR and the FRA compiled a report containing tank car accidents from 1958 to 1971 [54]. They also conducted individual investigations which contain more detail of major accidents [55,56]. This table also includes the reports of two special commissions of inquiry into accidents in Canada [57,58]. Also included is an internal study of a PLG truck accident at Salmon Arm commissioned by TC [59].

The UKAEA also compiled a list of accidents involving pressurized liquified gases from 1958 to 1986. This compilation also contained some basic analysis which was taken from a report by Holden and Reeves [40]. Table 7 also con-

TABLE 7

Case studies

Title/date	Author(s) [ref.]	Sponsor	Focus	Findings	Recommended further work	Comments
Sequence of events following Crescent City derailment/ 1970	C.E. Reedy [55]	Association of American Railroads	- Report on events surrounding an accident at Crescent City			- 16 Cars derailed of which 10 had a PLG as lading - 6 Explosions occurred over a 55 hour period - Gives distance that fragments were thrown
Summary of ruptured tank cars involved in past accidents/1971	W.E. Westin [54]	Association of American Railroads	- A listing of data from accidents involving explosions			- No reference made to fill level at time of accident - Covers the period from 1958–1971 - Gives distance that fragments were thrown
Sequence of events following Houston Texas derailment/ 1971	C.E. Reedy [56]	Association of American Railroads	- Report on events surrounding an accident at Houston Texas			- 16 Cars derailed - 2 Explosions occurred over a short period of time - Gives distance that fragments were thrown
Analysis of the pneumatic burst of a large seamless steel pressure vessel in natural gas service/ 1979	B.W. Christ [60]	U.S. Department of Transport	- Report on the metallurgical analysis of the pressure vessel that failed in an accident near Litchfield	- The cylinder ruptured due to environmentally assisted cracking from the presence of hydrogen sulphide in the natural gas		- One of 12 new pressurized gas cylinders ruptured on the back of a tube trailer - Rupture was at 2200–2500 psi during filling - 11 Fragments were formed and they were thrown between 200 and 2000 ft (60–600 m) - Gives distance that fragments were thrown
Report of the Mississauga railway accident inquiry/ 1980	G.M. Grange [57]	Canadian Transport Commission	- Report on the events surrounding an accident at Mississauga	- Accident caused by overheated bearing - Recommended changes to operating procedures to improve safety	- Research should be conducted into the adequacy of safety devices presently in tank cars	- 23 Cars derailed of which 3 contained propane - 3 Explosions occurred within 1/2 an hour of the accident - Gives distance that fragments were thrown

Summary report on propane bulk trick rupture near Salmon Arm, BC June 13, 1984	R.S. Charlton J.M. Heslop [59]	Transport Canada, Transport Dangerous Goods Directorate	- Report on the events surrounding the accident near Salmon Arm	- Rupture was due to the reduction of the steel strength resulting from over heating from a fire - The leak was caused by the shearing off of an external pump's hose attachment - The propane flow rate to sustain the fire was far less than that required to activate the excess flow valve	- Various improvements on design and operating procedures were recommended to improve safety	- 3000 gal (11000 l) Tank truck exploded - Tank fixtures were damaged in accident which caused leakage - Tank was situated on a hill over a train track and when the tank exploded (BLEVE) the tank rocketed into a passing train derailing freight cars
Report of the inquiry into the failure of UTLX 9846 on Feb. 28, 1984 in the CN Company's MacMillan Yard in the Township of Vaughan Ontario/ 1985	J. Magee [58]	Canadian Transport Commission	- Report on events surrounding the accident at Vaughan Ontario	- Failure caused by impact		- An empty tank car ruptured in a switching yard - Report is concerned with who was responsible - It does give the distance the head was hurled
Assessment of missile hazards: Review of incident experience relevant to major hazard plant/1986	P.L. Holden [65]	United Kingdom Atomic Energy Authority	- A list of data from accidents involving explosions of tank cars road tankers and storage vessels	- BLEVE events seldom create more than 4 fragments - Non-fire events project more fragments (average 3.08) compared to fire events (average 2.49) - End tubs are 3 times as likely to be projected axially than other directions - End tubs travel further than other missiles - If fire is the cause of catastrophic failure in a cylindrical vessel then there is an 80% chance of missiles being formed when the vessel explodes - Mode of failure does not influence range - Spherical vessels fail in more fragments than cylindrical vessels	- The following need more measurements to yield conclusions: - Angle of launch from horizontal - Distance missiles projected separating bouncing and deflecting distance from through the air travel - The difference in the number of fragments between fire and non-fire events - The direction of launch relative to the axis of the tank car	- Suggests that for spheres the size influences distance and number of fragments (the larger the vessel the more and the longer the fragments are thrown)

TABLE 7 (continued)

Title/date	Author(s) [ref.]	Sponsor	Focus	Findings	Recommended further work	Comments
Investigation into the circumstances surrounding an accident in Nijmegen involving a tanker/ 1983	J.B.R. van der Schaaf C.F. Steunenberg [61]	TNO, The Hague, The Netherlands	- Outline of the events of a fire at a fuel station receiving a delivery of LPG from a road tanker	- Tank ruptured in the vapour space at a place impinged by flame after thinning occurred - Tank was subjected to temperatures of about 600 °C at rupture site and pressure of between 1800 and 2700 kPa - Fire ball was 40 m diameter and on top of a column 25 m diameter and 25 m high (for 10 s)		- Road tanker had no safety valve but the storage tank did - Tanker exploded after 25 min of exposure to flame - Tanker moved 4 m, side of tanker hurled 50 m and parts hurled up to 125 m - Fill about 85% (400 kPa) at time of rupture
Analysis of the LPG incident in San Juan Juan Ixhuatepec, Mexico City, 19 November 1984/ 1985	C.M. Pietersen S. Cendejas-Huerta [63]	TNO and Academy of Scientific Investigations of Michoacan, Mexico	- Detailed investigation of the disaster in Mexico City - Comparison of theoretical models to observed damage	- No significant overpressures were generated by vapour cloud combustion in the built-up area of San Juan Ixhuatepec - Damage mechanism of an LPG explosion is not just the lifted fireball but also ground level fires and spreading unburned LPG - Blast overpressures calculated from flash evaporation models over estimated the overpressures observed - Effects of heat radiation are over estimated by models - The close lay-out of the site may have contributed to the rate of escalation of the incident - For fragments thrown > 100 m the direction of travel depends on the orientation of the cylinder	- Further development of explosion models is required - Emergency services should take into account a fast development of this type of incident	- Contains detailed account of incident sequence of events - Shows damage caused in neighbourhood - Compares known BLEVE events of similar magnitude with this incident - Discusses newspaper reports of the incident - Discusses emergency handling of incident - Includes eyewitness accounts of events - Reports mass and range thrown for 84 of the largest fragments tabularly and schematically (over a map)

BLEVE in a LPG storage yard/1986	G.R. Collins [66]	Stockton Fire Department, CA	- Outline of the events at a LPG storage yard in California	- Explosion caused by fire resulting from PRV malfunction and solar radiation - A PRV on a 10 or 25 gal cylinder vented to release pressure (from solar exposure) and fragmented causing total loss of containment and ignition		- 5 min after first cylinder other 10 and 25 cal cylinders exploded causing flames to impinge on a 500 gal tank - PRV of the 500 gal cylinder began to vent after 8 min and exploded causing a 90 m high and 45 m wide fire ball
Failure analysis of an amine-absorber pressure vessel/1987	H.I. McHenry D.T. Read T.R. Shives [62]	National Bureau of Standards	- Report on the explosive failure of an amine-absorber pressure vessel	- Failure occurred circumferentially adjacent to a repair weld near the base of the vertical cylinder - Failure was caused by hydrogen stress cracking (800 mm long and 90% deep crack)		- The vessel came apart circumferentially near the base and the released propane exploded - The top 14 m of the 18.8 m vertical cylinder rocketed 1000 m
Analysis of the LPG disaster in Mexico City/1988	C.M. Pietersen [64]	TNO	- Analysis of the disaster in Mexico City by comparing it to existing disaster models	- Models of vapour cloud dispersion are not adequate to clouds of this scale - Models of fire ball size under predict the size seen here - The confined space of the storage facility helped the creation of overpressures	- Models to predict the effects of overpressures need to be developed - Models of the fire ball dimensions from BLEVE's are also inadequate and need work	- 9 Major explosions - 2nd and 7th were the largest (0.5 on the Richter scale) - Vapour cloud developed from pipe or cylinder leak and rose to 2 m before it ignited causing an unconfined vapour explosion and damage to buildings and storage vessels - Fragments from 44 of 48 cylinders that exploded were thrown between 100 and 1200 m - Other 4 cylinders formed very small pieces

tains journal articles and internal reports that detail non-rail accidents; a pneumatic burst [60], a storage site [61], a process cylinder [62] and a storage site [63,64]. The Dutch TNO investigation of the LPG disaster in Mexico City in cooperation with the Academy of Scientific Investigations of Michoacan Mexico is extremely useful and comprehensive [63].

The information gathered from case studies sheds some light on several topics of interest including failure modes, effects of fill conditions and projectiles.

Failure modes

The information on PLG container failure modes that come from accident reports indicate there are two common failure modes for PLG container explosions.

The most common mode is where the rupture begins in the axial direction (usually in wall next to the vapour space) and then branches in the circumferential direction to form fragments. This common failure mode of PLG storage vessels has been well documented. This mode can generate several different specific failure patterns. Westin [54] categorizes seven different failure patterns by the number and type of fragments generated.

The other common failure mode for PLG containers is where rupture begins in the circumferential direction and remains that way generating one or two large vessel fragments or tubs. Westin [54] categorizes two different failure patterns for this mode. What parameters determine which of these failure modes and patterns occur is still not fully understood.

Fill conditions

No references have been found that make a direct link between the severity of an explosion and the fill level of a PLG vessel at rupture. Few accident studies have enough information to establish fill conditions at the time of rupture. However, two case studies have been found that do estimate fill level.

Fill level was calculated in one detailed study of a rail tank car accident [56]. In the accident sixteen cars were derailed and two cars of vinyl chloride were punctured and started to burn. After 45 min the first car exploded followed almost immediately by the second. The remains of the first car showed the impact puncture hole to be 89 mm by 8 mm. Since the orientation of the tank was known from photographs calculations were done to estimate the amount of vinyl chloride that could escape in 45 min. The calculations showed the tank had a fill level of approximately 70% when it ruptured and the temperature of the lading was under 16°C. At rupture the tank formed two rocket tubs one taking up the majority of the car (over 3/4). The largest tub was thrown 100 m. The smaller tub was thrown 68 m.

Another case study that refers to fill level is the 1985 Magee inquiry [58]. In this case rupture was induced by impact at a switching yard. The ruptured tank blew its head off even though it was listed as "empty, last containing butane". The rail tank car had 380 kPa to 483 kPa of butane and natural gas inside it (i.e. 364 kg to 545 kg). Upon impact from another car, during switching, the first car exploded and the head was blown 38 m.

Projectiles

All the case studies referenced contain information about the distances that fragments were thrown. Most case studies do not include a detailed investigation of an accident scene where all the fragments are recovered and measurements taken of the fragment distance thrown vs. fragment mass. In general, accident data consists of eyewitness accounts and photographs, and the information on fragments generally omits any mention of mass and probably only accounts for the largest pieces.

There were a few studies that did go into detail about all the fragments and where the rupture originated on the tank. These include the report on the Salmon Arm by Charlton and Heslop [59], the report on a truck accident in Nijmegen, The Netherlands by Van der Schaaf and Steunenberg [61] and the analysis of the Mexico City disaster [63,64].

Case studies compared to experimental studies

The compiled accident summaries of Holden [65] and Westin [54] give enough information to plot a histogram of fragment distance hurled. Some

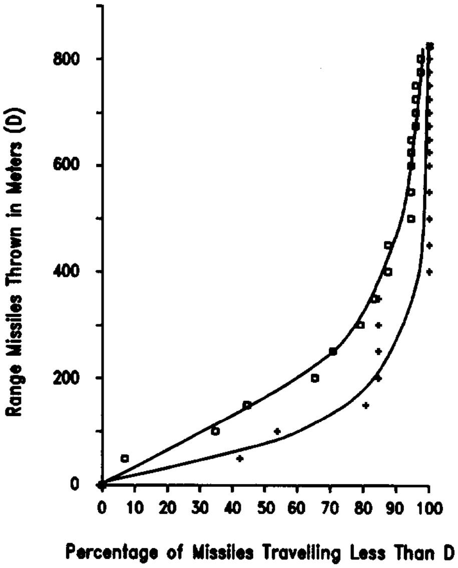

Fig. 2. Cumulative histogram comparing data from case studies (□) and experimental studies (+) showing the distance fragments are hurled after catastrophic failure. Case studies compiled by Holden [65] and by Westin [54] (total of 61 samples) is compared with experimental work done by Anderson and Norris [3] and Schulz-Forberg et al. [12] (total of 27 samples).

articles about fire engulfment tests where catastrophic ruptures occurred contain enough information to plot similar histograms. The full scale rail tank car fire engulfment test of the AAR and the FRA [3] and the three small stationary storage vessel engulfment tests done by Schulz-Forberg et al. [12] all contain the necessary information to plot the histogram. Figure 2 is a comparison of the cumulative histograms of the 61 fragments recorded in Holden's [65] and Westin's [54] compiled accident reports and the 21 fragments from the fire engulfment tests of Anderson and Norris [3] and Schulz-Forberg et al. [12].

The differences between the two graphs may be caused by the sample sizes for the two histograms. Another difference that should be noted is the number of fragments from each rupture. The accident report data recorded 61 fragments from 60 ruptures. The experimental data recorded 27 fragments from 4 ruptures. Reports on experimental studies record all vessel fragments including the smaller ones. While, as indicated previously, accident reports tend to neglect these less noticeable projectiles. Because of this, accident reports may give a misleading representation of the projectile hazards from PLG container explosions.

Research needs

Based on the findings of the literature search a number of research needs have been identified.

Fire impingement

Fire impingement studies (both experiments and modelling) has advanced our understanding of thermal ruptures considerably. However, we are not yet able to predict the resulting release severity with confidence. In addition, many of the current models are limited in that they are empirically based and therefore are only reliable for certain vessel scales. Further research is necessary to extend the applicability of these models to larger scale facilities.

BLEVE's

BLEVE's are widely accepted as being the worst kind of PLG release and yet we still do not have accurate methods of predicting when and where they will occur. This is clearly an area requiring research.

Vessel failure modes

Many articles or reports have been written on the failure modes of PLG vessels. These reports include: Westin [54], Anderson and Norris [3], Early and Interrante [4], Christ [60], Charlton and Heslop [59], Baker [44], Baum [45], Schulz-Forberg et al. [12] and McHenry et al. [62]. All these reports, except for McHenry [62] deal with tanks where rupture began in an axial direction and then at some point or points the cracks branched in the circumferential direction generating fragments. The report by McHenry et al. [62] deals with a process cylinder where rupture began in a circumferential direction and remained that way (i.e. a head blew off). While no recommendations were made to conduct research into failure modes, the determining factors that govern which failure mode occurs in an explosion are not well understood.

It is believed by the authors that failure modes and projectile distances are strongly related. For example, rocket type failures of vessels can lead to large projectile distances and extreme projectile hazards. A better understanding of failure modes and mechanisms could possibly lead to the elimination of rocket type failure modes and the associated hazards.

Blast and projectile effects on structures

Pritchard [52] recommends that the aerodynamic characteristics of deforming structures be investigated and that more explosion tunnel tests be conducted on a wider variety of dimensions and loads. Jowett [50] recommends that some areas of projectile penetration into concrete and metal barriers needs further work. These areas include: the influence of target welds; the effect of non normal impact and; the difference between thin flat targets and thin curved targets. A better understanding of these factors could lead to better design of safety containment structures.

Projectile hazards

Authors of reports reviewed in this study have made the recommendation that more data on projectile hazards is needed. Holden and Reeves [40] noticed that the size of PLG vessels seems to have an effect on the distance that fragments are hurled. They state that more data is required to determine the relationship between vessel size and fragment distance hurled. Holden [65] recommends that more parameters need to be investigated than are presently possible through the use of official accident reports. He stated that more data is needed on the following parameters; angle of launch, distance thrown until first bounce and the direction of launch with respect to the tank axis. Baum [47] also observed a lack of data on PLG container failure.

Short comings in the ability of models to predict missile behaviour from PLG tank explosions exist. Baum [45,47] notes that current models make the assumption that no fluid leakage between fragments occurs in the launch stage. This means that these models give absolute upper limit estimates of launch velocities which can not be obtained. Baum [47] has found that many possible missile generation patterns for PLG vessels do not even have crude models for prediction. He states that model development is needed in this area. Baker [43] also recommends modelling studies be conducted to improve the state of knowledge for the prediction of projectile behaviour.

Conclusions

This literature review has investigated the state of knowledge relating to the failure of PLG vessels and the associated hazards. It is clear from the literature available that many investigators have been actively studying this area and continue to do so.

As a result of this study a number of research needs have been summarized. It is clear that much work is still needed before we fully understand the hazards associated with the accidental release of PLG's.

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