A NEW ESTIMATE OF THE LIKELIHOOD OF SPONTANEOUS CATASTROPHIC FAILURE OF PRESSURISED LPG STORAGE VESSELS

IJ O'Donnell[1], DW Phillips (AMIChemE)[1] and PW Winter[2]
[1]SERCO ASSURANCE
[2]AEA TECHNOLOGY

A key input for quantified safety assessments for Control of Major Accident Hazards (COMAH) reports is the reliability of pressurised plant. Liquid Petroleum Gas (LPG) bullets, with capacities generally in the range from 1Te to 100Te, are an increasingly common example of such plant items, reflecting the growing consumption of LPG as a fuel for heating and for transport. Almost all such vessels are used downstream of the production process, and consequently store only LPG of commercial purity, essentially free of contaminants such as water or acids that can introduce corrosion problems.

Improvements in the design, operation and protection of such vessels from external hazards have focussed attention on a failure mode often termed "cold catastrophic failure". In this, the vessel is supposed to fail during normal operation due to brittle fracture, arising from the uncontrolled growth of a manufacturing defect, and causing a gross disruptive failure of the vessel. Most published rates for such failures are based on vessel performance and integrity assessments from the 1980′s or earlier, with typical reliability values of the order of 10^{-6} per vessel year.

In a major new study this rate has been re-examined, using a dual approach. The first, based on worldwide statistics of vessel performance and population, supports reliabilities for small vessels of 10^{-8} per vessel year, and 10^{-7} per vessel year for large vessels. The controlling factor for small and large vessels is the vessel population since none of the incident databases consulted revealed any unambiguous example of such a failure.

The second approach, independent of the first and using Monte Carlo simulations of a fracture mechanics model, has generated reliabilities consistent with the results from the statistical analysis. A detailed study of three (two large and one small) LPG bullets gave reliability values for normal operation of 10^{-7} per vessel year, and in some of the cases as low as 10^{-9} per vessel year. The study also considered the effects on reliability of very low temperatures, as might occur in the event of adiabatic chilling during blow-down, and of excessive pressurisation from over-filling. Both of these types of rare events, whilst having noticeably higher conditional failure probabilities than for normal operation, were shown to have minimal effect on overall vessel reliability due to their low frequency of occurrence.

Such low failure rate values focus attention on the rigour of the model, and the assumptions used. Both these aspects have been considered, in part through the use of numerous sensitivity studies.

These studies also afforded some significant insights into the dependence of the calculated reliabilities on factors such as proof testing, defect density and vessel size. Equally significant is the finding of the relative insensitivity of the calculated reliabilities to material properties, and particularly toughness.

If these results are accepted then it is likely that the assessed safety risk from LPG storage can be revised downwards. There are also some implications from the work for pressure vessel design codes, underlining the importance of proof testing, and specifically the importance of both the test pressure and test temperature.

INTRODUCTION

A key input for quantified safety assessments for COMAH and other safety reports is the reliability of pressurised plant. LPG bullets are an increasingly common example of such plant items, reflecting the growing consumption of LPG as a fuel for heating and for transport. These vessels are cylindrical welded steel containers with domed ends, mounted horizontally on saddles, as shown schematically below.

Improvements in the design, operation and protection of such vessels from external hazards have focussed attention on a failure mode often termed “cold catastrophic failure”, in which the vessel could fail during normal operation due to brittle fracture. Most published rates for such failures are based on vessel performance and integrity assessments from the 1980’s or earlier, with typical reliability values of the order of 10^{-6} per vessel year. Also, these assessments depend on a small number of primary sources of information, and the use of judgement to extrapolate from these limited data[1].

In this major new study this rate has been re-examined, using a dual approach of statistical and fracture analysis.

STATISTICAL ANALYSIS

In simple terms, the statistical reliability of LPG bullets failing by “cold catastrophic failure” over a given time period is the ratio of the number of reported such events to the average population of relevant vessels in service over that same period. In practice, issues such as the number of events, the completeness of the data, the uniformity (“stationarity” in statistical terminology) of the incident and vessel population, the clarity of the

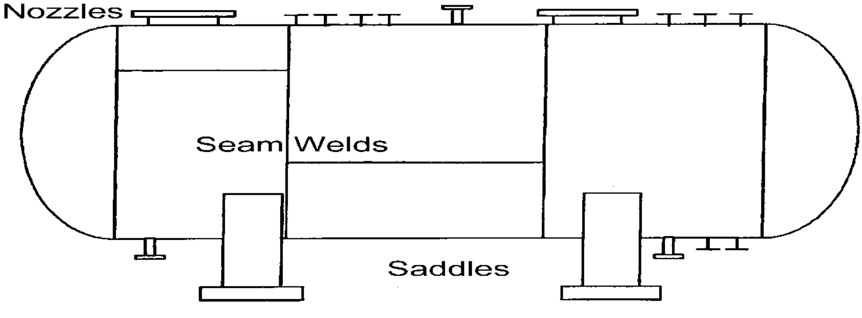

Figure 1. Schematic of a typical LPG bullet (vessel)

description and the consistency of definition complicate the interpretation of this simple calculation.

The work reported here can be seen as a more comprehensive survey than has been reported previously[2].

INCIDENTS

There are a growing number of databases of industrial incidents that include events relevant to the process and petrochemical industries. From these it is possible to identify incidents that might be relevant to cold catastrophic failure of LPG bullets. None of the databases claims to be complete, particularly as regards minor incidents, nor incidents outside the main data collection areas of Europe and North America, nor incidents that occurred in the less recent past, e.g. before 1960.

Ten databases were searched, claiming to cover in total over 50,000 events[3–12]. Many of these events appear in more than one database, so the number of separate events is probably closer to 20,000. From these, a process of screening based on the definitions of failure and vessel type was used to remove irrelevant instances. For example, the initial trawl of MHIDAS identifies 32 possible events, none of which passed subsequent scrutiny. Overall, only four candidate reports relevant to cold catastrophic failures of LPG bullets were identified for more detailed review. These were:

1. Catastrophic failure of a low temperature pressurised CO_2 storage tank in the UK, in 1986, reported by AOTC. This event was not reported by any other database, occurred in a vessel with a maximum operating temperature of −30°C. This is below the temperature range generally encountered by LPG bullets and in the range for which normal steels exhibit increasingly brittle behaviour. In addition, CO_2 can be corrosive for steel.
2. Weld failure of a non-pressurised propane storage tank in Japan, in 1962, reported by MARS and TNO. H_2S contaminants in the propane had contributed to crack growth in the weld of the high strength steel used to fabricate the vessel.
3. Shear tearing failure of a high pressure caustic ethene degassing drum in the USA, in 1984, reported by OLYMPUS. Although the tear initiated in a weld defect, propagation had been by tearing of plate material due to gross over-pressurisation, in turn due to faulty vent line design, and resulting in permanent plastic deformation in the failure zone.
4. Brittle failure of a pressurised natural gas liquids (NGL) vessel in the USA, in 1984, also reported by OLYMPUS. The failure resulted from over-pressurisation due to corrosion products jamming the relief valve closed. The failure occurred when the ambient temperature was low enough (−23°C) for the vessel steel to have been brittle.

In each instance it was felt that there were factors that made the event almost certainly not relevant to the cold catastrophic failure of static LPG bullets containing high purity LPG under normal operating conditions. These factors were corrosion and/or over-pressurisation due to faulty design, maintenance or operation.

In the statistical data analysis we report here, reliabilities were calculated twice; once based on there having been no relevant failures and a second time based on there having been one relevant failure. The latter is to help quantify the effect on the results of data incompleteness or mis-interpretation and, arguably, the possibility that the first incident of the four above not being conclusively rejected on the evidence available.

VESSEL POPULATION

There are several sources of information, provided by the industry, about the number and size of LPG bullets in service[13–15]. These sources indicate, in broad terms:

- A steady worldwide increase in LPG consumption and number of LPG bullets in service.
- A longer history of LPG storage in the US (dating back to around 1940) than Europe (dating back mainly to 1970) and the rest of the world.
- Most of the growth in vessel population since 1990 has been outside the more established North American and European markets.
- A very small, and regionally dependent, proportion of large (>6600 kg capacity) LPG bullets, with ratios of the number of large to small vessels ranging from some 1:50 for Europe to 1:500 or so for the USA.
- A total worldwide vessel population in 2000 of some 50 million, with some 10% of these in Europe and 30% in the USA.

Table 1 summarises this population information for the year 2000, in terms of accumulated vessel years of operating experience.

RELIABILITY RESULTS

If there is a total vessel population of 50 million, which has grown linearly over a 30-year period, then some 750 million vessel years of operating experience will have been accumulated. No other type of relatively large pressure vessel seems likely to have accumulated such an extensive experience base. If in addition it is assumed that there has been only one reported instance of cold catastrophic failure in that population, then we are driven to the conclusion that the average failure rate will be of the order of 10^{-9} per vessel year.

Table 1. Summary of accumulated vessel years of operating experience by region

	Region		
Tank size	N America	W&C Europe	Rest of World
Small	2.8×10^8	5.9×10^7	3.4×10^8
Large	3.6×10^5	1.2×10^6	1.8×10^6

Table 2. World mean vessel failure rates with lower and upper confidence limits assuming one failure in each size category

Tank size	CL	50%	90%	95%	Mean
Small	lower	4.2×10^{-10}	7.6×10^{-11}	3.7×10^{-11}	1.5×10^{-9}
	upper	4.0×10^{-9}	7.0×10^{-9}	8.2×10^{-9}	
Large	lower	8.7×10^{-8}	1.6×10^{-8}	7.7×10^{-9}	3.0×10^{-7}
	upper	8.2×10^{-7}	1.4×10^{-6}	1.7×10^{-6}	

Table 2 above summarises this position, with a little more statistical subtlety through the derivation of mean failure rates at different confidence levels. In Table 3, the assumption is that there have been no incidents of cold catastrophic failure, e.g. the mean failure rate is zero. The confidence intervals on the mean failure rates have been calculated using the assumption that the underlying process is described by the Poisson distribution.

Therefore, this first approach, based on worldwide statistics of vessel performance and population, supports reliabilities for small vessels of order 10^{-9} per vessel year, and 10^{-7} per vessel year for large vessels. The controlling factor for small and large vessels is the vessel population since none of the incident databases consulted revealed any unambiguous example of such a failure.

SENSITIVITIES

The interpretation of these statistical results requires some understanding of their sensitivity to the complicating factors mentioned above. We offer the following comments:

- Number of events: with so few relevant events, the results are sensitive to the decision whether any particular incident falls within the definition. We have attempted to screen out potential events with care, and based on as much information as possible. Our view is that there are no reported incidents that are unambiguously examples of cold catastrophic failure of any size of LPG bullet or comparable vessel (in terms of its design and its service) under normal operating conditions.

Table 3. Upper confidence limits for vessel failure rates assuming zero failures in each size category

Tank size	50%	90%	95%	Mean
Small	1.0×10^{-9}	3.4×10^{-9}	4.4×10^{-9}	0
Large	2.1×10^{-7}	7.0×10^{-7}	9.1×10^{-7}	0

- Completeness of the data: cold catastrophic failure of an LPG bullet would be a major incident, and it is likely to be reported. In addition, most of the operating experience with such vessels has been in the last 20 years, again militating against under reporting. We cannot rule out the possibility that there may have been such an incident, perhaps in the earlier period of experience, for example in the USA in the 1940's.
- Uniformity of the incident and vessel population: major pressure vessel design codes such as BS 5500, API and ASME have been relatively stable for more than 20 years. There have been changes in, for example, the degree of protection provided for LPG bullets against extreme loads such as Boiling Liquid Expanding Vapour Explosions (BLEVE's), but this should not directly affect the cold catastrophic failure mode. We therefore believe that there is no significant underlying factor that would materially alter the likelihood of this failure mode over the period in which most of the operating experience has been achieved.
- Clarity of the description: many event reports are less than comprehensive, and we have attempted to follow up the four candidate failures relevant to cold catastrophic failures of LPG bullets by searching for additional industry reports. This has been successful with three of the four, leaving only one failure that cannot be conclusively rejected.
- Consistency of definition: we have applied definitions of failure mode and vessel type consistently for the interrogation of all the data sources examined.

FRACTURE ANALYSIS

The second approach, independent of the first and using Monte Carlo simulations of a fracture mechanics model, has generated reliabilities consistent with the results from the statistical analysis. In this, the calculation takes distributions of defect sizes and fracture toughness, and examines whether, under the applied loading, the defect is or can grow to a critical size[16]. This is the point at which catastrophic failure can, and is assumed here to, occur.

This calculation is specific to a particular vessel and its operating history. Because of the absence of any significant time dependent degradation mechanism — i.e. fatigue and corrosion can both be discounted, from observation and analysis, the calculated probability of failure is the failure over the normal operating lifetime, and not the annual failure rate. We have assumed an average vessel age of 15 years (representative of the worldwide average), so the annual failure rate is $1/15$ of the failure probability. As the number of vessel operating years of experience increases then the annual failure rate calculated by this method reduces.

DEFECTS

Very few pressure vessels have been subjected to the detailed examination needed to characterise all the potentially significant defects in it resulting from its manufacture. One of the exceptions to this is from work undertaken by the UK nuclear industry, using materials taken from thick-walled steel pressure vessels fabricated under conditions typical of design codes, plate fabrication and welding practices of the mid twentieth century. We have assumed that the defects found from this are representative of those that would occur in thicker LPG bullets. The main features of this distribution of defect sizes[17] are:

- Most defects (90% or more) are in the welds or associated heat affected zones (HAZ), rather than the parent plate.
- There are typically 12 defects per cubic metre of weld metal.
- The number of defects decreases exponentially with increasing defect size.

The assumptions made regarding defect densities are important and there are significant uncertainties associated with their definition[17]. In this study, therefore, we have tested the affect on reliability of allowing variations in defect density of up to 100 per cubic metre of weld metal. In this study, the potential variation in defect aspect ratio has been accounted for by allowing defects to vary in shape between roughly circular, penny-shaped cracks and extended defects with a length to through-wall depth ratio of 100.

TOUGHNESS

Fracture mechanics uses a material property termed fracture toughness to calculate whether the stress intensity at a crack tip is sufficient to overcome material resistance, and so grow. The stress intensity increases with the applied loading and with defect length. For the materials used to fabricate LPG bullets, the toughness properties in the operating temperature envelope are in the ‘transition regime’, between an upper shelf, high toughness region and a lower shelf, low toughness region. Thus, fracture can potentially occur under conditions where the load or defect length is increasing and/or the temperature (and toughness) is falling.

Fracture toughness can be measured using one of a number of test methods. These methods are rarely routine and fracture toughness tests are not generally required by design codes. Simpler, surrogate, test methods that measure impact strength are generally required by design codes, and this is the case for the LPG bullets analysed. However, Charpy impact toughness parameters have been correlated with fracture toughness[18], and we have used this method to characterise the toughness distribution at any temperature. This method describes the statistical distribution of toughness at any temperature relative to a Reference Temperature T_o. The appropriate value of T_o, including an allowance for the correlation errors, is obtained from the Charpy impact results. To facilitate a comparison of reliability between different vessel geometries a common T_o value of $-53^\circ C \pm 15^\circ C$ has been used. This is based on the analysis of Charpy data from a large vessel located in Scotland. In fact it was shown that the failure rate was insensitive to the choice of T_o used in the analysis.

LOADS

In normal operation, the main active load on a static LPG bullet is due to the vapour pressure of its liquefied contents. This load is temperature dependent and reduces as temperature falls. Other normal operational loads, from self-weight and from attached pipework, are relatively trivial under normal operation. Also, thermal fatigue in normal operation is trivial, because of the relatively stable thermal environment (a 10°C cyclic variation is typical in filling operations). There is no other fatigue mechanism identified for static vessels. The vessels analysed have not had any post weld heat treatment (PWHT), and it is believed that this will be the case for most of the vessel population. In the non-PWHT condition, welding residual stresses are high, and assumed to be at yield stress levels, and these have been accounted for in the analysis.

Outside the envelope of normal operation, many extreme load cases can be imagined and have been recorded in incident databases[3–12]. These extreme load cases may be mitigated or catered for in the design. Such load cases include:

i. External corrosion, from e.g. moisture trapped under insulation and failure of galvanic protection.
ii. Fire engulfment, resulting in higher pressure and reduced strength.
iii. External loading, from impact or seismic events, resulting in higher general and local stresses.
iv. Chilling through adiabatic blow down, resulting in reduced pressure and reduced toughness.
v. Over-filling, resulting in higher pressure and so higher stresses.

Such load cases are relatively unlikely. Cases i–iii concern external hazards or maintenance failures and are outside the scope of this study. Cases iv and v are outside the envelope of ‘normal operation’ but have been considered here in sensitivity studies.

PRE-SERVICE SCREENING

All LPG bullets are subject to some pre-service inspection and testing. Pre-service inspection may find larger defects; if the inspection is only visual then only surface breaking defects can be found. Radiographic, ultrasonic or other volumetric inspection can also find buried defects. Any defect found will be sentenced: larger defects usually will be repaired. This will reduce the prospect for subsequent in service failure. The worth of such inspection in improving vessel integrity has been thoroughly investigated and reported. Since the capability of volumetric inspection is highly variable, in this work we have assumed that no volumetric inspection has been performed. A sensitivity study has examined the effects of including a volumetric ultrasonic inspection.

A second means of pre-service screening of defective LPG bullets is from the proof hydro-test. In this, the vessel is pumped up with water at ambient temperature to a higher (e.g. 1.4 times) pressure than the design pressure (the pressure at which the stresses in the vessel are, by design, within acceptable levels for the materials used). This overload is intended to fail any defects that might be close to a critical size at the design pressure.

In the fracture analysis, the benefits of proof testing are recognised in a number of ways. Firstly, mechanical relaxation of the welding residual stress is allowed for. This reduces the loads on the defects, and has the effect of reducing the number of failures that are identified under normal operating conditions (referred to as 'unscreened failures' below). Secondly, for those failures that are identified under normal operating conditions, the 'vessel' is subjected to proof test loading and it is noted whether or not a failure in the proof test is also registered. If a proof test failure is registered, then it is assumed that this vessel would not have entered service and hence this potential failure is screened out.

Finally, if a failure is noted under normal operation and this is not screened out by the proof test then it is noted whether or not the vessel would be protected by a phenomena known as warm pre-stressing (WPS). In this case, the overload in proof testing has an important secondary effect of putting the material at the tip of sub-critical defects into a compressive stress field under normal loads. In order to cause fracture it is necessary to overcome this compressive field and this leads to protection from fracture even at lower temperatures.

RESULTS

A detailed study of two large and one small LPG bullets was made using the probabilistic fracture model. The main features of these three vessels are described in Table 4.

Table 5 lists the number of failures calculated, under the same conditions for these three vessels, and shows their reduction by the proof test and by the resulting effect of warm pre-stressing. Failures due to buried and surface breaking defects are listed separately.

Figure 2 shows the conditional failure probabilities as a function of temperature for the large vessel in Scotland and the small vessel in Poland. The bands reflect the uncertainty associated with the definition of defect density. It can be seen that the conditional failure probability falls with increasing temperature, and naturally there are no failures at temperatures above the proof stress temperature of 15°C.

For temperatures within the normal operating envelope, these conditional probabilities are related to the annual failure rates by dividing them by the mean vessel lifetime. For events outside the normal operating envelope, the conditional probability must be divided by the interval between the events. For normal operation with the minimum temperature in the range $-10°C$ to $-25°C$, application of this method results in vessel annual failure rates of 10^{-7} or less for large vessels and around 10^{-9} for small vessels.

Table 4. Selected details of the LPG vessels analysed in this study

Location	Capacity	Wall Thickness	Diameter	Proof Stress	Weld Volume
Scotland	105 m^3	22 mm	3.7 m	203 MPa	0.017 m^3
Denmark	233 m^3	14.5 mm	3.4 m	230 MPa	0.021 m^3
Poland	3 m^3	5.85 mm	1.25 m	208 MPa	0.0002 m^3

Table 5. Raw failure data for each vessel obtained with the same T_o value and at an assessment temperature of $-10°C$

	Number of Failures in 10 million simulations, $T_o = -53°C$, Assessment Temperature $= -10°C$					
	Unscreened		After Proof Test Screening		After PT & WPS Screening	
Vessel	Buried	Surface Breaking	Buried	Surface Breaking	Buried	Surface Breaking
Scotland	653	6350	43	15	5	0
Denmark	149	14052	12	9	3	0
Poland	0	37757	0	11	0	7

SENSITIVITIES

Such low failure rate values focus attention on the rigour of the model, and the assumptions used. Both these aspects have been considered, in part through the use of numerous sensitivity studies. These studies also afforded some significant insights in the dependence

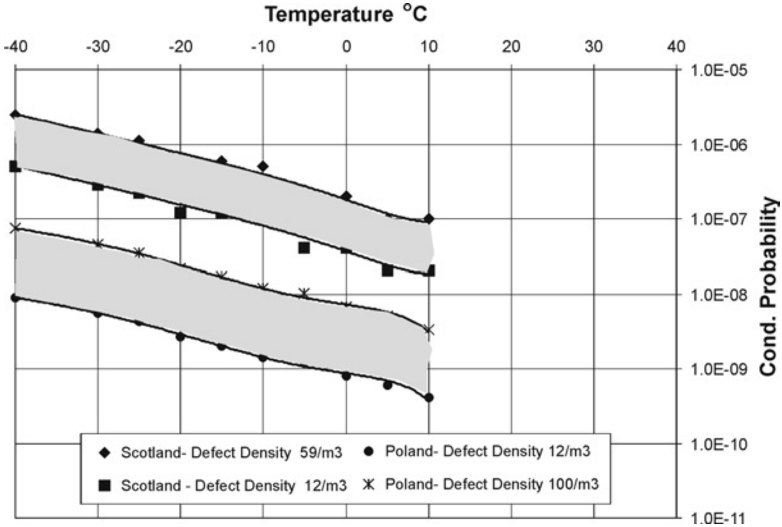

Figure 2. Conditional probability of failure as a function of temperature for the large vessel located in Scotland and small vessel located in Poland

of the calculated reliabilities on inspection, proof testing, vessel size, wall thickness, material properties, defect size, shape and density, and vessel pressure and temperature. These sensitivities are discussed below.

- Pre-service visual inspection: this is a universal practice and should find larger surface breaking defects. No credit was taken for the beneficial effect of this on integrity since it would complicate reliability comparisons between different thicknesses of vessel: a higher proportion of significant defects in thinner vessels would be detected.
- Pre-service volumetric inspection: based on published studies[19] this would reliably detect larger defects. No credit was taken for this beneficial effect on integrity since it is not a universal practice for all vessel sizes and design codes. Perhaps surprisingly, simulations have shown that the application of inspection has only a very marginal effect on reliability. However, this is understandable since the results showed that the assumed inspection capability did not significantly reduce the density of undetected defects in the size category that caused failure.
- Proof testing: the calculation shows that the vast majority of combinations of larger defects and lower toughness are revealed by the proof test. Furthermore, because the test screens out poor properties, the screened reliability becomes relatively insensitive to toughness. This removes most of the effect of uncertainty in toughness properties, and so makes relatively insignificant what could otherwise be a weakness in the conclusions drawn from the model.
- Vessel size: the total number of defects increases with the volume of defective material, and so increases approximately linearly with vessel length and diameter and with the square of the thickness. Consequently, smaller vessels are less likely to contain a significant defect, and so have a correspondingly higher reliability.
- Vessel wall thickness: the defect distribution used is derived from measurements on 25 mm thick steel vessels. Two effects result from this for thinner walled vessels:
    - Larger defects are more likely to be surface breaking and therefore more easily detectable: this increases vessel reliability.
    - Thinner vessels are less capable of supporting the compressive stresses associated with the beneficial effects of “warm pre-stressing”: this reduces vessel reliability, and in the limit becomes a more important effect than that of better detection. It does not have any significant influence on the still overwhelming effect of reduced number of defects in smaller vessels.
- Defect geometry: the main factors here are the defect aspect ratio (longer defects are more threatening, narrower defects are harder to detect) and depth below the surface. In this work we have varied these parameters, with defects ranging from circular to extended cracks, and distributed throughout the vessel wall.
- Defect density: while the properties of defect distribution cited above are reasonable, there is more recent work that suggests that the defect density may be underestimated, perhaps by as much as an order of magnitude for smaller defects. We have repeated the calculations with these higher defect concentrations. The effect decreases the calculated reliability, but overall reliability remains high.

- Vessel pressure and temperature: increased pressure gives a higher calculated failure rate. Raising the pressure from normal operating levels to the safety valve set pressure increases the failure rate by approximately two orders of magnitude. Decreased temperature also gives a higher calculated failure rate; lowering the temperature to $-40^\circ C$ raises the failure rate by about an order of magnitude. Based on anecdotal information, the frequency of these events is considered low enough for the overall reliability of the vessels not to be significantly affected.
- Fatigue: mechanical fatigue may be a significant loading and design consideration for vehicle mounted vessels, and thermal fatigue may become of interest for vessels exposed to unduly onerous environmental conditions where, for example, diurnal temperature variation is high. However, for the static European vessels studied here, fatigue was an insignificant mechanism for defect growth.
- Corrosion: chemical attack within an existing defect can generate high rates of defect growth, as evidenced by the numerous reported "in service" failures of vessels subject to such effects. Vessels used for storage of commercial grade LPG do not suffer from any reported internal corrosion, although there can be external corrosion in cases where the vessel is not properly maintained.

CONCLUSIONS

Statistical analysis can tell us in a straightforward and practical way what has been, but offers little insight into why things were that way. In contrast, theoretical mechanistic modelling is designed to offer those insights and, when developed into a reliability assessment tool, can also provide a prediction of what is to be obtained from analysis of future statistics. In combination, the two approaches provide the most convincing and useful means of estimating the reliability of a mechanical component.

The results reported here provide authoritative support for the widely held opinion in the industry that "cold catastrophic failure" of LPG bullets is an incredible event. We believe that there is convincing evidence for the reliability of large LPG bullets for this failure mode to be no more than 10^{-7} per vessel year in normal operation. Smaller LPG bullets exhibit an even better reliability, with probably even more convincing evidence for reliability values at or below 10^{-9} per vessel year, again for normal operation.

These reliability values are, to the authors' knowledge, higher than has been previously proposed for any large manufactured pressure part component. It comes about because of the relative lightness of their normal duty and the highly effective pre-service screening provided by the proof test. If these reliability values are accepted then it is likely that the assessed safety risk of LPG storage can be revised downwards. Also, any additional work that might be justified to further reduce that risk can be focussed on other relatively more important failure mechanisms and hazards.

Finally, there are also some implications from the work for pressure vessel design codes, underlining the importance of proof testing, and specifically the importance of both the test pressure and test temperature in screening out defective vessels pre-service. The basis of these implications is particularly clear because of the unusually extensive vessel experience that supports the conclusions.

ACKNOWLEDGEMENT

The authors wish to record that this work benefited from the funding support and technical inputs of BP, whose contribution is gratefully acknowledged.

REFERENCES

1. Logenberg, M., 1998, Derivation of failure frequencies for LoC cases, TNO Report R 98/501.
2. Melchers, R. E., and Feutrill, W. R., 2001, Risk assessment of LPG automotive refuelling facilities, *Reliability Engineering & System Safety*, **74**: 283–290.
3. MHIDAS: HSE/AEA Technology Major Hazards Incidents Database.
4. MARS: Major Accident Reporting System consisting of 15 databases covering incidents reported to the EU by European Union member states.
5. AOTC: Associated Offices Technical Committee, an association of engineering and insurance companies — database of pressure vessel failures developed in conjunction with Safety and Reliability Directorate of the United Kingdom Atomic Energy Authority.
6. The Accident Database: I Chem E database of world wide major hazard and process related incidents based on BP Chemicals accident files.
7. PC-FACTS: PC version of the TNO database FACTS of world wide accidents with hazardous materials.
8. ENSAD: Energy-related Severe Accidents Database maintained by the Paul Scherrer Institute of recorded accidents world wide in the energy sector.
9. PSID: AIChE Process Safety Incident Database derived from IRAS, the Incident Reporting and Analysis System developed by Exxon Research and Engineering Company.
10. PERD, AIChE Process Equipment Reliability Database.
11. OLYMPUS, Database of Refining Safety reports.
12. Ility Engineering: Finnish reliability engineering company — record of major incidents in the process industries.
13. AEGPL response to BP enquiry on European tank numbers.
14. Statistical Review of Global LP Gas 2001, World LP Gas Association.
15. Private communication from Bob Myers, World LP Gas Association.
16. BS7910:1999 Guidance on Methods for Assessing the Acceptability of Flaws in Fusion Welded Structures, BSI 1999.
17. Chapman, O. J. V., and. Simonen, F. A., 1998, RR-Prodigal — A Model for Estimating the Probabilities of Defects in Reactor Pressure Vessel Welds, U. S. Nuclear Regulatory Commission Report No. NUREG/CR-5505.
18. ASTM Standard, E1921-97, Test Method for the Determination of Reference Temperature, T_o, for Ferritic Steel in the Transition Regime.
19. The Second Report of the Study Group on the Integrity of Pressurised Light Water Reactor Pressure Vessels (LWRSG) under the chairmanship of Dr W Marshall, UKAEA, March 1982.