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Household LPG cylinder fracture and a boiling liquid expanding vapor explosion

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Liquefied petroleum gas (LPG) cylinders are designed as thin-wall pressure vessels consisting of a cylindrical body and two almost hemispherical bottoms made of low carbon steel and welded together. LPG cylinders design, manufacturing, inspection and testing follow specific rules, Norms and Regulations. Pressure vessel design theory along with National Regulations and Product Specifications in force provide the initial design parameters and safety margin assumptions. A serious accident occurred on April 2, 2015 at Loutron village, close to the city of Amfilochia, in western Greece, explosion of an LPG bottle at a local restaurant. Five fatalities were reported at the time of the accident and three more injured were pronounced dead some months later. The accident gained extended publicity from the media arising concerns about safety in LPG distribution and operation. The local police requested an expert's appraisement from the Mechanical Engineering and Aeronautics Department of the University of Patras, for the evaluation of the accident's contributing factors. The accident investigated was a «boiling liquid expanding vapour explosion», and revealed potential threats from the operation of aged LPG bottles, and marginal inspection and testing procedures followed. A detailed analysis of the LPG cylinder operational characteristics along with a systematic design approach, fatigue, and failure analysis is presented here. The legislation in force, Regulations and Norms are also reviewed.

Keywords: LPG, BLEVE accident, crack growth, membrane theory, stress analysis, fatigue

Liquefied petroleum gas (LPG) has been in use as household fuel all over the world for several decades. LPG (propane or butane) is a colorless liquid readily evaporating into a gas, used as a fuel in heating appliances and vehicles. According to the ADR Regulation it is designated as Class 2 — Gases.

Recently, LPG is used as an aerosol propellant and a refrigerant, replacing chlorofluorocarbons. It is transported and stored as liquid and burnt as gas. LPG is stored and handled as a liquid when under pressure inside a LPG gas container. Aluminium and glass-fiber containers gain growing interest in the last decade.

The cylinders are covered by strict Norms and Regulations and have to be marked as: Identification (LAB) number, test pressure, stamped in MPa or kPa for post 1980 cylinders, filling pressure, water capacity in litres or kg for post 1980 cylinders, and empty weight or tare weight (including valve and fittings) in kg for post 1980 cylinders. Identification of cylinders for re-testing is accompanied by colored plastic rings retained by the valve. Design of LPG cylinders is performed according to the membrane theory of symmetrical shells [1].

Accidents involving LPG cylinders for household use may cause fire, explosion, loss of lives, adverse acute or chronic health effects, a threat to public health, and environmental damage. A sense of false security has always been with people at large that the man-created problems will somehow take care of themselves or disappear in time. Sometimes human error is implicated as a direct cause of the incident but often the human errors are underlying problems — poor safety management systems or poor safety culture.

Hardware failures also occur. These may be direct causes of failure as in structural collapse or brittle fracture, but may also be underlying causes such as poor design, for example. Often official enquiries into important incidents seek to obtain a detailed and complete understanding of all the relevant contributing factors. The pursuit of 'completeness' is considered to be important because it provides a more rich account of the event and so helps to ensure that lessons are learnt for the future [1].

The increasing use of LPG has enhanced the risk of a «boiling liquid expanding vapor explosion» (BLEVE). Reports on major incidences with LPG cylinders that exploded in a household, workshop, or on a car, or a train appear frequently. Those explosions also set off fires and cause secondary effects [2–6]. At other times accounts of incidents seem to emphasize one particular point of view. It is not always clear why this should be the case but the expertise and interests of individuals and organizations may be relevant.

However, such accounts will tend to be incomplete and lack richness. Important lessons may be missed. This is an important human dimension to accident investigation because the direction of the investigation may be determined by the expertise and interests of the organizations and the individuals involved.

In general terms in accident case studies the following issues are likely to be important: How did it happen? What was the sequence of events? What were the direct hardware causes? What were the underlying hardware causes? What were the direct human causes? What were the underlying human causes? [1].

An accident occurred on February 4, 2015 at Loutron village, close to the city of Amfilochia, in western Greece, explosion of an LPG pressure cylinder stored inside a local restaurant. Five fatalities were reported at the time of the incident, 11 severely injured, some of them were pronounced dead months later. The accident gained extended publicity from the media, and concerns arising about safety in LPG distribution and operation.

The local Police department requested an expert's appraisement from the Mechanical Engineering and Aeronautics Department of the University of Patras, in the frame of the official investigation following similar accidents. Figure 1 shows an external and internal view of the disintegrated restaurant after an LPG pressure cylinder explosion [2].

According to witnesses an LPG cylinder for domestic use caught fire and started flying like a burning rocket across the shop area. Due to this flight people were injured, internal walls were demolished, and an explosion like sound was heard all the way to the most remote village homes. The accident has revealed a number of potential threats from the distribution and operation of LPG cylinders, conformity to Norms and Specifications in force, and the inspection and testing procedures followed.

Figure 2 shows the LPG cylinder after the BLEVE explosion with the fractured side weld. The LPG cylinder On top of the cylinder the flow vane was intact and tightly closed. The cylinder diameter and length were measured 250 mm and 400 mm respectively. The cylinder's bottoms height was measured 60 mm.

On the cylinder top protection structure (Figure 2, *a*) it is indicated the year of construction, 1965, the manufacturer of the cylinder, shell thickness 2.8 mm, tank volume 25 l, max volume capacity 23.8 l, empty weight 12.6 kg, and capacity: butane 10.9 kg, and propane 13.0 kg. On the top protection frame there is the indication 20 with large bold numbers, presumably the test pressure of the LPG cylinder. The damage to the side weld is shown in Figure 2. The fractured cylinder weld of length 170 by 30 mm wide opening is also depicted in Figure 2, *b*.

a *b*

Figure 1. Damages to the restaurant's openings from the blast wave after the LPG pressure cylinder explosion and injured persons outside the restaurant (*a*), and the interior disintegrated (*b*)

a *b*

Figure 2. The LPG cylinder after the BLEVE explosion, the upper protection, year of construction 1965, pressure test 2 MPa (*a*), cylinder length 400 mm, diameter 250 mm, spherical bottoms height 60 mm, radius of curvature R = 280 mm, and the weld failure (*b*)

The cracking pattern of the cylinder (see Figure 2) indicates internal gaseous detonation associated with supersonic speed of the combustion wave front. Triggering of this detonation in LPG containers is due to a sudden depressurization of the container leading to instantaneous and violent vaporization of the content, causing the BLEVE.

Figure 3 shows details of the part of the cylinder connected to the lower dome (*a*) and the 170 mm long side welding fracture (*c*). Examination of the fractured weld of the cylindrical part of the shell shows that weld penetration reaches 1.10–1.50 mm depth out of the 2.80 mm shell thickness at a length of 30 mm of the fracture. Furthermore, careful examination of the area around the fracture both in the cylinder and the dome (see Figure 2 and 3) reveal corrosion defects and corrosion pits.

Examination of the lower dome beneath the crack opening on the cylinder revealed an area with significant corrosion pits and minor crack initiation (see Figure 3, *b*). Also, local damages due to impact was observed at the fractured area of the lower dome stimulating the crack initiation. The site of identified provides information that pre-cracking caused by fatigue, corrosion pits, stress corrosion, and material defects led to crack propa-

a *b* *c*

Figure 3. The LPG cylinder after the BLEVE explosion, the 170 mm fractured cylinder lateral weld, the lower dome peripheral weld (*a*), corrosion defects and corrosion pits at the lower dome (*b*) and lateral cylinder weld penetration 1.10–1.50 mm out of the 2.80 mm shell thickness at a length of 40 mm (*c*)

gation, and furthermore to rupture. This fatigue crack was slowly developed until a substantial leak of the cylinder content was released to the atmosphere, leading to a BLEVE.

The accident investigated here was a BLEVE due to a structural flaw of the container. It is the most difficult case of an accident that can happen wherever liquefied pressurized gas is released [6–9]. The analysis will focus: 1) on the Regulations and specifications applicable to the design, operation, maintenance and periodic inspection of LPG equipment (contributed by the first author); 2) the LPG cylinder design (2nd author); 3) Welds design (second and third authors); 4) fatigue crack and fracture initiation (third and fourth authors); 5) the accident reconstruction (fourth author); 6) discussion (all authors).

The first author is employed in a large shipyard firm incorporating LPG sea transportation, has contributed in Norms and Regulations in force for the LPG cylinders for household applications and relevant safety issues. The second author a graduate assistant of the Mechanical Engineering and Aeronautics Department of the University of Patras, now a crew trainer and cabin purser in the Emirates air carrier, provides the analytic work for stress analysis and weld design of pressure cylinders, out of handouts of a homework assignment in the Machine Elements course.

The third and fourth authors are faculty members of the University of Patras, students and research associates of Professor A.D. Dimarogonas, and have been involved in all phases of design, manufacturing, type approval and testing of industrial equipment from different positions in industry and academia. Their teaching and research interests include design and dynamics, vibration engineering, machine health monitoring, and structural integrity.

Expertize of all authors in design, and safety was combined for a thorough investigation of a serious accident, along with remarks on the application of relevant Regulations and Norms and product specifications.

The analysis is based on the textbook of Professor A.D. Dimarogonas *Machine Design, A CAD Approach* [1], for the courses *Machine Elements* and *Dynamics of Machines* taught at the 3rd and 4th year of studies of the Mechanical Engineering and Aeronautics Department of the University of Patras [1]. It should be mentioned here that the Department is focusing in Design Theory and a wealth of textbooks from Mir Publishers have supported teaching and research since 1972, when the Mechanical Engineering Department was launched at the University of Patras [8–16].

The case study reported here provides a good example of teaching and research activity of a Design oriented Technical University Department. In this review important issues of design, and the legal frame in the field of household LPG pressure cylinders design, manufacturing, inspection and testing practices, distribution, service-life follow-up, and the legal frame in the field are considered.

LPG cylinders design standards and regulations. LPG and its components (principally propane and butane) are the most important members of the Low Pressure Liquefiable Gases category. LPG is composed of various hydrocarbons: propane, propylene, butane, or butylene. LPG is odorless but a stench agent is added to facilitate detection in case of a leak. The pressure in a cylinder of a liquefied gas is the pressure of the vapour phase. This is dependent only on the gas composition and the temperature of the vapour and of the liquid surface, provided the cylinder has not been overfilled.

Before filling the LPG cylinders they have to be checked for leaks by soaping the valves or immersing the cylinder and valves in a water bath, or a thorough inspection of the welds for leaks. The filling of cylinders with liquefiable gases has to be controlled accurately by weight putting the cylinder on authority approved scale. The gross weight (as read on the scales) minus the tare weight (as marked on the cylinder) divided by the water capacity must be equal to or less than the permitted filling ratio, i.e.: Gross weight must be less than or equal to (Filling ratio x water capacity) + tare weight.

If a cylinder is over-filled, then the expansion of the liquid as the temperature increases may cause the cylinder to become «liquid-full», i.e. with no remaining ullage space. If the temperature continues to rise, the pressure in the cylinder will rise disproportionally. If there is no safety relief valve, or it fails to operate, the cylinder may burst after only a small rise in temperature [2].

All containers of liquefiable gases must have sufficient ullage (vapour space) that the liquid will not expand to fill the container at foreseeable temperatures. When compressed moderately at normal temperature, LPG becomes liquid. When gas is withdrawn, the pressure drops and the liquid reverts to gas. Pressure drops to zero at –43 °C for propane (just below the boiling point) and the pressure increases substantially at higher temperatures. The pressure for LPG (propane) ranges from 4 0.4 MPa at 0 °C to 0.5 MPa at 54 °C.

The corresponding pressure for LPG (butane) is 0.0152 MPa at 0 °C and 0.5 MPa at 54 °C. The pressure cylinders are filled with 80–85 % LPG. LPG mainly traded is either propane or a mixture of butane-propane (70–30 %). Less frequently the cylinders are filled with butane. The pressure in the propane bottle in winter amounts up to 0.45 MPa and in summer up to 1.00 MPa. The pressure for the butane-propane mixture becomes 0.20 MPa in winter and 0.65 MPa in summer [2].

One of the earliest standards applied on Gas Cylinders and Containers is the British standard BS 5355:1976 The International Standard Organization Technical Committee ISO/TC 58/SC 3 is responsible for the preparation of Norms and Standards concerning LPG cylinder design i.e. ICS 23.020.35 Gas cylinders. ISO 4706:2008 Gas cylinders — Refillable welded steel cylinders — Test pressure 6 MPa and below.

ISO/DIS 9809-2. Gas cylinders — Design, construction and testing of refillable seamless steel gas cylinders and tubes — Part 2: Quenched and tempered steel cylinders and tubes with tensile strength greater than or equal to 1,100 MPa. ISO/DIS 9809-3. Gas cylinders — Design, construction and testing of refillable seamless steel gas cylinders and tubes — Part 3: Normalized steel cylinders and tubes. ISO/AWI 9809-4 Gas cylinders — Refillable seamless steel gas cylinders — Design, construction and testing — Part 4: Stainless steel cylinders with an R_m value of less than 1,100 MPa.

ISO 11119-1:2012 Gas cylinders — Refillable composite gas cylinders and tubes — Design, construction and testing — Part 1: Hoop wrapped fibre reinforced composite gas cylinders and tubes up to 450 l. ISO/WD 11119-2 Gas cylinders — Refillable composite gas cylinders and tubes — Design, construction and testing — Part 2: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with load-sharing metal liners.

According to the aforementioned Norms and Standards essential tests to be conducted on cylinders before they get certified and put in operation include among others: Acceptance test, Burst and volumetric expansion test, Water-pressure test, Pneumatic leak test, Radiographic examination, and Fatigue test/Cycle test. These procedures should only be done by qualified personnel, after gas free.

In Greece refilling of LPG bottles is carried out in accordance with the provisions of Decree D3/14858/1993 (Government Gazette 477/B/1-7-1993) on the definition of technical specifications for the design, construction, safe operation and protection of storage, bottling, distribution of LPG and installations for its use in industrial, craft and professional activities'.

Under the Ministerial Decree Y.A. 14165/Φ17.4/373/1993 (Government Gazette 673/B/2-9-1993) LPG pressure cylinders must be inspected within nine years from the date of the above Ministerial Decree (1993) and then be re-checked every 10 years in a hydraulic pressure test at 3.2 MPa.

From the accident investigation it was found that the LPG pressure cylinder inspected either was not monitored by a systematic serial number registration and follow-up from the distributor, or was not refilled from the company owing the cylinder, according to standards and the legislation in force. Since September 1993 all LPG pressure cylinders in operation in the country had to be inspected within nine years from that date, and then be re-checked every 10 years at 3.2 MPa hydraulic pressure test.

The Intervals between periodic requalification of gas cylinders depend on specific criteria and procedures addressed i.e. in ISO-10464 and EN 1440 for requalification. The criteria to be chosen depend on various design and manufacturing norms followed before putting the product in operation. Those might include among others: whether the cylinders are designed, manufactured and tested according to internationally recognized standards, e.g.

ISO-22991, a national standard or an equivalent; whether there is a system of external protection against corrosion; whether the cylinders are being filled in accordance with the criteria contained in an internationally recognized standard, e.g. ISO 10691, a national standard or an equivalent. From the examination of the gas cylinder under investigation it is concluded that similar criteria were not followed during the last half century of the gas cylinder operation.

Cylinder shell design evaluation. LPG cylinders are designed as thin-wall pressure vessels. The design of thin-walled pressure vessels is subject to strict rules and specifications due to the dangers they pose in the event of a failure. Regulations and specifications are applicable to the design, operation, maintenance and periodic inspection of the equipment. The pressure in a cylinder of a liquefied gas is the pressure of the vapour phase, depending on the gas composition and the temperature of the vapour and of the liquid surface, provided the cylinder has not been over-filled.

In addition to the design requirements, the requirements of the National Regulations and Product Specifications apply [1]. The bottles consist of a cylindrical body with a longitudinal welding in the cylinder's side and two almost hemispherical bottoms, the domes, welded circumferentially with the cylinder. This is the three piece design. The two piece design consists of two domed ends connected together by weld. They are made of low carbon steel (usually AISI 1020) with a Yield Limit S_y = 300–420 MPa and fatigue tensile strength limit S'_n = 190 MPa.

Sizing of a structural component is performed by comparing the forces that each section must carry to the capacity of the material it is made of to carry forces without failing. In thin-walled pressure vessels (Figure 4), two stresses are developed in the shell, the meridian σ_m, and the circumferential σ_t. Stresses in the direction of thickness is considered to be zero according to the membrane theory. For a cylindrical pressure vessel with internal pressure p, radius R, all forces equilibrium along the direction perpendicular to the surface of the container yields Laplace equation [1]:

$$\frac{\sigma_t}{\rho_t}+\frac{\sigma_m}{\rho_m}=\frac{p}{t} \qquad (1)$$

where σ_t is the circumferential (hoop) stress; ρ_t, ρ_m are the corresponding radii respectively; σ_m is the meridional or axial stress; p is the internal pressure of the container; t is the thickness of the cylinder shell.

From Figure 4 summing up forces in the z-direction yields:

$$\sigma_m 2\pi Rt\cos\theta=\pi R^2 p, \qquad (2)$$

where θ is the angle locating the membrane element in the z direction.

For a pressure cylinder at the circular cylindrical part are calculated stresses [1]:

• the meridional (axial)

$$\sigma_m=\frac{pR}{2t}; \qquad (3)$$

• the circumferential

$$\sigma_t=\frac{pR}{t}, \qquad (4)$$

where R is the cylinder radius.

The equivalent stress is calculated by von Mises Theory for deformation as

$$\sigma_{eqNM}=\sqrt{\sigma_m^2+\sigma_t^2-\sigma_m\sigma_t}\le\frac{S_y}{N}, \qquad (5)$$

where S_y is the material continuous strength (yield strength); N is the safety factor for thin-walled vessel applications, N = 3.

According to the distortion energy criterion of failure, the von Misses Theorem, formulated in equation (5) along with equations (3) and (4), the following equation yields [1]

$$\frac{3}{4}\left(\frac{pR}{t}\right)^2=\left(\frac{S_y}{N}\right)^2. \qquad (6)$$

The inspected pressure cylinder was made of steel sheet, with thickness t = 2.80 mm. Low carbon steel AISI 1020 (DIN C22) is used for LPG cylinders manufacturing. The mechanical properties of the AISI 1020 steel are: yield strength S_y = 320 MPa, S_u = 500 MPa, and S_n = 190 MPa the elasticity limit [1]. For the design evaluation the test pressure p = 2.5 MPa and safety factor N = 3 will be assumed herewith.

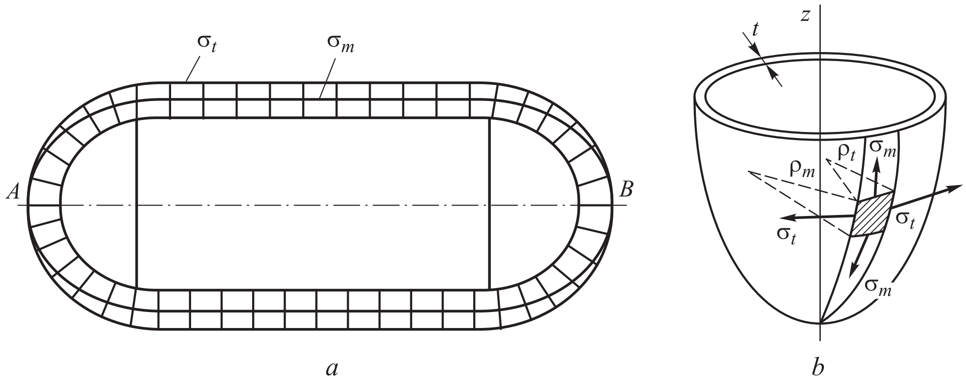

Figure 4. A thin walled pressure vessel, profiles of the circumferential stress σs_t, the meridional or axial stress σ_m (a) and equilibrium of a membrane element (b)

For the cylindrical shell (R = 125 mm), the solution of equations (1)–(6) yield for the circular cylindrical part: axial (longitudinal) stress σ_m = = 55.8 MPa, circumferential stress σ_t = 111.6 MPa, equivalent stress σ_{eqNM} = 96.6 MPa. The equivalent stress calculated is lower than the ratio S_y/N = = 320/3 = 106.6 MPa, yielding a safe design for the cylinder. Instead, the tangential stress σ_t acting on the peripheral weld is similar to the ratio S_y/N yielding marginal design.

For the domes the radius of curvature was measured R_d = 235 mm. Then for the test pressure 2.5 MPa from equations (1)–(6) the circumferential and axial stress on the dome head (points A and B) due to symmetry are $\sigma_t = \sigma_m$ and

$$\sigma_t = \frac{pR_d}{2t}. \qquad (7)$$

Then equation (7) yields $\sigma_t = \sigma_m = \sigma_{eqNM}$ = = 105.0 N/mm^2. This value is equal to the ratio S_y/N = 106.6 N/mm^2, and therefore the conditions for safe design are valid for the domes heads.

The solution of equation (7) for the domes and the cylindrical shell reveal correct selection of the corresponding radii of curvature, yielding identical stresses, a prerequisite for the selection of same thickness metal sheet for all parts of the LPG pressure cylinder [1].

Cylinder side weld. The rupture took place in the area of welding the cylindrical part of the shell of the pressure cylinder with the lower spherical dome (see Figure 3). This is an area of increased local stresses. In addition, the rupture crosses two adjacent welds, of a Tee shape junction, yielding a complicated stress field. From the examination of the ruptured cylinder lateral butt weld it was investigated inadequate weld depth (see Figure 4).

The weld thickness is less than 3 mm, thus no preparation of the edges was required as it is the case in the cylinder investigated. Plastic deformation of the ruptured part of the lateral weld (see Figure 2) indicates a bursting failure. In engineering practice, the allowable stresses, safety and stress concentration factors are based on the convention that failure is due to shear at the narrowest section (throat) of the weld. Due to catastrophic failures of early welds in pressure vessels and steel constructions, the design of welds is highly regulated [1].

The design verification of the butt weld will provide information concerning maximum strength of the weakened part of the weld shown in the ruptured seam, with improper weld depth penetration, called cold weld. The lateral butt weld of the cylindrical shell is subjected to a tensile loading. Tensile force at the shell lateral seam with low weld penetration (see Figure 3) will be assumed as

$$P = \sigma_t bt, \qquad (8)$$

where b is the length of the lateral weld with low depth penetration, b = 50 mm; t = 1.3 mm.

Further, the design corresponds to low cycle loading of the pressure vessel. The stress distribution in the weld area investigated is complicated due to the incomplete weld penetration (cold weld) in the cylinder side weld and the neighboring circumferential bottom weld. The design equation is in general [1]

$$\sigma_{av} = \frac{K_f P}{bt} = \frac{S_y}{N}, \qquad (9)$$

where σ_{av} is the mean tensile stress in the cold weld area calculated from equation (9); P is the weld tensile force; K_f is stress fatigue stress concentration factor ranging from 1 to 2 for static and dynamic loading, respectively.

For a slowly fluctuating load due to daily temperature changes and the loading-unloading conditions of the LPG cylinder, the stress fatigue stress coefficient is selected K_f=2 [1]. Then the tensile force acting on the weakened part of the weld (cold weld) is calculated from equation (8) for internal pressure range 0.4–3.0 MPa, ranging from 100 to 6500 N. Accordingly, the stress in the cold weld area is calculated from equation (9), ranging from σ_{av} = = 70 MPa to σ_{av} = 500 MPa. Results from the solution of equations (8) and (9) are shown in Figure 5.

In Figure 5 the tensile stress (upper curve) at the section with reduced weld penetration (cold weld), ranges from 75 MPa corresponding to an operating pressure of 0.04 MPa, up to 320 MPa corresponding to an operating pressure of 2 MPa. From Figure 5 it appears that the stress calculated above for the weakened area of the welding, σ_t = = 175 MPa for normal operation of the LPG cylinder (up to 1 MPa internal pressure) is lower than the material fatigue strength limit S'_n = 192 N/mm^2 [1], and the design is quite safe even for low cycle fatigue operation.

Furthermore, cylinder operation at 40–50 °C ambient temperature, yields 1.7–2.0 MPa internal pressure, and the stress in the reduced penetration section weld lies in the area 275–320 MPa as shown in Figure 5, all values being lower than the

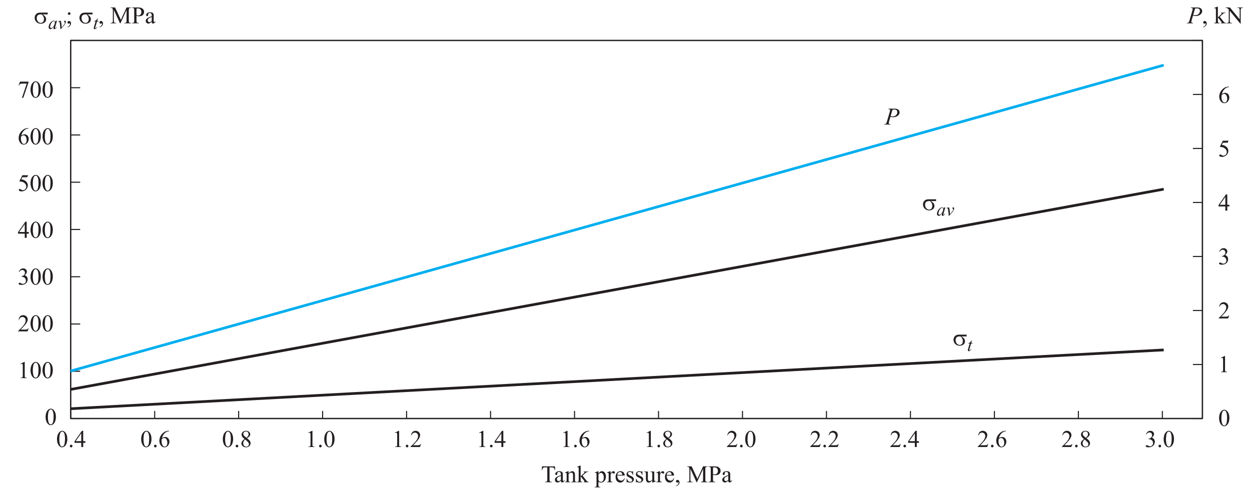

Figure 5. Tensile force at the reduced penetration (cold weld area) P, tensile stress σ_{av} at cold weld and circumferential stress σ_t at the lateral cylinder weld

permissible yield stress of the material (S_y = = 326 N/mm^2).

The stress values calculated in Figure 5 indicate safe functioning of the weld with reduced penetration, for the test pressure at 2 MPa that the cylinder was supposed to withstand. From Figure 5 it can be seen that the stress calculated at the cold weld area becomes σ_{av} = 320 MPa at an internal cylinder pressure 2 MPa. The stress σ_{av} = 320 MPa is equal to the material yield strength.

The latter indicates that the cylinder was capable to withstand the 2 MPa test pressure as stamped on the upper protection frame (see Figure 2). This test pressure had been applied once at least, and the cylinder could pass it successfully. It is assumed that this operation is rare and does not reduce significantly the fatigue life expectancy of the structure.

Fatigue crack and brittle fracture initiation. In any structure tension stresses occur in regions associated with stress concentration features and residual stresses due to welding or forming, or impact loads. In practice significant defects are usually located in a weld region and in addition to stress concentration and residual stresses, the defects may be associated with areas subjected to adverse metallurgical changes.

Fatigue failure originates from a minute flaw discontinuity of the material after the loading results in local plastic deformation. Impact loading also yielding local plastic deformation originates fatigue failure. Fractures once initiated, can propagate rapidly under low applied stresses, causing extensive damage.

Initial notch, loading geometry and material properties determine not only the load required to precipitate fracture and the initial fracture angle, but also the subsequent path the fracture will follow, i.e. the notch must seek a path of release. In tension the fracture path follows closely the trajectories of points of minimum strain energy [1, 17–20].

Examination of the LPG cylinder revealed corrosion defects and corrosion pits in the area of the Tee weld junction connecting the ruptured cylinder shell weld and the bottom dome circumferential weld (see Figure 2 and 3). Apart from corrosion defects plastic deformation of the bottom dome of the pressure cylinder can be identified on the dome external surface below the peripheral weld along with minute flaws, and cracks initiation points can be also observed. The whole area around the crack at the bottom dome as shown in Figure 6 is an area of increased stress concentration. This situation indicates a pronounced structural weakness of the bottom dome and a failure occurrence.

Figure 6 shows the crack initiation and branching of the crack on the bottom dome. The lower edge of the crack starts from the peripheral weld connecting the bottom dome with the lower support ring frame (see Figure 3, *a*). Then the crack propagates heading the peripheral weld with the cylinder (Tee-weld). There are two branches of this crack, one heading to the left at an angle of 115° (from a horizontal axis), and a branch heading 75° to the right towards the cylinder side weld.

The left branch of the same crack initiation is still covered by paint indicating a less fast propagation than the right branch. The right

Figure 6. The crack initiation and branching of the crack on the bottom close to the peripheral weld (connecting the bottom dome with the lower support ring frame)

branch of the crack propagating towards the peripheral weld with the cylinder and fractured causing the liquid to escape and a pressure drop.

Fracture toughness is the property describing the ability of a material to resist fracture, one of the most important material properties in design applications. The linear-elastic fracture toughness of a material at which a thin crack in the material begins to grow is determined from the stress intensity factor [1]. The stress intensity factor K describes the magnitude of the elastic crack tip stress field.

Also, K correlates the crack growth and fracture behavior of materials provided that the crack tip stress field remains predominantly elastic. The utility of the stress intensity factor K follows the observation that for every material, when this factor reaches a critical value, brittle fracture will follow even for highly ductile materials.

Assuming the dome area with the crack once initiated is a strip in uniform tension σ, perpendicular to the crack plane, the stress intensity factor K is related to the stress and the crack length according to the following equation

$$K = \sigma_0 \left[\pi a\right]^{\frac{1}{2}} F\left(a\right), \tag{10}$$

where σ_0 is the mean tensile stress in the crack area; a is the crack length; $F\left(a\right)$ is a function depending on crack and specimen geometry [1].

For an infinite strip, that is, if the strip boundary is very far from the crack $F(a) = 1$. For the case under consideration two cases will be examined along with the appropriate assumptions for the stress field: 1) considering the crack initiation in Figure 6 as a surface crack located at mid-span of an infinite strip of width $2b$ (Figure 7, *a*), under the action of a tensile stress σ acting on the strip, and 2) considering the crack as an edge crack of depth a, and $2b = 2.8$ mm the bottom dome thickness (Figure 7, *b*) gain under the action of a tensile stress σ acting on the strip.

Then equation (10) yields the corresponding stress intensity factors for each case. The function $F(a)$ associated with stress and the crack length for the crack configurations shown in Figure 7, *a* and Figure 7, *b* is respectively [1]. For the cracked strip shown in Figure 7, *a*, strip width $2b$ and a surface crack opening $2a$, the stress intensity factor is calculated from equation (10), assuming $F(a) = f(a/b)$, $a/b = \lambda$, and the values of $f(a/b)$ can be found in [1] (APPENDIX B) as

$$f\left(\frac{a}{b}\right) = f\left(\lambda\right) = \left(1 - 0.5\lambda + 0.37\lambda^2 - 0.044\lambda^3\right) / (1-\lambda)^{1/2}. \tag{11}$$

For the cracked strip shown in Fig 7, *b*, strip of thickness $2b$ and an edge crack of depth a, the stress intensity factor is calculated from equation

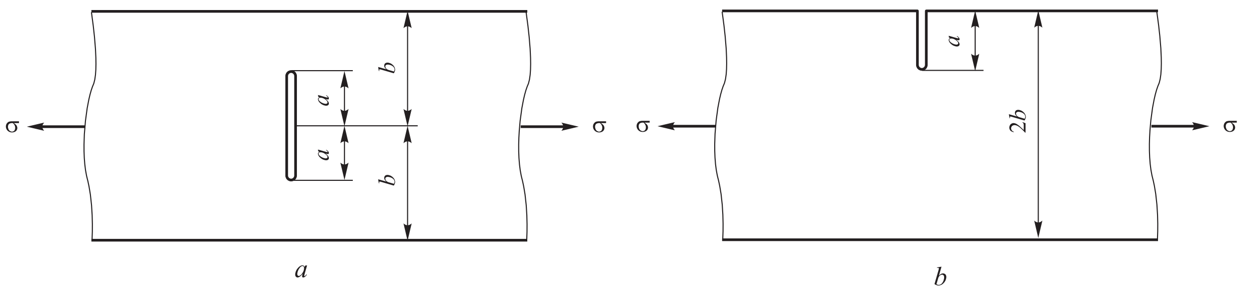

Figure 7. A strip of metal subjected to a tensile stresses σ:
a — strip width $2b$, surface crack of length $= 2a$; *b* — strip thickness $2b$, with an edge crack of depth a

(10), assuming $F(a) = f(a/b)$, and $a/b = \lambda$, the values $f(\lambda)$ can be found again in [1] as

$$f(\lambda) = \left(\frac{2}{\pi\lambda}\right)^{1/2} \times$$
$$\times \frac{\left(0.752 + 2.02\lambda + 0.37\lambda^2 - 0.044\lambda^3\right) \Big/ \left[1 - \sin\left(\frac{\pi\lambda}{2}\right)\right]}{\cos\left(\frac{\pi\lambda}{2}\right)}. \qquad (12)$$

Then assuming 1 MPa working pressure, from Figure 5 yields the circumferential stress σ_t = = 175 N/mm^2 (175 MPa), and the solutions of equations (10)–(12) for the stress intensity factor for the cases of an edge crack and a surface crack (see Figure 7) are shown in Figure 8.

The stress intensity factors curves shown in Figure 8 provide the stress threshold for brittle crack initiation at the bottom dome. It can be seen from Figure 8 that in case of a surface crack in a strip of width 50 mm, for a/b = 0.79, yielding a crack length 2a = 39 mm, the stress intensity factor becomes K = 196 MPa larger than the material fatigue tensile strength limit S_n' = = 192 MPa (192 N/mm^2). This stress state leads to a fatigue crack propagation.

On the other hand, for an edge crack, and a/b = = 0.50, yielding a crack length $a = b = t/2$ = 1.4 mm, and a/b = 1.50, yielding a crack length a = 1.5 b = = 1.5t/2 = 2.1 mm. In other words, for an edge crack of depth 1.4 mm, 50% the dome thickness, the stress intensity factor becomes K = 329 MPa. For crack depth 2.1 mm, 77 % of the dome thickness, the stress intensity factor becomes K = = 438 MPa, both limits being larger than the material Yield Limit S_y = 300–420 MPa, and rupture will occur.

From the preceding analysis it follows that the minute flaws observed on the bottom dome could affect crack initiation and propagation. For a

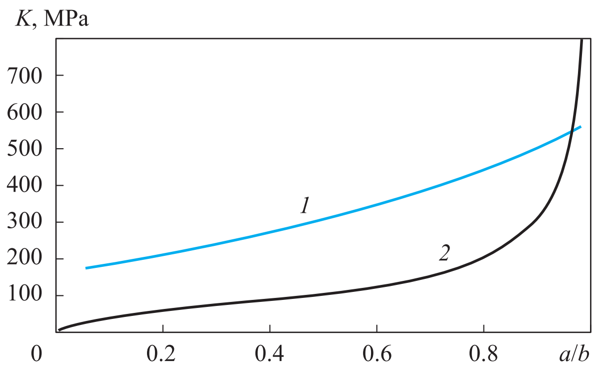

Figure 8. Stress intensity factors for an edge crack (*1*) and a surface crack (*2*)

length of a surface crack 2a = 39 mm similar to the crack shown in Figure6, crack propagation could be the case for low cycle fatigue loading. Then the analysis provides an estimation of the depth of an edge crack on the bottom dome surface that produces a stress field with tensile stresses larger than the material Yield Limit yielding rupture.

The accident reconstruction and the bleve. The BLEVE occurs wherever a pressure-liquefied gas (PLG) exists. If a container with a PLG suffers structural failure due to creep, fatigue, or fire-induced or any other cause of failure, this may lead to a sudden depressurization of the container. As a result, the LPG will suddenly be transformed into a fluid which is «superheated» with respect to the precipitously lowered pressure. Depending on the nature of the chemical, quantity of superheated liquid present, and the mechanism of the container failure, such a situation can lead to instantaneous and violent vaporization of the contents, causing a BLEVE.

Published data on the AISI 1020 steel operational performance has shown that the dominating degradation mechanism is erosion-corrosion. The mechanism observed in the cylinder under investigation is called stress-corrosion cracking, usually in metals under the action of periodically applied tensile stress in a corrosively active environment, also common in areas where residual stresses remain after machining, heat treatment, forming, and welding.

Stresses and forces analysis was performed for the part of the lateral cylinder weld with reduced weld penetration observed at the ruptured seam. From the analysis it yields that the LPG cylinder could sustain a temperature rise on the vessel surface up to 50 °C, resulting to a pressure rise of the liquid contained up to 1.7–2.0 MPa depending on the liquid mixture contained.

From the previous analysis it follows that fatigue failure originated from a minute flaw, or discontinuity of the material due to impact and corrosion pits. As a rough estimation the LPG pressure cylinder operation consists of 1–12 fill-discharge cycles per month, yielding 600–7200 cycles during the 50 years of operation of the cylinder. Operation under 10000 cycles belong to the Low cycle fatigue region, and no appreciable reduction to the maximum stress allowed is expected. In addition, daily temperature changes and the cylinder are under pressure might increase the operation cycles by 50 %, leading to the threshold of the 10,000 cycles and the requirement of fatigue analysis.

Low cycle fatigue loading in the presence of the stress intensity factors calculated before caused the flaw to gradually increase, and form a propagating crack until the remaining section of the material could no longer sustain the load. Then the crack propagates rapidly, causing final failure. This crack propagation and rupture shown in Figure 6 led to the subsequent gas discharge in the atmosphere and the BLEVE explosion.

For a vessel containing PLG, a liquid confined at a temperature above its atmospheric pressure boiling point, a weld failure followed by a liquid vapor release results in the liquid level in the vessel to fall. The liquid is effective in cooling that part of the vessel wall that is in contact with it, but the vapor is not. The proportion of the vessel wall in contact with liquid, causing cooling, decreases as the liquid vaporizes. After a time, the portion of the metal sheet not cooled by liquid becomes exposed to the heat load, it weakens by creep, fatigue, or corrosion, and then further rupture occurs.

The suddenly vaporizing liquid-with several hundred-to over a thousand times increase in its volume-plus the expansion of the already existing vapor, generate an overpressure blast wave. The magnitude of the blast wave is much higher than the one caused by a similar vapor cloud explosion. This blasting wave inside the vessel produced the rupture of the weld in the cylinder lateral welding and the bottom dome that was already weakened by corrosion (see Figure 2 and 3).

The vessel was not shattered, but instead it was propelled inside the room. The upper welded protective frame was separated from the cylinder, and deformed due to collisions with the walls and ceiling during air travel. This mechanism of the propelled vessel sent it shooting at high velocity in all directions demolishing internal walls, and also causing fatalities.

It was a safe coincidence that the missile did not damage other vessels in the same area storing liquefied gas under pressure. This could cause them to undergo BLEVE as well. Further, the mixture of liquid/gas released by the explosion catches fire, giving rise to a fireball in the interior of the building as noticed by witnesses also (see Figure 1).

Discussion of the results and conclusions. From the accident investigated and the analysis of the various issues presented herewith, important findings can be summarized. The issues of safety and reliability in engineering design are an integral part of human — product interaction and greatly affect perceived quality of any industrial product. Sometimes human error is implicated as a direct cause of an incident but often the human errors are underlying problems — poor safety management systems or poor safety culture.

Hardware failures also occur. These may be direct causes of failure as in structural collapse or brittle fracture, but may also be underlying causes such as poor design, for example. Often official enquiries into important incidents seek to obtain a detailed and complete understanding of all the relevant contributing factors. The pursuit of «completeness» is considered to be important because it provides a more rich account of the event and so helps to ensure that lessons are learnt for the future.

The examination of the LPG pressure cylinder and the analysis performed led to the conclusion that corrosion pits and corrosion defects, along with impact loading at the bottom dome, minute flaws were developed, and a low cycle fatigue crack propagation occurred. When the crack propagated until the remaining section of the material could no longer sustain the load, the crack on the bottom dome opened, LPG gas was discharged to the atmosphere, and a BLEVE explosion occurred.

The blast wave inside the cylinder forced the cylinder shell to deform accordingly and the overstressed cylinder lateral weld ruptured. The deformed part of the lateral seam weld followed the form of the cylinder mode of vibration caused by the blast wave. The cylinder investigated was capable to withstand a pressure test up to 2 MPa.

According to the stamp on the protective head frame a 2 MPa test occurred once at least, presumably before 1993. The reduced weld penetration at the lateral seam weld could marginally sustain pressure loading even at temperatures up to 50° C (2 MPa), but it was not strong enough to bear the blasting wave, and tore apart.

The LPG cylinder investigated revealed poor quality control and safety management from the pressure vessel holding company. The pressure cylinder was constructed in 1965. The cylinder shell inspection revealed poor condition due to impact and corrosion pits. Although the quality control management presupposes that detailed list of loading and testing history of this specific pressure cylinder, it was found that the cylinder's investigated serial number was not registered in the company's list.

Also, the regulations prohibit charging of a cylinder unless it is in good condition, and adequate precautions to prevent damage to cylinders during transportation have been taken. From the cylinder external examination it could be assumed that this LPG cylinder was not recharged by authorized agents, and either overfilling could not be avoided, or due to the flaws of the bottom dome and cylinder, it had to be rejected and not being refilled again. Additionally, if the 3.2 MPa pressure test had been applied, as foreseen by the Ministerial Decree of 1993, either the pressure cylinder would fail, or plastic flow would occur, leading to the cylinder rejection.

The accident considered shows potential threats from the operation of aged LPG cylinders, and marginal inspection and testing procedures followed, the importance of carrying out a risk assessment study to identify and implement control measures even for simple tasks such as storage of LPG cylinders in appropriate ventilated areas, and proper handling by the users.

Labor procedures and workplace safety measures, and testing and handling of LPG devices by authorized, trained personnel guarantee a secure working environment for workers and the public. The accident investigated and the legal constraints concerning product liability presented provide a good basis for a thorough consideration of the appropriate procedures for the design evaluation, and testing of LPG cylinders for household use.

The registration of all LPG bottles in operation by a systematic identification coding and proper follow-up from the distributor, along with a list of drawings, manufacturer's certificate of conformity, list of Norms and Regulations applied provides additional safety of humans from injury and property loss, and the effects in the environment.

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