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# Integrity and service life of LPG carafes

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## Abstract

The reliability of 10 kg liquefied petroleum gas carafes used nowadays in Argentine households is evaluated in this study. Chemical, mechanical and metallographic studies were performed to determine base metal, weld metal and heat affected zone conditions. Residual stresses were measured in both inner and outer surfaces of the carafes. Lower bound values of fracture toughness ($K_{IC}$) were determined from upper shelf Charpy energy (CVN). Charpy tests at 0 °C were carried out. A marked increase in toughness of the base plate was found, as the date of fabrication increases.

Diverse degrees of non-conformities, resulting in significant defects usually undetectable by external inspection, were found in the circumferential welds of 25% of all carafes manufactured before 1990. The number and criticality of these defects falls markedly in the carafes built after 1990.

Serious errors during reconditioning, such as repairs of leaks and scratches, are indicative of a poor approach to the rehabilitation of the vessels. It is recommended to evaluate changes in the rehabilitation procedures and standards. A gradual process of substitution of the carafes built prior to 1990 is also recommended.

*Keywords:* Reliability; Liquefied petroleum gas; Household carafes; Weld defects

## 1. Introduction

Any component or equipment is designed for a specified period of safe operation, during which time the failure risk is deemed acceptable. This establishes a design service life for the component [1]. When it becomes apparent that the degree of deterioration is such that the risk of failure is considerably increased, the component reaches the end of its service life and should be taken out of service.

In this study the reliability of 10 kg vessels used for the supply of liquefied petroleum gas (LPG) in Argentina is evaluated. A 10 kg LPG carafe is a vessel built in thin plate, rolled and welded, as shown in Fig. 1. The use of low carbon steel, 0.2% C approximately, is specified in order to assure weldability and toughness. There are approximately 15 million units in use in Argentina, half of which were manufactured prior to 1980, and with some of these carafes for household use up to 40 years old. It is a primordial function of the State and its regulatory agencies to define standards to maintain an acceptable level of risk associated with the supply and use of these pressure vessels [2]. The users may well ignore the risks associated with inappropriate handling and use of a vessel containing a flammable gas at high pressure, with most carafes used in homes by people with no experience of management of pressurized vessels. Unsafe practices, such as heating to increase the gas pressure, are not uncommon in low-income households. In the case of failure of a household carafe the consequences are usually fatal, due to the proximity of people to stoves, ovens and other gas fired home appliances. It is therefore essential that government regulations ensure the integrity of the carafes for their entire service life.

During their service life the carafes are subjected to a series of damage mechanisms that can limit their service life. The most probable mechanisms of in-service degradation of LPG carafes are fatigue, corrosion, mechanical damage by blows or punching, and overloads. In previous work by the authors [3], the failure of a vintage 10 kg LPG balloon or carafe manufactured in 1968 was investigated in parallel with an experimental study of material properties and fabrication procedures of other vessels of similar age. It was shown that many of the carafes had potentially critical

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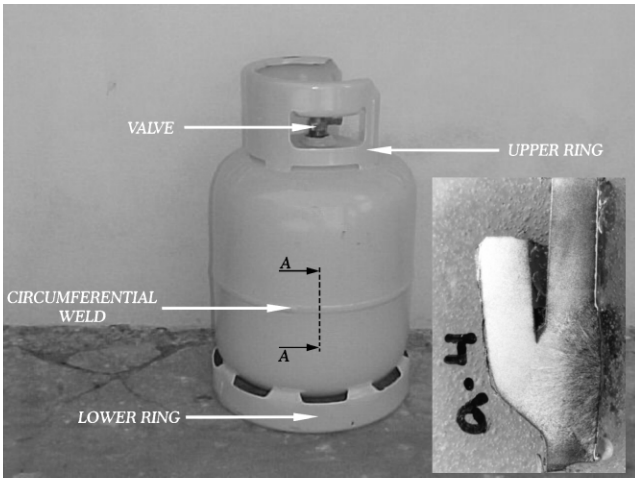

Fig. 1. 10 kg LPG carafe.

fabrication and in-service defects, especially in the circumferential welds. It was concluded that continuing use of these vessels would be potentially dangerous, especially when the effectiveness of the post weld stress relief treatment could not be guaranteed.

The objective of the current study is to extend the studies to sample all the carafes currently in use in Argentina, and to determine if modification of the national standards regulating the service life of the LPG carafes are required. It is necessary to verify if the current requirements of periodic inspection every 10 years, along with an infinite design life, can assure the integrity of a carafe for the complete term between inspections. It is also important to assess the effect that changes in fabrication technologies have had on decreasing the risks associated with the use of the carafes.

## 2. Experimental procedure

A failure is defined as the point where a particular imperfection, or defect, attains a size that compromises the use of the vessel, with the extreme cases being plastic collapse and fast fracture.

The welds are subjected to stress concentrations acting in small regions around geometrical discontinuities. If the post weld heat treatment (PWHT) is not completely effective, welding residual stresses are added to the stresses due to internal pressure. The presence of defects in these critical regions can dramatically reduce the reliability of the carafes. The influence of material toughness, fabrication defects and in-service degradation mechanisms on the reliability of the carafes was assessed, following the established procedures for Fitness for service evaluations [4].

Table 1
Base plate mechanical properties according to their antiquity

| Sample | Reduction in area (%) | Elongation (%) | Yield strength (MPa) | UTS (MPa) |
|---|---|---|---|---|
| 6-24 | 33 | 14.3 | 275 | 398 |
| 7-17 | 56 | 28 | 250 | 351 |
| 7-19 | 64 | 30 | 238 | 303 |
| 8-1 | 64 | 28 | 239 | 359 |
| 8-16 | 62 | 24 | 240 | 329 |
| 9-4 | 67 | 29 | 279 | 370 |
| 9-10 | 68 | 24 | 275 | 387 |

Table 2
Fracture mechanics properties at 0 °C

| Sample | Charpy (10 × 10, J) | | | $K_{IC}$ (CVN, MPa m$^{1/2}$) | | |
|---|---|---|---|---|---|---|
| Series/specimen | Base | Weld | HAZ | Base | Weld | HAZ |
| 6-14 | 44 | 36 | 48 | 48 | 43 | 51 |
| 6-15 | 100 | 68 | 92 | 68 | 73 | 64 |
| 6-20 | 80 | 40 | 68 | 70 | 45 | 63 |
| 6-22 | 60 | 44 | 48 | 59 | 48 | 51 |
| 6-23 | 60 | 60 | 56 | 59 | 59 | 57 |
| 9-4 | 104 | 64 | 76 | 80 | 61 | 68 |
| 9-5 | 72 | 100 | 64 | 64 | 78 | 61 |
| 9-7 | 116 | 56 | 92 | 84 | 57 | 74 |
| 9-9 | 124 | 88 | 116 | 87 | 72 | 84 |
| 9-10 | 112 | 68 | 80 | 83 | 63 | 70 |

During the 1960s and 1970s there were several dozen manufacturers in Argentina, most of them were small companies with minimal qualifications and control. The characteristics of the steels and construction procedures have been studied in a sample of 62 randomly chosen carafes, all of which were in use in Argentine homes prior to the study. The sample includes units fabricated between 1960 and 2000, with series 6–9 corresponding to the successive decades of fabrication. Chemical analyses and mechanical property determination were carried out on representative samples. Metallographic studies were performed to determine base metal, weld metal and heat affected zone (HAZ) microstructures in the samples.

The tensile test results are summarized in Table 1. Note a marked increase in ductility and a slight decrease in strength of the base plate, as the date of fabrication increases. Charpy tests at 0 °C were carried out on the base metal, weld and HAZ samples, notched perpendicularly to the plate surface, to assess the resistance of these materials to both circumferential and longitudinal fracture propagation. Charpy tests were carried out using subsize 10 mm × 2.5 mm specimens. Following the procedures in API 579 Appendix F [4], the results are multiplied by 4 in Table 2, to allow for a direct comparison with standardized values. An important scatter among the different materials can be appreciated.

Lower bound values of fracture toughness ($K_{IC}$) were conservatively determined for carafe materials following the correlation by Rolfe, Barsom and Novak [5] between upper shelf Charpy energy (CVN) and $K_{IC}$ for ferritic steels

$$(K_{IC}/\sigma_{ys})^2 = 5((\text{CVN}/\sigma_{ys}) - 0.05) \tag{1}$$

Table 3
Base metal chemical composition according to antiquity

| Nominal composition | Old argentine standard | New steels | | | |
|---|---|---|---|---|---|
| | | A 31 GL | A 34 GL | A 42 GL | A 45 GL |
| C% max | 0.2 | 0.06/0.13 | 0.15 | 0.18 | 0.19 |
| C% + (Mn/6)% max | – | – | 0.32 | 0.38 | – |
| Mn% max | 0.2 | 0.6 | – | – | 1.35 |
| P% max | 0.04 | 0.03 | 0.03 | 0.03 | 0.03 |
| S% max | 0.05 | 0.035 | 0.035 | 0.035 | 0.035 |
| Si% max | 0.02 | – | – | – | – |
| Cu% max | 0.25 | – | – | – | – |

where $\sigma_{ys}$ is yield strength (USA units). $K_{IC}$ can be directly applied to define critical crack sizes $a_c$, using simple fracture equations such as

$$K_{IC} = K_{applied} = Y\sigma_{applied}\sqrt{(\pi a_c)} \quad (2)$$

where $a_c$ is the critical size of the crack depth $a$, and $Y$ is a correction factor influenced by geometry and load conditions. Defect criticality in the elastic–plastic conditions typically found in thin plates are handled by defining an effective applied $K$, using the correction formula based on the strip-yield model [11]:

$$K_{eff} = \sigma_{ys}(8a \ln \sec(\pi\sigma_{applied}/2\sigma_{ys})/\pi)^{1/2} \quad (3)$$

Table 3 indicates the national chemical composition requirements for the steels used as base plate for the carafes. Two stages are identified [6,7]. Carafes built after the local introduction of new steelmaking processes, ca. 1990, have requirements of maximum carbon equivalent, and the levels of acceptable impurities are sensibly lower than for the previous materials. In this way, cleaner and tougher steels are obtained, improving both the formability and weldability [8]. Table 4 shows chemical composition of the base plate steels. Note the large scatter in carbon contents (between 0.03 and 0.18%) and impurities such as phosphorus (between 0.010 and 0.025) and sulfur (between 0.007 and 0.32%). This implies important variations in both the formability and weldability.

To investigate the presence of hard spots and possible hydrogen embrittleness, especially in the HAZ, Vickers microhardness tests were carried out on carafes with widely different carbon equivalent. No appreciable increases in hardness were detected. Cross-sections of the welds were polished and subsequently etched with 5% Nital.

Residual stresses were measured in both inner and outer surfaces of the carafes. Particular attention was paid to those vessels showing the most critical defects as defined in Section 3. Typical results, corresponding to the SMAR carafe built in the 60s, are presented in Fig. 2. In the figure, circumferential stresses are shown as a function of the distance from the circumferential weld, for both the outer and inner surfaces.

## 3. Non-conformities in old carafes

All 62 carafes selected for this study contained defects that could be attributed to the fabrication process. The most common defect leading to rejection during the 10-year period between inspections is external corrosion, typically in the lower cap. These are easily visible volumetric defects. Other typical defects are gouges and undercuts following removal and replacement of handles and lower rings, bumps, and sometimes the vessels being inflated due to overpressure (e.g. when heated or refilled). All these defects are appropriately characterized by the standards as reason for rejection, and the vessels should be destroyed [6,9,10].

The fabrication defects that more commonly give rise to rejection are related to poor weld workmanship. The most frequent is poor weld toe and reinforcement geometries,

Table 4
Chemical composition of base metal from selected carafes

| Sample | C% | Si% | Mn% | P% | S% | Cr% | Ni% | Mo% | Ti% | Cu% |
|---|---|---|---|---|---|---|---|---|---|---|
| 6-11 | 0.04 | <0.01 | 0.34 | 0.025 | 0.007 | 0.05 | 0.03 | <0.01 | <0.01 | 0.07 |
| 6-14 | 0.18 | 0.04 | 0.44 | 0.011 | 0.016 | 0.03 | 0.01 | <0.01 | <0.01 | 0.03 |
| 6-15 | 0.03 | <0.01 | 0.27 | 0.010 | 0.009 | 0.04 | <0.01 | <0.01 | <0.01 | 0.02 |
| 6-16 | 0.16 | 0.05 | 0.34 | 0.011 | 0.032 | 0.04 | 0.04 | <0.01 | <0.01 | 0.30 |
| 6-20 | 0.18 | 0.06 | 0.32 | 0.023 | 0.032 | 0.03 | 0.02 | <0.01 | <0.01 | 0.04 |
| 7-17 | 0.03 | <0.01 | 0.32 | 0.010 | 0.012 | 0.03 | <0.01 | <0.01 | <0.01 | 0.02 |
| 8-01 | 0.13 | <0.01 | 0.45 | 0.013 | 0.049 | 0.05 | <0.01 | <0.01 | <0.01 | 0.04 |
| 9-04 | 0.07 | 0.02 | 0.22 | 0.021 | 0.012 | 0.04 | <0.01 | <0.01 | <0.01 | 0.01 |

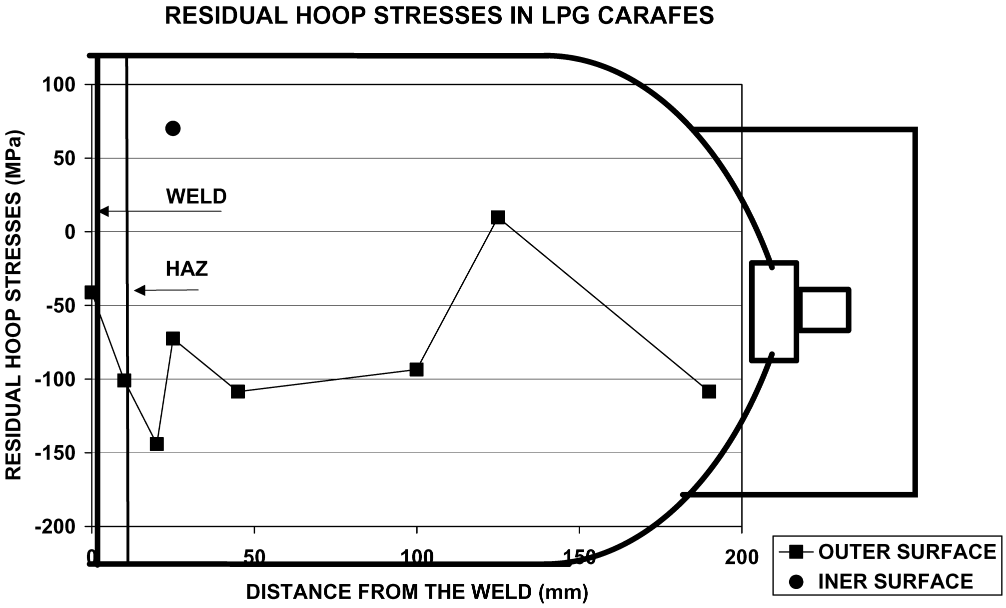

Fig. 2. Residual hoop stresses in carafes.

thereby generating moderate stress raisers. Other weld defects are potentially more dangerous. Cross-sections of all assessed welds were polished and subsequently etched with 5% Nital. The inset in Fig. 1 ( × 5, series 9) shows a cross-section of a good quality cap-to-cap circumferential weld. The backing strip is made by forming one of the caps, and the SAW weld is completed in one or two passes. There is a large tolerance in the width of the backing strip, provided that it gives an adequate geometry to the weld root. The groove formed in the outer surface of the cap in which the backing strip is formed is smooth and not very deep.

In a previous paper by the authors [3] a series of defects was detected in carafes built during the 1960s. Some vessels were found to be welded using manual procedures, instead of the specified submerged arc weld. In one case, the automatic circumferential weld deviated, and a new weld bead was laid. In two vessels faulty repairs were carried out during reconditioning, including the repair of a small gas leak in the circumferential weld. Typical non-conformities in circumferential welds were poor geometry of the backing strip, and lack of fusion. In many cases these defects do not affect appreciably the section strength, but in others the defect is accompanied by lack of penetration. These defects were, in some cases, effectively extended by inclusions, lack of fusion and other defects in the interface between the fused metal and coarse grained HAZ. The most dangerous defect in that series of tests was the defect shown in Fig. 3 ( × 5) [3]. Two weld passes can be seen, one beside the other, with the apparent function of correcting a lateral undercut. Note the planar defect, apparently originated in a hot crack in weld metal. This defect is through the thickness, and seriously affects the strength of the joint. In Section 4, the results of the continuing studies for series 7–9 are presented.

## 4. Metallographic characterization of defects

Diverse degrees of non-conformities, resulting in significant defects, were found in the circumferential welds of 25% of all carafes manufactured before 1990. Once again the most common is a lack of fusion between the weld bead

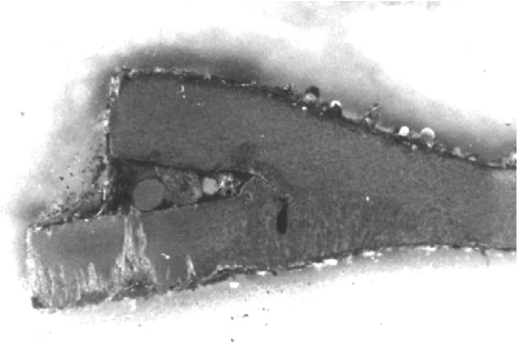

Fig. 3. Cross-section of weld, after etching with Nital 5%. Two weld passes are seen. Note the planar defect ( × 5). Plate thickness: 2.8 mm.

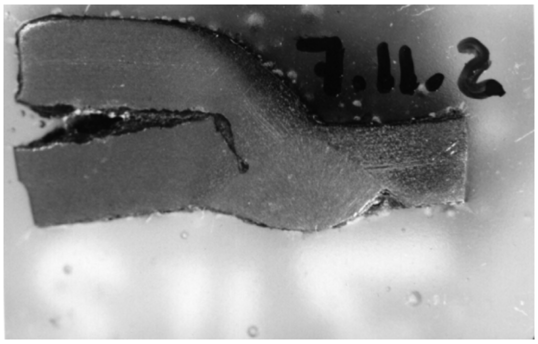

Fig. 4. Reduction of 50% is observed in the resistant section to the longitudinal stresses. Plate thickness: 2.8 mm.

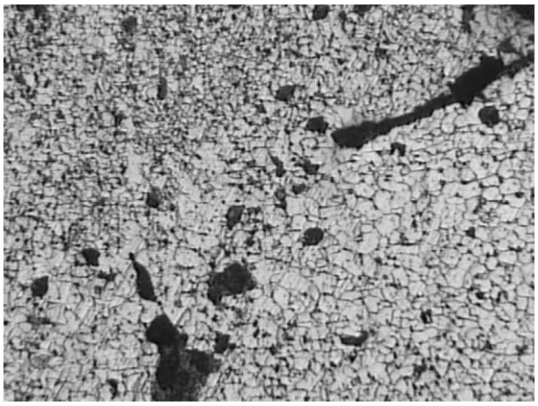

Fig. 5. Very sharp tips of defects ( × 100).

and the backing strip. In Fig. 4 a reduction of 50% is observed in the resistant section subject to longitudinal stresses, and generates a sharp 1.5 mm deep notch susceptible to propagation in service [11,12]. Fig. 4 also shows poor geometry of the backing strip and discontinuous defects due to lack of fusion. Fig. 5 ( × 100) shows that the tips of these defects can be very sharp, and can then continue in the form of inclusions, lack of fusion and other defects within the fusion line between weld (left) and coarse grained HAZ (right). This sample also has a deep undercut at the weld toe in the outer surface. Consequently, during its use this carafe presented a high risk of failure.

In the example shown in Fig. 6 (series 7) the inner surface of the circumferential weld is shown. The width of the backing strip is variable, and the surplus metal present after forming had not been machined out. This defect is common in the carafes of series 70 and 80, and can be attributed to cost reduction during fabrication. This variable width generates weld root geometries which in turn are also very variable. Fig. 7 ( × 5) shows a cross-section in one of the extreme cases. The backing strip does not operate as such, in that it is completely open, and the weld root shows severe lack of fusion, which, as it is perpendicular to the thickness, generating a potentially dangerous stress raiser.

Fig. 8 ( × 5) shows a circumferential weld with potentially very dangerous defects. The backing strip is again poorly formed, and fails to work as such. The crack-like through-thickness lack of fusion defect is seen in greater detail in Fig. 9 ( × 100). In Fig. 10, an extreme case of lack of fusion is observed. In this case the backing strip is well formed, but the first weld pass was laid outside the groove, and therefore the joint is fulfilled only by the second pass. Due to this, the weld shows incomplete penetration, with the resistant section only half the nominal plate thickness. Fortunately, the tip of this defect is not very sharp. An approximate calculation indicates that the strength of this section is only a quarter of the nominal strength of the carafe.

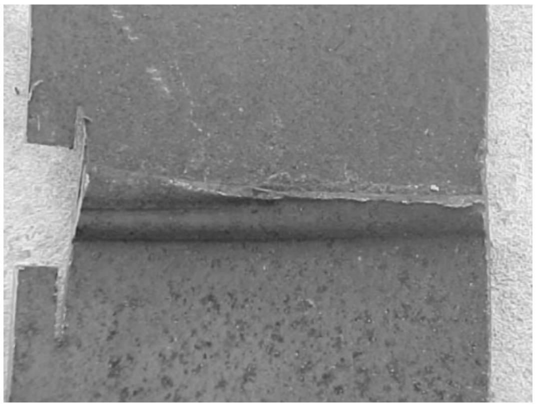

Fig. 6. Inner surface of the circumferential weld.

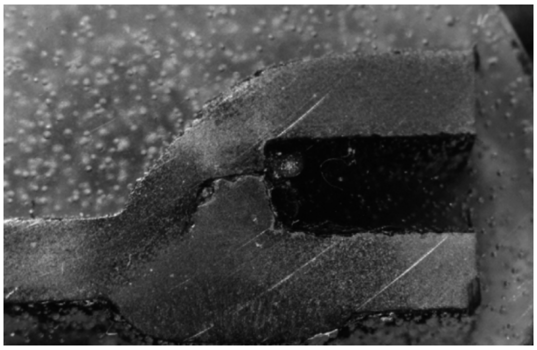

Fig. 7. A cross-section of one of the extreme cases ( × 5). Plate thickness: 2.8 mm.

When these and other geometric defects are coupled with microstructural defects, failure probabilities increase alarmingly. Weld root defects can include inclusions, cracks and other defects, because poor protection of the molten weld metal facilitates the presence of impurities, fundamentally oxides, together with hydrogen arising from surface contamination and the atmosphere. For example, in Fig. 11 ( × 100, sample 7-6) lack of penetration in the weld root (upper right) is associated with through-thickness lateral lack of fusion (lower left) and inclusions. A crack is also observed (middle), originated in the inner surface in the weld metal. This crack was probably due to hydrogen contamination, and it is doubly dangerous as it is through-thickness, and it is indicative of a weld material with very poor toughness.

In the series 7 and 8 the base plate material is frequently

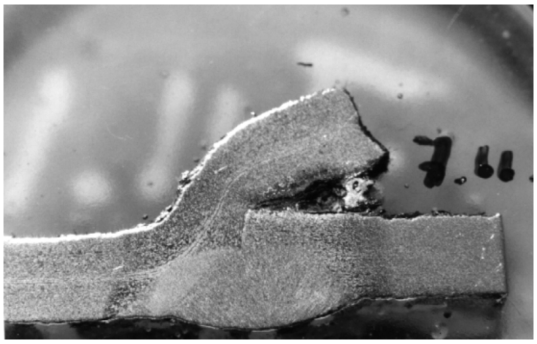

Fig. 8. A circumferential weld with really dangerous defects. Not well formed backing strip. Plate thickness: 2.8 mm.

Fig. 9. Crack like through the thickness lack of fusion defect in more detail ( × 100).

strongly banded, as observed in Figs. 9–11. It was mentioned previously that this type of materials exhibits strong mechanical anisotropy. This anisotropy is sometimes accompanied by laminations, but in all cases these were located in the backing strip, which is not subject to high stresses in the through-thickness direction. The base plate of sample 8-16 showed some type of surface treatment, possibly due to it being originally destined for another use. In an extreme case, the reduced transverse toughness gave rise to a crack in the backing strip, see Fig. 12. Cracks parallel to the surface of the base plate are indicative of a material with insufficient transverse ductility to withstand the large plastic deformations associated with the forming of the caps.

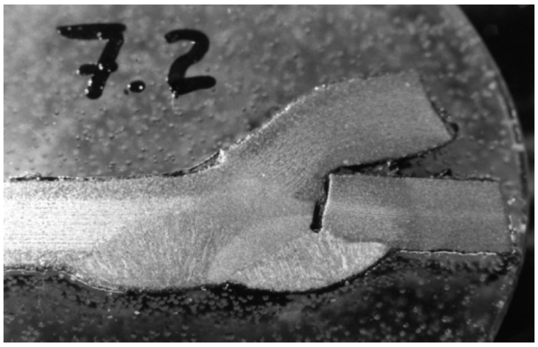

Fig. 10. First weld pass laid outside the groove. The joint is fulfilled only by the second pass. Plate thickness: 2.8 mm.

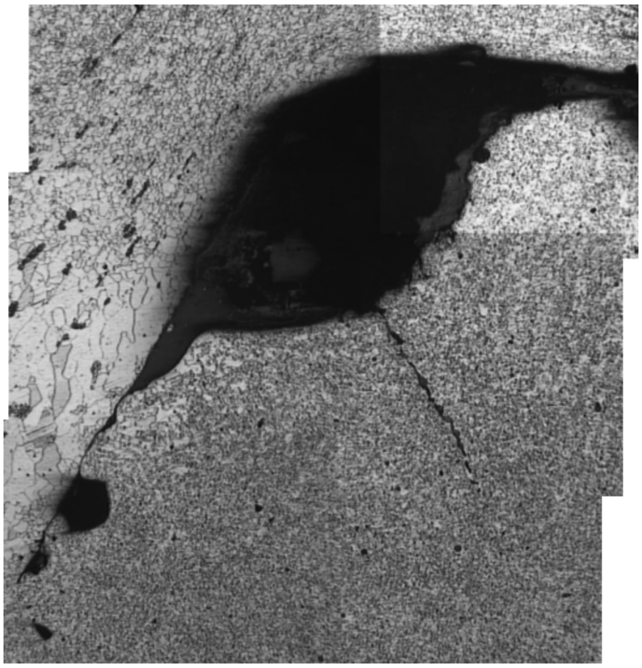

Fig. 11. Lack of penetration in the weld root (upper right) associated with the thickness, lateral lack of fusion (lower left) and inclusions ( × 100, sample 7-6).

Evaluations on vessels manufactured after 1995 include both domestic and imported samples. Only one manufactured (80, INEAR) has been represented in all series. No fabrication defects were detected in these new carafes. The base materials show very little banding, weld reinforcements are smooth, with no signs of lateral undercuts or lack of fusion. Weld and HAZ microstructures do not show signs of defects. Their mechanical properties, see Table 2, are much better than those of previous series.

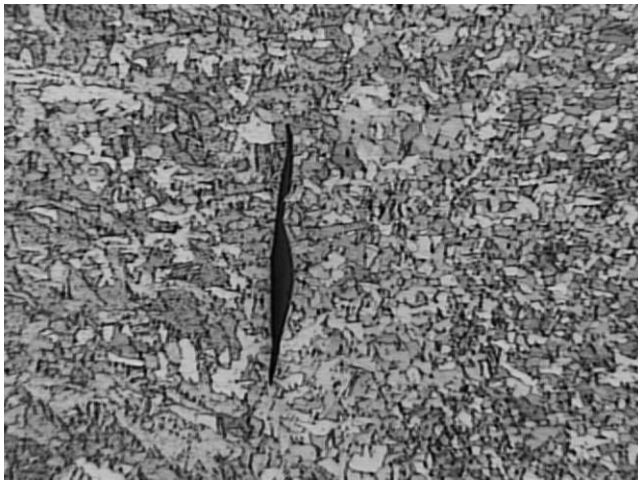

Fig. 12. A crack in the backing strip ( × 100).

## 5. Technical and legal limits of service life and rehabilitation

Argentine Standards [6,7] stipulate that each carafe should be subjected to hydrostatic tests every 10 years, to a pressure of 34 kg/cm$^2$, double the maximum allowable operating pressure (MAOP). The only additional test required by the regulations is visual inspection, in order to detect external defects, such as corrosion, macroscopic deformations, faulty repairs, etc. Hydrostatic testing is in general a means of evaluating the in-service integrity of pressure vessels. It defines, in both legal and practical senses, the MAOP of a new vessel [13]. The effectiveness of a periodic hydrostatic retest is defined in terms of the relationship between the test pressure and operation pressure. Retesting a carafe well above the operating pressure demonstrates the absence of defects that could cause an in-service failure, although sometimes growth of cracks may occur when the applied loads during the test are close to the failure levels in the presence of a pre-existing flaw [7,8].

Technological improvements have taken place since the Argentine Standard for the construction and inspection of carafes was enforced in the 1970s [6,7]. Some of these changes have been reflected in the standards of other countries. Current fabrication and quality control requirements demand PWHT to 640 °C. A comparative evaluation of documents and standards from different countries was carried out. These include Argentina, Chile, ISO, Mexico, Uruguay, Repsol Spain, USA [8,10,14–18]. All these are for the most part consistent, the differences relating to the characteristics of each LPG market (dimensions, volume, etc.). The age of the standards varies between 2 and 25 years. The most modern is the Mexican Standard, released in 1999, and it raises certain issues that deserve a detailed discussion [17].

This standard was developed after a change in the percentage of butane and propane in the LPG vessels. The standard defines that within a few years all existing carafes should be replaced by new vessels. These in turn will have a 12-year service life. Fabrication of LPG vessels in Mexico is similar to that of the United States, so this standard was designed to take into account the inspection procedures defined by the USA Department of the Transport (DOT). This stipulates that cylinders with specifications 4BA and 4BW for LPG service should be reinspected 12 years after fabrication, and those that do not fulfill all safety requirements of standards 4BA, 4BW and CGA-C6 should be destroyed. New inspections are scheduled every 12 years if the inspection includes a hydrostatic test; every 7 years if a pneumatic test is used; or every 5 years if inspection is only visual. Considering the lack of qualified laboratories to carry out the tests, the Mexican Standard does not stipulate periodic tests. It requires instead, a visual verification previous to each fill, and establishes a 12-year maximum service life, after which the carafe should be destroyed.

The quality of construction of the vessels varies widely according to both the manufacturer and fabrication date. Non-conformities are usually undetectable by external inspection. By 1965 there were more than 100 registered manufacturers, some with little quality control. Within the overall total of 62 analyzed samples, of the seven carafes with more severe fabrication defects three were made by SMAR, two by Liqui Gas and two by Contimet, all between 1963 and 1972. However, the quality and reliability of the vessels is not directly related to its age. Seemingly, there was a period in the 1970s where quality control within the state owned local plate supplying company was inadequate, which probably affected the reliability of the vessels built at that time.

## 6. Discussion

One of the main technological advances in recent years has been the improvement in fracture toughness of the materials. Fracture toughness is the mechanical property that most influences the risks associated with the use of the carafes. On the one hand, increased toughness means a greater resistance to larger defects, but on the other hand, in the case of failure, the toughness of base metal, weld and HAZ define to a large extent whether failure occurs by a blowout (fracture) or leaks. Potential damage in the first case is much larger than in the second. Risk is defined as the failure probability multiplied by the damage that it would cause. Therefore, toughness plays an important part in reducing the risk of failure of the vessels.

Other constructive aspects that can influence the failure risk are welding and non-destructive testing, coating, and PWHT methods. Three possible PWHT conditions exist. Argentinean carafe makers did not have the means to provide reliable high temperature PWHT until well into the 1980s. Without a stress relieving treatment, the tensile residual stresses longitudinal to the weld can be of a similar magnitude to the base metal yield strength, while the transverse residual stresses are about half of that value. For the normal butane–propane pressures, residual stresses can be up to about 5 times the stresses due to gas pressure in a carafe. The current tendency in Argentina is to carry out a stress relief treatment at temperatures between 600 and 650 °C. There is a trend now to move to thermal treatments at temperatures up to 900 °C, that is, annealing. In this way the initial ductility of the materials is totally recovered.

Applied stresses due to internal pressure are about twice as large in the circumferential direction than longitudinally. This is why many large defects evaluated in this study did not lead to explosions. Residual stresses may affect the criticality of flaws and burst pressures of the carafes. The experimental evaluation of circumferential residual stresses in the carafes, see Fig. 2, shows that in the region of the weld these are mostly compressive in the outer surface, with maximum values of about 100 MPa. Tensile residual stresses are found in the inner surface of the base metal close to the weld (square symbol), with a maximum value of 70 MPa. Residual stresses in the outer surface become tensile only close to the caps. This distribution leads to the conclusion that the original high-pressure hydrostatic test yields the weld and surrounding material of the body, while the caps only deform elastically. Therefore, the original high-pressure hydrostatic test could be considered a reliable way to reduce residual stresses. However, a relatively large bending component is found in the vicinity of the weld, probably due to the stiffening effect of the backing strip. Consequently, the largest tensile stresses act on the inside of the carafe wall, where defects undetected during visual inspection are most probably located.

The reliability of the carafes is fundamentally bound to the quality of base plate, forming and welding processes, weld materials and procedures, and PWHT. The comparative evaluation of vessels of different ages, indicate that the number and criticality of defects falls markedly in the carafes built after 1990. A marked increase in the average ductility and toughness of the base metal is observed as the date of fabrication increases. Average toughness of base metal, weld and HAZ of the modern carafes are around 10% higher than for the old materials, and in the case of base metal this difference can approach 50%. Eqs. (1)–(3) show that the critical defect size increases linearly with the CVN of the material.

Repairing externally faulty welds often covered the evidence of serious defects in the weld root. Serious errors during reconditioning, such as repairs of leaks and scratches, are indicative of a poor approach to the rehabilitation of the vessels. This is apparently influenced by commercial restrictions imposed on the reconditioning inspectors. Rejection rates are 10–15% within each lot. An excessive number of rejections is perceived as an increase of the probability of losing the client. This situation understandably increases the risk of accidents such as explosions during operation of the carafes. New methodologies for the technical control of inspections are required, that would allow suppliers and users of the reconditioning service to better regulate the operations, and to increase the level of the inspections without unduly increasing the costs.

The main conclusion of this study is a strong recommendation for a gradual process of substitution of the carafes built prior to 1990. This date coincides with the improvement of toughness of base plates, and a reduction in the number of weld and other fabrication defects in the carafes. These findings lead to the conclusion that the probability of failure of the carafes dramatically falls for carafes built after 1990.

## 7. Conclusions

The reliability of 10 kg LPG carafes currently used in Argentine households is evaluated in this study. Fabrication and repair non-conformities are assessed. A marked decrease of the severity of defects and an increase in material toughness was found in carafes built after 1990. Serious errors during reconditioning, such as repairs of leaks and scratches, are indicative of a poor approach to the rehabilitation of the vessels. It is concluded that the methodologies for fabrication and inspection are not reliable. It is recommended to evaluate changes in the rehabilitation procedures and standards. A gradual process of substitution of the carafes built prior to 1990 is also recommended.

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