HYDROGEN FABRICATION CRACKING: HSE's INDUSTRIAL EXPERIENCE, AND RESEARCH INTO DEFECT DETECTION WITH A NUMBER OF NDT TECHNIQUES

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An operator of large LPG storage spheres first alerted HSE to the problems of Hydrogen Fabrication Cracking (HFC). During a routine inspection, a small weld repair was necessary, and during this procedure, large embedded defects were discovered. The HSE and the operator carried out a detailed investigation into the cracking on two spheres. In one sphere, 46% of the total weld length had to be repaired. Samples taken confirmed that the defects were HFC and had occurred during original manufacture. Further investigation identified that in the UK, a total of 25 LPG spheres had hydrogen related cracking. These vessels had been manufactured by three different organisations, using two design codes and two materials. The HSE's concerns were the condition of the other spheres in similar service, and how vessels with 100% manufacturing inspection could enter service with such large defects.

A research program was set up with Serco Assurance to investigate the generation of HFC defects and to assess the reliability of NDT techniques to detect the defects. Two types of samples were manufactured, the first having a high degree of constraint and moisture ingress. These samples cracked in a manner similar to solidification type cracking. Further samples were manufactured with lower levels of constrain and water ingress, and embedded HFC defects were generated that were identical to those found in the original spheres. It was found that only two faulty weld runs in a multi pass weld could generate HFC that could impair the total integrity of the weld. Radiography and ultrasonic inspection, representative of the procedures applied during vessel manufacture, was carried out on both types of samples. Radiography detected the solidification type cracking, but not for the full length of the defect, but did not detect any of the HFC defects. Ultrasonic inspection detected all defects, and these results were confirmed by sectioning the samples. Modelling techniques were applied to the radiography technique to evaluate the experimental results. Modifications were made to the samples and radiography technique to evaluate possible improvement of the detection rate. Recommendations on inspection techniques to detect this type of defect are given.

INTRODUCTION

The occurrence of cracks in Liquid Petroleum Gas (LPG) storage vessels has been known for a considerable time. The defects in these large vessels can be divided into two main causes:

i) Initial manufacturing defects due to the quality control of the manufacturing process being reduced by site conditions.
ii) In service defects due to process carryover of wet hydrogen sulphide or moisture.

J.E. Cantwell [1] surveyed 141 large LPG vessels for the occurrence of cracking in 1988. He found that approximately one third of all vessels were cracked. Cracks up to 12 mm deep × 1 m long were found, although most were under 3 mm × 25 mm. A number of important points were raised. At least three factors were considered to be responsible for the increased occurrence of cracking:-

a) The use of higher strength steels with increased tendency for fabrication and environmental hydrogen related cracking problems.
b) The introduction of more sophisticated pressure vessel design codes which allow a higher design stress.
c) More sensitive inspection techniques.

Cantwell's report stated that in certain circumstances, with specific plate chemistry, Post Weld Heat Treatment (PWHT) was not effective in reducing the Heat Affected Zone (HAZ) hardness and the susceptibility to Hydrogen cracking. It also recommended that any large LPG vessel that has not been properly inspected and have been in service for over 5 years should be scheduled for an early inspection.

I. Hrivnak [2] describes the Czechoslovakian experience with 12 vessels. The number of defects found by ultrasonic inspection ranged from 24 to 239 per vessel, and their total lengths ranged from 11 m to 193.5 m. In addition magnetic particle inspection detected a further 16 to 183 defects per vessel. Extensive work was carried out including research into a repair technique.

In the UK, a refinery reported problems of Hydrogen cracking in the early 1980's. In this case the spheres were designed to ASME VIII and manufactured from ASTM 516 Grade 70 material. The defects were detected during a refinery inspection following a failure of a pressure vessel in the same grade of material in the USA. Ten spheres fabricated by three manufacturers between the late 1970's and the early 1980's had defects in the circumferential welds adjacent to the lower crown weld. Initially surface breaking defects were detected, but as the investigation continued, subsurface cracks were also found. A total of 21 "boat" and one large material samples were taken from 3 spheres to confirm that the cracks had been hydrogen induced, at the time of manufacture. Additional surface breaking defects may have been due to Hydrogen Sulphide (H_2S) carry over, although this was not proved as tighter monitoring of the trace gases was introduced during the service life. A repair procedure and a revised inspection plan were introduced, and no further problems have been encountered to-date.

A survey carried out by the UK Engineering Equipment and Material Users Association (EEMUA) identified a further 13 Spheres containing original manufacture hydrogen cracks that had been repaired between 1982 and 1993. This paper follows an investigation that has been carried out by the United Kingdom Health and Safety Executive (HSE) from late 1997 to the present day into the structural integrity of two large LPG Spheres that had severe Hydrogen Fabrication Cracking (HFC).

SITE INVESTIGATION

DESIGN FEATURES

The spheres are large structures designed to BS 5500 [3] manufactured in 1980 using BS 1501-223-32B-LT40 material, 37.5/40 mm thick and 16.76 m diameter. The design service limits are a temperature range of $-40^{\circ}C$ to $+38^{\circ}C$, and a pressure range of zero to 14.5 Bar gauge. The design did not require PWHT for the site welds, although the vessels had PWHT on the nozzles and the shop welds of the petals (two petals welded together in the shop, then the petal sections welded together at site). All welds had been subjected to 100% radiography Non Destructive Testing (NDT) at site following construction.

DEFECT DETECTION

The defects in the spheres were not found until 1997, seventeen years after they were commissioned. The refinery only carried out sample Magnetic Particle Inspection (MPI) on both the inner and outer surfaces of all their spheres, and during one of these inspections an inner surface defect was identified which could not be removed by surface grinding alone. During the repair, pulse echo ultrasonic inspection of the root of the repair weld revealed additional embedded defects in the original weld.

Following the discovery of the embedded defects, the inspection procedure for this sphere was modified to 100% MPI on both the inside and outside, with 100% manual ultrasonic inspection being applied to the weld from the inside. Sphere A was found to have a large number of defects on the equator weld, with a small number in the other horizontal welds, and only three defect areas on the vertical welds between the petals. 30% of these were surface breaking defects, but the vast majority were defects approximately 10 mm below the inner surface of the sphere in the weld Heat Affected Zone.

Following the work on sphere A, the identical Sphere B was investigated. The equator weld of Sphere B was first inspected non-invasively by manual ultrasonic inspection. This indicated that a similar problem with embedded defects was present, and the sphere was decommissioned and a full inspection identical to sphere A carried out. This sphere had defects in most welds. Only 5.5% of cracks were surface breaking, the remaining being embedded as in sphere A. The low number of surface defects can be explained by the fact that the sphere had been subjected to 100% MPI in 1996, and other surface defects had been removed or repaired at that time. The defects found in Spheres A and B are summarised in Table 1, Figure 1 and Figure 2.

SAMPLING

For sphere A one "boat" sample was removed and sent to a laboratory for examination. Sphere B had six "boat" samples removed from the equator weld, which were investigated

Table 1. Summary of defects for spheres A and B

	Sphere A	Sphere B
Number of defects	148	350
Weld repair length (m)	55	213.4
Weld repair length (% of total weld length)	12	46
Detection by inner MPI (% of total defects)	27	5.5
Detection by outer MPI (% of total defects)	2.7	0
Detection by UT (% of total defects)	70.3	94.5
Maximum size defect	2 to 8 mm × 5.8 m 12 mm below inner surface	8 to 10 mm × 11 m 25 mm below inner surface

by two laboratories. The sample from sphere A was of an embedded crack. From sphere B, samples 1 to 4 were all embedded cracks (Figures 3 and 4), sample 5 was parent plate for chemical analysis, and sample 6 was an inner surface breaking defect. Tests carried out by both establishments gave the following results:

i) The source of the cracks appeared to be Hydrogen Fabrication Cracking (HFC) during original manufacture.
ii) The HAZs were considerably harder than the parent plate material. (Table 2.)

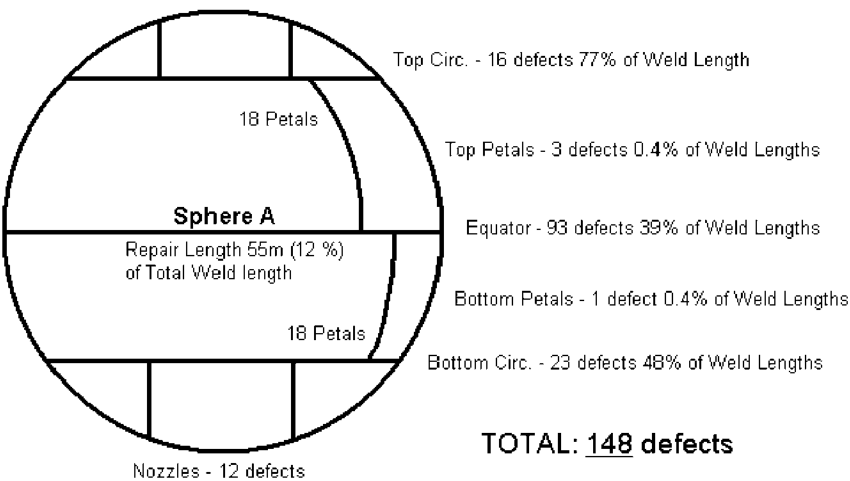

Figure 1. Defects detected sphere A

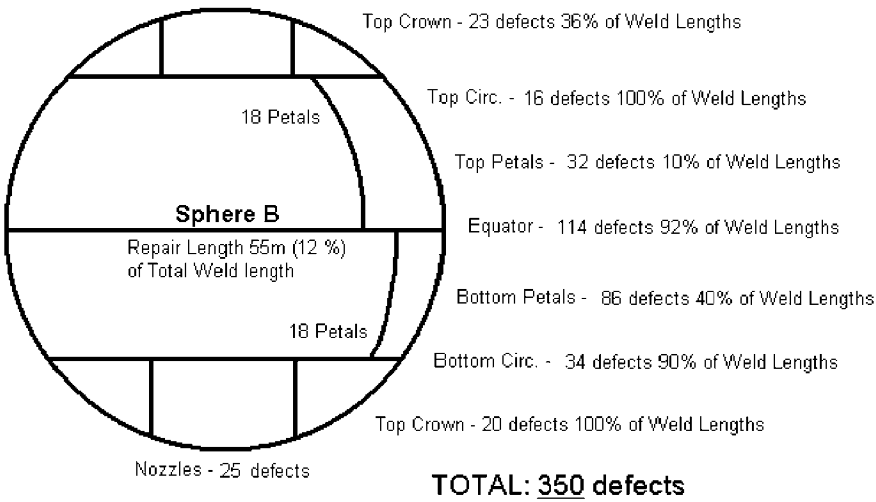

Figure 2. Defects detected sphere B

iii) The surface breaking defect exhibited no crack growth.
iv) The embedded defects exhibited crack growth towards both the inside and outside surfaces. The crack growth towards the inner surface was considerably larger and values measured are listed in Table 3.
v) The material composition was correct for BS 1501-223-32B-LT40.

CRITICAL DEFECT SIZE

Initial fracture assessment calculations using Level 1 of PD 6493 [4] with a Crack Tip Opening Displacement (CTOD) of 0.15 mm gave a critical crack size of 7 mm × 500 mm for surface breaking defects, 12 mm × 500 mm for a defect 3 mm below the

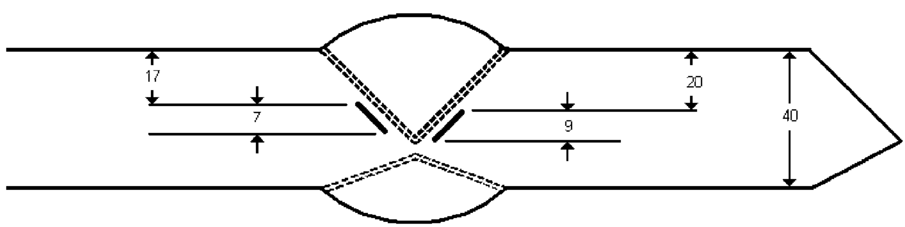

Figure 3. Boat samples 1 & 2 — crack locations

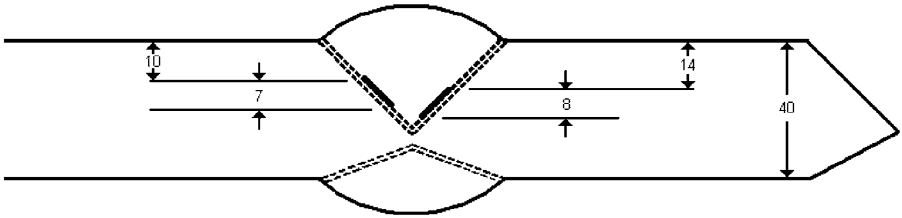

Figure 4. Boat samples 3 & 4 — crack locations

Table 2. Hardness survey

Sample	HAZ (HV)	Parent Plate Average (HV)	Weld Metal (HV)
1	447	197	216
2	441	197	216
3	391	186	204
4	317	186	182
6	401	186	215

inner surface, and 18 mm × 500 mm for a mid-wall defect. The assessment considered the fracture toughness at −20°C with the maximum design pressure.

The defects were in, or close to, the HAZ of the weld. The material fracture toughness used for these calculations was obtained from a sample of parent metal from another sphere. However, since the fracture properties can vary considerably within the HAZ, it was realised that parent metal values were not necessarily a lower bound. In addition, although the vessel was originally designed to operate at −20°C, the latest requirements require the vessel to be assessed to −40°C.

A more realistic Engineering Critical Assessment (ECA) is to consider the pressure/temperature relationship of the LPG, and carry out the calculations to consider the worst case with respect to the fracture toughness/temperature relationship of the material.

Table 3. Fatigue growth survey

Sphere	Sample	Fatigue Growth (mm)
A		0.15
B	1	0.6
B	2	0.3
B	3	0.8/1.0
B	4	0.2

FATIGUE CRACK GROWTH

Fatigue crack growth calculations were carried out based on input data supplied by the operator. These indicated that extremely low surface crack growth rates would be expected. However, the “boat” sampling found that up to 1 mm of fatigue crack growth was present for embedded defects. Assessment calculations of embedded defect crack growth were carried out and the values were approximately 200 times less than found in the samples. Further calculations were carried out to estimate if the presence of ‘peaking’ (i.e. local plate misalignment to the maximum allowed by the design code) could generate the crack growth measured, but, again this could not explain the crack growth found. In addition to the main shell welds, cracks on sphere B were found on the main outlet nozzle. These were so severe that the nozzle had to be removed, machined, and weld repaired before re-welding to the sphere. No details of the length of cracks were available, but it was evident that the crack must have grown from the weld into the parent metal by fatigue. This crack growth must have been considerably greater than the 1 mm found in the shell. As the nozzle welds had been PWHT, it is possible that another mechanism other than HFC initiated the defect in this location.

REPAIR STRATEGY

For surface breaking defects, the operators originally ground them out to the depth of the corrosion allowance. Following an Engineering Critical Assessment (ECA), the deeper cracks were ground out to the depth of an allowable surface breaking crack. This was done on the basis that a curved ground area would have a lower stress concentration than at a crack tip.

Due to the lack of material properties required to give an accurate ECA, the operator decided to repair all surface and embedded defects detected. For the embedded cracks, the operator initially ground out the crack locally, and then repaired the weld with the identical weld procedure used in the original manufacture. In certain cases considerable problems were experienced with the repair weld, one weld being re-repaired four times. The crack removal technique was then modified to remove the whole of the inner section of weld, which appeared to solve the problem.

EXPERIMENTAL INVESTIGATION

SAMPLE PRODUCTION

The objectives of the experimental work were to gather data on the effectiveness of the manufacturing NDT at detecting hydrogen cracking and to gather data which could be used to generate a stress model to predict crack gape and hence detectability. A secondary objective was to investigate how residual stresses effect the onset and detectability of hydrogen cracking. Whilst the three factors (hydrogen, tensile stress and susceptible microstructure) which contribute to hydrogen cracking are well known and avoidance of cracking can be achieved by negating any one of these factors, it is not always possible to produce cracking even when all three are present as they may occur during manufacture. The project had to rely on the cracking that was generated in the samples produced.

The experiment design and the production of the subsequent samples was undertaken by MB Engineering Services Ltd. at their works in Motherwell and their laboratories at Aberdeen. After production of a trial weld, four sets of 5 weld samples were produced. The material used in the experimental work was off-cut material from the production of an actual LPG sphere. This was 43 mm thick carbon steel of grade EN 10028-3:1993 P355NL1, CEV = 0.41.

The weld profile was as shown in Figure 5. The welding procedure was the same as that used for the manufacture of LPG spheres with a modification to allow the insertion of weld beads from wet electrodes. Before laying down a wet bead, the weld was cooled back to ambient temperature, 10°C. Each sample contained 150 mm of weld. Two forms of restraint were used. In Sets 1 and 2 the weld was laid down in a letterbox slit as used in a modified Lehigh Restraint Test [5]. Initial tests with a large number of wet weld beads gave extensive cracking in the weld. The cracking was similar in appearance to solidification type cracking, and did not replicate the cracks found in the spheres. In Sets 3 and 4 two separate pieces of parent material were welded as a butt weld using strongbacks as restraint. The reduction in restraint, together with a reduced number of wet weld beads gave cracks identical to those found in the spheres. Two samples had only two wet weld beads, but this was sufficient to generate the HFC. The details of the different samples are given in Table 4.

NDT ASSESSMENT

All the butt welds were inspected on completion of welding and then at 12, 24, 48 and 96 hours after completion using both Magnetic Particle Inspection and Ultrasonic Inspection. The intervals were chosen to allow any delayed cracking to be observed. Radiography was performed at 48 hours after completion of the weld which would

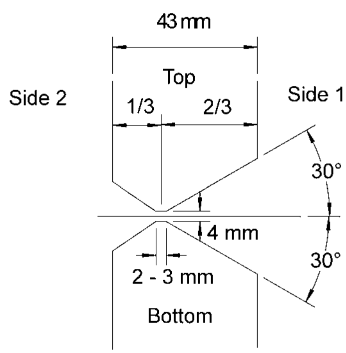

Figure 5. Geometry of the weld profile used in test samples

Table 4. Details of welded samples

Samples	Restraint	No. of Wet Weld Beads	Typical Gape	Comments on Cracking
Trial	Letter box	All beads were wet	Typically 0.05 mm to 0.15 mm	Extensive crack in weld metal running nearly through wall.
Set 1	Letter box	Butt 1: 6 wet beads laid individually on upper fusion face, 4 on Side 1, 2 on Side 2. Butt 2: 5 beads 3 on Side 1–2 adjacent, 2 on Side 2 Butts 3, 4 & 5: 5 individual beads 3 on Side 1, 2 on Side 2	Typically 0.02 mm to 0.2 mm	Variety of cracks: Butt 1 extensive crack in weld, Butt 2 small crack in HAZ, Butts 3 & 4, cracks in weld root, Butt 5 no crack.
Set 2	Letter box	9 wet beads laid on upper fusion face as 3 pairs on Side 1 and 3 adjacent beads on Side 2.	Typically 0.07 mm to 0.3 mm	Extensive cracking in all Butts along upper fusion face in HAZ and weld.
Set 3	Strongbacks	9 wet beads laid on upper fusion face as 3 pairs on Side 1 and 3 adjacent beads on Side 2.	Typically 0.01 mm to 0.07 mm	Extensive cracking in all Butts along upper fusion face in HAZ and weld but branched and more random in orientation.
Set 4	Strongbacks	Butt 1 as Set 3. Butt 2 & 3 pair of wet beads on upper fusion face on Side 1 only. Butt 4 & 5 pair of wet beads on upper fusion face on both Side 1 and Side 2.	Typically 0.01 mm to 0.05 mm	As Set 3 but smaller through wall extent with reduced number of wet beads.

have been the time radiography would have been applied during the manufacture of an actual LPG sphere and is the earliest time recommended by the British Standard [6]. All the inspection procedures used were those that would have been used in the manufacture of an actual sphere.

The radiography detected the majority of cracks in the welds in Sets 1 and 2. However, none of the cracks in Sets 3 and 4 were detected. Of the 27 distinct cracks in the welds, only 9 were detected by the manufacturing radiography. Thus the overall probability of detection for the manufacturing radiographic technique was only 33%, compared with a value of 96% for manual pulse-echo ultrasonic inspection.

The macrograph analysis showed that the gapes of the cracks in Sets 1 and 2 were substantially higher than those in Sets 3 and 4, and that the radiographic detectability of these examples of HFC correlated with crack gape. Only cracks with a maximum gape of 0.08 mm or more were detected in this study.

The radiography was performed with the weld caps on and with the radiation source directly above the centre of the weld, so that the radiation beam was approximately normally incident on the weld surface. Most of the cracks followed the weld fusion face and so were inclined at a significant angle ($\sim 30^\circ$) to the vertical. These cracks were not therefore well oriented to the radiation beam and so poor detectability of the cracks with narrow gapes is not unexpected.

The weld caps gave significant irregular density variations on the standard radiographs which made identification of low contrast fine crack-like indications difficult. Additional radiographs were taken on three welds once the weld caps were removed: a "normal" radiograph with the radiation source centred over the radiograph; two angled radiographs with the radiation source positioned so that the beam centre line was aligned with each of the main weld fusion faces. For defects aligned along the weld fusion face, this technique substantially reduces the mis-orientation relative to the radiation beam and would be expected to improve crack detectability.

The removal of the weld cap produced radiographs which are substantially easier to interpret and may well have improved defect sensitivity (and less likelihood of false calls). The angled beam radiography gave significantly improved defect detectability in two of the three welds examined. In one of these, the crack could only be detected using the angled radiography technique.

Results from theoretical modelling [7] of the radiography inspections supported the experimental results.

The manual pulse-echo ultrasonic inspection was carried out using standard angled pulse-echo shear wave probes (45°, 60°, 70°). The inspections were carried out to ASME Article 5 2001, and the acceptance criteria were to ASME VIII D1 AP12 2000. The reporting level used was 50% of the signal height from a 3 mm side-drilled hole. Of the 27 distinct known cracks in the weld, all but one was detected with manual pulse-echo, giving an overall probability of detection (POD) of 96%. The missed defect was a small defect in Set 1, Butt 2 (TWE 7 mm, but length unknown), which was seen on the macrograph for this weld.

However, as the welds were not comprehensively sectioned at a fine interval in the along weld direction, it is possible that there were some small cracks in the welds which were not detected by the NDT and were not present at the weld locations covered by the single macrographs taken for each weld.

The defects in the samples were relatively easy to detect using pulse-echo ultrasound for the following main reasons:

The defects were generally highly extended in the along weld direction, often running the full length of the specimens;

The mean defect through-wall extent was 18 mm (40% of the wall thickness);

The defects or at least some sizeable facets were well oriented for detection using standard angled shear wave probes, using either half skip techniques through the weld or full skip techniques off the backwall.

In addition, the observed HFC defect amplitudes were generally well above the 50% DAC ultrasonic reporting level, which is consistent with the above factors, and confirms that in general these particular defects were relatively easy to detect using manual pulse-echo ultrasound.

Theoretical modelling of the ultrasonic inspections highlighted reduced detectability if the defects were small in through wall extent or if they were smooth and perpendicular to the inspection surface.

DISCUSSION

Hydrogen cracking was not detected on the final inspection after manufacture for the following reasons:

a) The present practice of waiting 48 hours after welding before carrying out radiography was not in operation at the time of manufacture.
b) Radiography does not easily detect tight cracks (low values of gape). In this case it is likely that the residual stresses at the welds would be tensile at the surface, and compressive in the centre. As the majority of the defects found were approximately 10 mm below the surface, they would have been in the as-welded compressive stress region, which would have reduced the gape to a minimum. Previous unpublished research work stated that buried HAZ defects formed by a brittle mechanism are not suited to detection by radiography. However, this project did not evaluate the effect of residual stress distribution on detectability.

The two spheres were constructed during the winter when control of pre-heat would be particularly difficult. The defects in the spheres form two distinct patterns which could be linked to the degree of quality control during fabrication:-

i) Those in all horizontal welds.
ii) Those in all welds.

While the factors that contribute to hydrogen cracking (e.g. damp welding rods, low preheat, high residual stresses, high local hardness) are well known, it can be postulated that for the horizontal welds in cases (i) it is possible to have a lower heat input during the welding of such welds in comparison to the vertical welds, and this could be a contributing factor. In case (ii) where every weld was affected, including the shop fabricated PWHT ones, any combination of factors could be the source of the hydrogen cracking.

Tolerable defect sizes calculated from Engineering Critical Assessments varied considerably depending upon the assumed fracture toughness. While some information was available for parent plate properties, accurate values of the fracture toughness of the HAZ were not available. Accurate calculations required the fracture toughness of the HAZ at the full temperature range of the vessel. Depending upon the assumed fracture toughness, the defects had a margin of safety, or were only just tolerable. The concerns of the HSE were:-

i) What was the lowest fracture toughness for the course grained HAZ?
ii) What was the sizing accuracy of the NDT?
iii) Was the measured fatigue crack growth of 1 mm the largest on the sphere?

The boat samples were all taken from one area of the equator weld, and other welds in other locations could have been subjected to higher values of fluctuating loadings with even greater fatigue crack growth.

iv) If surface breaking cracks and embedded cracks were present in the same section of weld, could interaction occur resulting in coalescence with the critical size defect being attained at the operating pressure?

In view of the above factors the Refinery decided to repair all of the defects that had been detected.

The spheres had the classic combination of high values of hardness in the coarse grain HAZ, high residual stresses as no PWHT was carried out, site fabrication in adverse conditions, and an inspection method which has a poor detection rate with this type of defect.

This investigation highlights the fallacy of assuming that there are no embedded defects in a vessel if it has been inspected during manufacture. Whilst it is accepted that NDT is just one quality assurance activity during manufacture, the experimental work highlights the importance of the need to consider the actual detection capability and the limitations of the any technique applied.

The HSE has now requested operators of site built LPG storage spheres to include ultrasonic volumetric inspection in their in-service-inspection programme rather than relying on surface inspection techniques alone.

CONCLUSIONS

UK experience has shown that in large site fabricated LPG spheres, hydrogen cracking has occurred in 25 vessels, designed to two standards, made by three manufacturers, from two material specifications.

Two of these LPG spheres have been subjected to a detailed inspection and a large number of defects found. These defects have mainly been embedded defects associated with the HAZ of the weld. Six of these defects have been metallurgically examined and have been found to be original fabrication defects, the embedded defects exhibiting unexpected fatigue crack growth.

The experimental study showed that typical manufacturing radiography has significant limitations for the reliable detection of hydrogen cracking in weld heat affected zones. Of the cracks generated in the programme only 33% of the overall population were detected. In Sets 3 & 4 none of the defects were detected as they had gapes less than 0.08 mm.

Theoretical modelling confirmed that poor detection performance is due mainly to the high mis-orientation angles between the crack directions and that of the radiation beam, combined with the narrow gapes of many of the cracks generated in the experimental programme.

Improved radiography crack detectability can be obtained by removal of the weld caps and by use of an angled technique, in which the radiation source position is adjusted to give radiation beams which align with each weld fusion face in turn. Even with these improved methods cracks with the narrowest gapes will not be detected, unless their mis-orientation angles are only a few degrees.

The typical manufacturing manual pulse-echo ultrasonic inspection technique, showed a high detectability of the hydrogen cracking, with 96% of the known cracks in the weld being detected (only one was not detected). The cracks generated in the experimental programme gave high ultrasonic signal amplitudes well above the detection threshold. Reduced detectability would have been observed for defects with smaller through-wall extents (3–5 mm), and for smooth defects which are oriented within c. 10° of the vertical.

To confirm the continued fitness for purpose of a pressure vessel, all potential defects, generated during manufacture and in service need to be assessed. The coverage, type and sensitivity of the initial manufacturing inspection has to be assessed with regards to potential defects missed, and repeat inspections using an alternative technique may be necessary.

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