Journal of Loss Prevention in the Process Industries 43 (2016) 263–272

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

A survey of flaws near welds detected by side angle ultrasound examination of anhydrous ammonia nurse tanks

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ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form
14 April 2016
Accepted 22 May 2016
Available online 25 May 2016

Keywords:
Non-destructive inspection
Welds
Surface cracks
Stress corrosion cracking
Residual stress
Stress relief
Anhydrous ammonia
Safety

ABSTRACT

A sample of 532 anhydrous ammonia nurse tanks with manufacture dates ranging from the 1950's to 2011 were examined during 2012 by side angle ultrasound to measure the locations, sizes, and orientations of flaw indications. The indications were most frequently located on the head side of the head-to-shell welds and oriented perpendicular to the weld line in the welds' heat affected zones. On average newer tanks had more indications than older tanks. Tanks that had been given a post-weld stress relief anneal had markedly fewer indications.

1. Introduction

Anhydrous ammonia (NH_3) is a toxic chemical used as an agricultural fertilizer distributed to farm fields via nurse tanks (Fig. 1), which hold NH_3 in liquid form under pressure. The steels used to manufacture nurse tanks are all low-carbon, low-alloy steels with mixed ferrite-pearlite microstructures (e.g., ASTM A285, ASTM A455, and ASTM A516 grade 70). The Fertilizer Institute estimates that about 200,000 nurse tanks are in use in the United States; many are between 20 and 50 years old.

An international survey conducted in 1982 found that over half of all inspected spherical ammonia tanks contained cracks (Blanken et al., 1983). Anhydrous ammonia was reported in 1997 to be the most frequently released hazardous substance (HSEES,). Liquefied ammonia flash vaporizes upon depressurization and causes severe burns if it contacts human tissue (Welch, 2006). The dangers posed by unintended NH_3 releases make the safe storage and transport of anhydrous ammonia an important concern for both agricultural workers and the general public.

Nurse tank failures can occur either by leaking or by explosion. Explosions have caused severe injury, death, and extensive property damage. Such failures are often attributed to stress corrosion cracking (SCC) (Dawson, 1956; Anhydrous ammonia nurse tank, ; National Transportation Safety Board, 2003; Minnesota Dept. of Labor and Industry, ; Packer Engineering, 2008). SCC is crack formation and propagation in metal caused by the combined effects of corrosion and straining of the metal from residual or applied tensile stresses. Since nurse tanks do not contain manways, magnetic particle and fluorescent dye penetrant inspection methods cannot be used to find incipient cracks on the tank's interior surfaces unless the tank is cut open. Hydrostatic pressure testing, external visual examination, and ultrasound wall thickness measurements are the only inspection methods in wide use today. Prior studies

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http://dx.doi.org/10.1016/j.jlp.2016.05.025
0950-4230/

Fig. 1. Anhydrous ammonia nurse tank mounted on running gear. (Photo courtesy of the Federal Motor Carrier Safety Administration.)

have shown that SCC can occur by three mechanisms: active path dissolution, hydrogen embrittlement, and film-induced cleavage (Cottis, 2000; Woodtli and Kieselbach, 2000; Wilde, 1981; Lunde and Nyborg, 1987; Jones et al., 1977; Jones, 1992). Numerous reports have been published on the effects of water, oxygen, nitrogen, and carbon dioxide on SCC in ammonia tanks (NACE International, ; Newman et al., 1989; Jones and Wilde, 1977; Nyborg and Lunde, ; Great Britain, 1986; Hutchings et al., 1971; Loginow, 1986).

Nurse tanks are fabricated by forming steel plates into cylindrical and hemispherical shapes, then welding those components into a completed tank. Steel in the fusion and heat-affected zones (HAZ) of welds is particularly susceptible to SCC because the metal retains high residual stresses from welding, which remain in the tank throughout its service life (Becker et al., 2014, 2015). Some regions near a weld retain a tensile residual stress; others retain a residual compressive stress. Tensile stresses are essential for SCC initiation and propagation, so only those regions with residual tensile stresses are vulnerable to SCC.

Some nurse tanks have been given stress relief anneals after welding to reduce residual stresses, but the great majority of the U.S. nurse tank fleet has not received stress relief annealing after welding. Accident analyses performed on failed nurse tanks often report that the crack leading to failure started near a weld (Minnesota Dept. of Labor and Industry,). Observations of cracks in and near welds typically show transgranular crack propagation in the fusion zone and intergranular propagation in the heat-affected zone.

Stress corrosion crack initiation and propagation are stochastic processes, and the current understanding of SCC is inadequate to allow reliable prediction of whether a given piece of steel will develop a stress corrosion crack when loaded in tension and immersed in NH_3. Predictive models have been proposed for both crack initiation and crack propagation, but these models are approximate at best because the interplay of factors affecting crack initiation and growth rates is complex and incompletely understood. Moreover, data are lacking on the number, size, and orientation of cracks in nurse tanks that have been in service for many years. This study was performed to attempt to provide such information on cracks and other flaws in a large population of nurse tanks that are currently in service.

2. Materials and methods for measuring flaw size, location, and orientation

Ultrasound examination of the nurse tanks was generally performed in accordance with the ASME Boiler and Pressure Vessel Code 2011a Section V Article 4: Ultrasonic Examination Methods for Welds. The nurse tank survey followed this standard with one exception. Student employees performed the inspections, and they did not have the number of hours of experience to be certified inspectors, as required by that code. For this study, the undergraduate student inspectors were given 80 h of training in ultrasound inspection by an Air Force-certified Level 7 inspector, the highest level in the Air Force.

The transducers used were 12.7 mm, 5 MHz, 45-degree, quick-change wedges. Transducer wedges had to be replaced frequently because the areas being measured often contained weld spatter, which caused rapid wear on the wedges from being pushed across the rough surfaces. EZAvenger ultrasound units were used for all inspections. Details of the inspection methods used are described more fully elsewhere (U.S. Dept. of Transportation, 2013). The sensitivity level set for inspection was capable of detecting cracks as small as 1 mm deep and 6 mm long.

During June–August 2012, 532 tanks owned by farm cooperative companies in central Iowa, USA were examined by ultrasound. Only areas near welds were examined, generally in a band approximately 200 mm wide centered on the weld. Ultrasound cannot discriminate perfectly between cracks and other defects in tank steel. In recognition of this fact, the term *indications* is generally used to describe ultrasound reflections that reveal a discontinuity in the metal. Indications are usually cracks, but other types of discontinuities not considered defects can also generate indications.

A mixture of 3800-L (1000-gallon) and 5500-L (1450-gallon) tanks was inspected. In 2012 the Iowa Department of Agriculture and Land Stewardship staff inspected 21,522 sets of nurse tank running gear (the wheels and suspension for nurse tanks) in Iowa; each set of running gear holds one or two tanks. Thus, the number of tanks tested by this research project represents roughly 2% of the total nurse tank fleet in Iowa. Fig. 2 displays the numbers and years of manufacture for the tanks inspected. As Fig. 2 shows, most tanks manufactured before the mid-1980's had a 3800-L capacity, and more recently manufactured tanks usually had a 5500-L capacity.

2.1. Methods used to select tanks for inspection

Only tanks with legible data plates (which display the year of

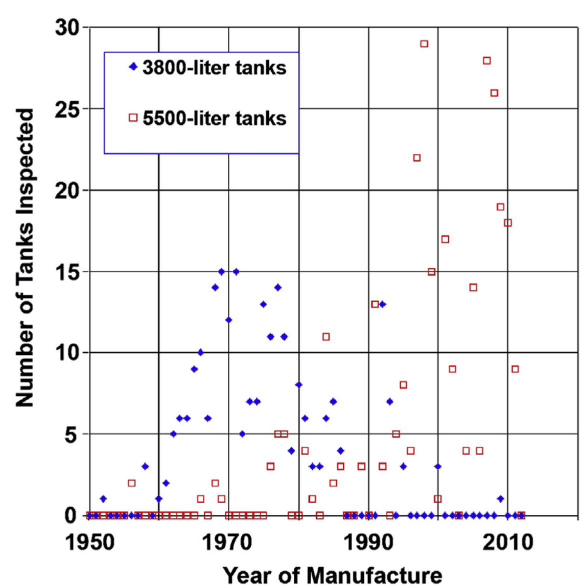

Fig. 2. Scatterplot of the tanks inspected as a function of year of manufacture.