Brittle Fractures of Cylindrical Steel Storage Tanks for Petroleum and Petroleum Products in the North

I I Buslaeva¹

¹The Yakut Scientific Centre of the Siberian Branch of the Russian Academy of Sciences, 2 Petrovskogo Street, 677980, Yakutsk, Russia

E-mail: buslajeva@mail.ru

Abstract. This article discusses brittle fracture accidents of petroleum and petroleum products storage tanks that occurred in Yakutia. Operational safety of tanks in the cryolithozone is reduced by harsh natural and climatic conditions, the uniform and differential settlements of the shell and bottom, long-term operation associated with the degradation of structures and materials in such climatic conditions. The main factor contributing to brittle fracture is extreme low ambient temperature, which reduces the ductility and resistance to brittle fracture of steel structures and welds. The uniform and differential settlements of the tank lead to appearance of dangerous stress-strain state of shell and its general and local deformations. A sharp change in the air temperature causes thermal stresses in the statically indeterminate structures of the tank. Analysis of tank accidents in Yakutia shows that places of crack initiation are assembly welds and their heat-affected zones, the metallurgical and corrosion defects of the base metal. Dangerous areas of the tank are shell-to-bottom connections and attachments of piping nozzles to the shell. The main cause of the considered accidents is the use of low-carbon steel that does not recommend to the oil tank operation in the climatic conditions of the cryolithozone.

1. Introduction

The reliable operation of cylindrical steel storage tanks for petroleum and petroleum products in the North is of great importance for the preservation of vulnerable northern ecosystems, the safety of an oil depot staff, as well as for ensuring the living conditions of population in harsh climate. In the Republic of Sakha (Yakutia), 136 diesel power plants provide electricity and heat to approximately 105 thousand people over an area of 2.4 million square kilometers (this is more than 2/3 of the Republic area). In case of a tank failure with the spill of petroleum products, the costs of their emergency delivery to the remote areas of the Republic increase manifold because of the undeveloped transport network. The oil depots and diesel power plants in Yakutia mainly operate the vertical cylindrical steel storage tanks with capacity ranging from 100 to 5000 m³. Built in the permafrost zone, these welded tanks were usually installed on sand cushions. Permafrost thawing can cause to ground subsidence and the tank settlements.

In Yakutia, the significant quantity of storage tanks was constructed in the Soviet times; therefore their design lifetime has been exhausted or is close to being exhausted. Inspection of these objects reveal the violations of tank geometric shapes, the dents and other imperfections of the shell and bottom, the uniform and differential settlements, corrosion damages, the welding defects, etc [1]. The parameters of these damages and defects often exceed permissible limits of regulations.
The tank structures are designed for the following design loads: the dead load of structures, the internal pressure of the stored oil product, the overpressure, the partial vacuum, the snow and wind loads. Structural analysis does not take into account the settlements and tilt of the tank, the changes in air temperatures. Namely these types of loads have extreme values in the cryolithozone.

Based on the analysis of statistical data on the tank accidents in the Russian Federation for 30 years, the authors of the article [2] have stated that the most frequent occurrences are brittle failures (63.1%), as well as explosions and fires (12.4%). Propagation of brittle cracks in the shell leads to tank complete destruction and contamination of adjacent territories and aquatic environment with oil products. The spilled petroleum products can damage the nearby tanks and piping. The economic damage from such accidents, taking into account environmental consequences, is many times higher than the tank construction costs. The authors note that most of the tank brittle fractures are caused by the welding defects or the cracks of low-cycle fatigue, which arise near the places of stress concentration.

The causes of tank accidents are associated with the conditions of their operation. Russia is the largest country in the world by total area, therefore the natural and climatic conditions on its territory are extremely diverse, as well as the other operating conditions of tanks. Ensuring reliability of oil storage tanks mainly depends on the conditions and modes of operation, the quality of the project and building, compliance with operating and maintenance rules.

2. Materials
Yakutia is supplied with petroleum products during the short summer period of river navigation. Therefore, the tanks in Yakutia have the following mode of operation during the year: single filling with fuel and long-term storage. This mode of tank operation does not contribute to the fatigue damage development of structural steel. Operational safety of tanks in the cryolithozone is reduced by the harsh natural and climatic conditions, the uniform and differential settlements of the shell and bottom, the long-term operation associated with the degradation of structures and materials in such climatic conditions.

The sharply continental climate of Yakutia is characterized by the extreme low air temperatures and the significant diurnal temperature variations. Thus, for Yakutsk, the minimum air temperature was recorded at −64.4 °C [3], that is, the climate temperatures may be lower than the brittle-to-ductile transition temperature of some structural steels, which increases the probability of tank brittle failure. The maximum air temperature in Yakutsk reached +38.4 °C. Accordingly, an annual temperature range was 102.8 °C. The maximum diurnal temperature variations during the year vary from about 21 to 30 °C.

The tank accidents usually occur not for one reason, but under the action of a complex of unfavorable factors, and the contribution of each of them to the creation of an emergency is ambiguous. The analysis of tank failures that occurred in specific conditions allows us to understand the main causes of the appearance and development of accidents for these conditions, to identify critical areas in the structures and, if possible, to outline ways to improve the safety of operation. The following describes the accidents with brittle failures of tanks in Yakutia.

Accident 1. At the Ust'-Kuyga oil depot, the tank with a capacity of 700 m³ completely collapsed on February 2, 1979 at an air temperature of −57 °C [4]. The tank was built in 1977. The spill amounted to 624 tons of summer diesel fuel. A brittle crack propagated in the base metal vertically to the entire height of the shell. According to the direction of the chevron-shaped pattern on the fracture surface, experts have established that the crack originated in the weld of the shell-to-bottom connection. Corrosion pits were found on the wall. Consistent with the results of chemical composition analysis and mechanical tests of the samples cut from the shell, the steel was determined as low-carbon steel St3kp, equivalent to S235JRG1 (1.0036 European structural steel) [5]. The main reason for the tank accident was the use of carbon steel, which is susceptible to brittle fracture.

Accident 2. On January 8, 1986, the tank of Nizhneyansk oil depot was catastrophic failure at the when the air temperature dropped from −38 to −51 °C [3]. The tank with a capacity of 3000 m³ was
been in operation since 1969. It was installed on a reinforced concrete monolithic slab on a gravel-sand cushion. During the accident, 2,000 tons of summer diesel fuel spilled, the neighboring gasoline tanks and piping were damaged. As a result of accident inquiry, it was established that the destruction began in the wall area where the piping were attached. A crack spread over the entire height of the wall; its surface did not have a focal defect. The wall tore from the tank bottom in the base metal of a first course; the crack fracture surface had a coarse-grained structure. The chemical composition of the metal of the first shell course corresponds to steel VSt3sp or S235J0 (1.0114 European structural steel). The diameter of reinforcing plates for attaching the nozzles was only 315 mm with the shell opening diameter of 255 mm. The soviet standards recommended the diameter of 440 mm (570 mm according to modern Russian standards). The tank destruction occurred due to an increase in local stresses and a low ability of the low-carbon steel to resist brittle fracture.

Accident 3. On December 18, 1989, a tank accident occurred at the Amga oil depot at an air temperature of –52 °C [1]. With a tank capacity of 700 m³, the spill amounted to about 600 tons of diesel fuel. The tank was been in operation since 1977. Two cracks appeared in the weld of the nozzle reinforcing plate, which spread to the base metal of the wall. This plate had the shape of an octagon, while the tank design standards [6] recommend rounded edges of reinforcing plates. From the lower corner of this reinforcing plate, one crack spread in an arc to the right by 250 mm, and the other crack do towards the shell-to-bottom connection for a length of 200 mm. The maximum crack width was three millimeters. On the spectral analysis data, it was found that the tank wall was made of VSt3sp steel (S235J2G3, 1.0116). The tank had a large tilt towards the piping and a significant differential settlement along the bottom contour. As a result of the tank settlement, the piping rested on the ground at a distance of 1.8 m from the shell, which changed the stress-strain state of the wall place where the nozzle was attached. Additional stresses due to the impact of the piping, the decrease in air temperature, the use of steel with low resistance to brittle fracture were recognized as the causes of initiation and propagation of cracks.

Accident 4. On December 26, 2007, a 700 m³ tank of the Amga oil depot fully broken down [7]. Its service life had been counted since 1970. About 422 tons of crude oil was spilled. According to the data from the Amga meteorological station, the air temperature was about –34 °C. In the base metal of the bottom shell course, a primary oblique crack initiated, propagated and branched. Then one of the secondary cracks spread vertically to the upper shell course, where it divided into two branches. One branch propagated in the base metal to the right and stopped; the left crack reached the vertical weld and spread in it, which led to a complete rupture of the shell. The results of accident investigation showed that the initiation place of the primary oblique crack was located at a height of 600 mm from the bottom-to-shell joint. The crack was caused by a metallurgical defect in the form of a metal discontinuity, which developed into a fatigue crack over 37 years of operation. The chemical composition of the shell material was corresponded to the carbon steel St3ps (S235J0, 1.0114). The vertical crack fragilely propagated through three lower courses of the wall, turning into a ductile one on the upper three courses. According to the examination report, the tank destruction occurred due to the natural aging of the structural steel at the long operation in unfavorable climate and the low carbon steel use, which does not correspond to the climatic conditions of operation.

3. Discussions
The analysis of tank accidents in Yakutia shows that the places of crack initiation are the assembly welds and their heat-affected zones (HAZ), the metallurgical and corrosion defects of the base metal. The welded joints of the shell-to-bottom connection and the attachment of piping nozzles to the wall are the weak areas of the tank. The assembly welds are made by manual welding at a construction site, which does not guarantee their high quality. All the cracks occurred in the most loaded lower shell course. The moment stress-strain state of an edge effect arises from the design loads, the differential settlements and the ambient temperature changes near the shell-to-bottom connections. The edge effect stresses are added to the stresses of the membrane stress-strain state from various loads in the first shell course. In this place, the piping nozzles are attached to the wall. The nozzles transfer the
local loads to the shell from draining and filling operations, changes in length of the pipes due to its thermal expansion related to the ambient temperature changes, as well as from the differential settlements of the tank and piping [8]. The attached piping can also restrict the free deformation of the shell. It is known that even small concentrated loads induce the significant local bending stresses in the thin-walled cylindrical shell [9]. A dangerous combination of these stresses with the operating stresses from the design loads can lead to the occurrence of the shell limit state. Besides the openings for shell nozzles are strengthened with reinforcing plates. It changes the shell stiffness and the SSS at this location. In addition to the constructive concentration of stresses, there is the concentration of stresses in places where the weld has abrupt changes in thickness or appearance (surface irregularities, lacks of fusion, overlaps, etc.) and near the weld defects (cracks, undercuts, slag inclusions, porosity, etc.) [10]. Heterogeneity of the metal mechanical properties and the residual welding stresses in the nozzle welds and in their heat-affected zone are also noted. Thus, the complex non-stationary stress-strain state is arises in the wall near the shell nozzles.

All the destroyed tanks were made of low-carbon steel which is not recommended for the welded structures in this climatic region [11]. The tank accidents occurred at very low temperatures. In addition, the damaged tanks were filled with diesel fuel or crude oil; their viscosity increases much more than the viscosity of gasoline at low temperatures. When the air temperature decreases, the diesel fuel and crude oil gel near the tank wall, the formed layer acts as a heat insulator for the bulk of the stored liquid. The temperature of the wall follows the air temperature faster than the temperature of the fuel bulk. Temperature difference between the shell and the bottom of the tank is provided by large thermal inertia of a stored liquid and its thermal conductivity. This temperature difference leads to the thermal stresses in the statically indeterminate tank structures. These stresses contribute to the creation of the complex stress-strain state of tanks.

In the description of one accident the tank tilt was indicated as one of the failure reasons. Thawing permafrost soils of tank basement can lead to its significant tilt and differential settlement, which cause additional stresses in the shell and bottom.

4. Conclusion

Thus, it is possible to establish the following features of accidents of the tank for petroleum and petroleum products, typical for operating conditions in Yakutia.

1. The main factor contributing to the tank brittle destruction is the low ambient temperature, which reduces the ductility and resistance to brittle fracture of the metal of the shell and welds.

2. The differential settlements of the tank bases on permafrost soils lead to the formation of a dangerous stress-strain state, the general and local deformations of the shell.

3. A sharp decrease in the air temperature causes the thermal stresses in the statically indeterminate structures of the tank.

4. Long-term operation of tanks in the extreme climatic conditions leads to the degradation of the base metal and welds, reducing their mechanical properties, corrosion and a decrease in the initial design thickness of elements due to corrosive wear, accumulation and development of various defects and damages. The decrease in the values of the brittle-to-ductile transition temperatures of the tank metal is especially dangerous.

5. The initiation of cracks occurs mainly in the welds and their heat-affected zones. Dangerous places of the tank are shell-to-bottom connections and attachments of piping nozzles to the shell, where the stress concentration is combined with significant stresses from the design loads, the differential sediments of the base and the temperature influences of the environment. In addition, the piping nozzles transfer the local loads to the tank wall. An unfavorable combination of additional stresses with operating stresses from design loads at low ambient temperatures can lead to the occurrence of limit states of the metal in places of the stress concentration.

6. The cracks are occurred due to defects and damages to welds and base metal, which act as stress concentrators.
7. The use of low-carbon steel in the Soviet-built tanks, which is not recommended at low climatic temperatures, was the cause of most of the accidents of vertical steel tanks in Yakutia. Low alloy structural steel 09G2S (13Mn6) has shown sufficient reliability in these conditions.

The considered accidents of tanks allowed us to make the following conclusion. The operational safety of tanks in the cryolithozone is reduced by the extreme low air temperatures, the significant temperature variations, the large uniform and differential settlements of the tank, the long-term operation associated with the degradation of structures and materials in such climatic conditions.

Many steel cylindrical tanks for storage of petroleum and petroleum products operating in Yakutia are at the stage of aging and degradation of metal properties, including the weld metal. In this regard, their further operation is associated with a significant risk. In Yakutia, the tanks made of low-carbon steel should be taken out of service urgently, as well as tanks that are in the poor technical condition. This requires a technical inspection of the tanks, especially those that are operated beyond a standard service life.

5. References

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