

Cryogenic Tanks Recertification: Case Study for Operational-Life Extension

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Summary

Liquefied natural gas (LNG) and liquefied petroleum gas are usually stored in especially-low-temperature tanks, with different design configurations developed in the industry that use steels with specified low-temperature properties. This paper provides an overview of these properties and the behavior of 9%-nickel-alloyed high-strength steels for low-temperature applications. These steels have been recognized by the American Society of Mechanical Engineers code for cryogenic use since 1954 and have been widely used for LNG storage in competition with stainless steel, other austenitic alloys, and aluminum. In fact, austenitic stainless steels are used in cryogenic applications and can be used for building smaller storage tanks, but large containment vessels are usually welded from 9%-nickel steel because of expense considerations. This technology is well-established worldwide, and the first part of this paper is focused on 9%-nickel steel, its properties, and its use in LNG storage tanks. The different LNG-tank-design generations and their particularities will be described. A general overview of LNG-tank failures recorded in the industry will also be presented.

Inspection, repair, and alteration of atmospheric tanks that are designed according to *API Standard 650* (2007) are well-covered under *API Standard 653* (2014), unlike the cryogenic tanks generally designed according to *API Standard 620* (2013) or *BS 7777-4:1993* (1993); no standard exists to cover the inspection and repair/alteration requirements (when applicable) to recertify these tanks.

This paper provides a benchmarking of different cryogenic tanks in terms of operation life and type of containment (single-containment vs. double-containment tanks) in the LNG industry. The different options adopted to recertify these tanks will be detailed.

ADGAS operates three double-walled tanks that are reaching their design life. A longevity study was undertaken to recertify the tanks on the basis of different studies and inspection/operation/maintenance history combined with the benchmarking developed for cryogenic tanks. ADGAS adopted a risk-assessment approach to recertify the LNG tanks operated since 1985. The approach and the main outcomes of this study will be presented.

Introduction

Iron/nickel alloys are more corrosion resistant than carbon steels, but their relative ductility at low temperatures is the more-important reason for their use in oilfield applications.

Iron/nickel alloys are used for aboveground cryogenic storage tanks for storage of liquefied natural gas (LNG) because these alloys have sufficient ductility at LNG temperatures (-162°C). The addition of nickel to iron results in alloys in which the transition of high-temperature austenite to alpha ferrite is retarded. Alloys having 5 to 10% nickel will have a mixture of high iron alpha ferrite, which is subject to embrittlement at the low temperatures found in LNG-storage tanks and similar applications. The dual-

phased structure still has ferrite, but the resulting alloy is ductile enough for static structures such as storage tanks.

LNG-storage-tank iron/nickel alloys (9%-nickel alloys are most commonly used), with piping and similar attachments made from austenitic stainless steel, have better resistance to thermal fatigue. Corrosion is not a problem at cryogenic temperature, so galvanic coupling between nickel steel and stainless steel is not a source of problems.

Austenitic stainless steels at LNG temperatures may be used for building smaller storage tanks, but large containment vessels are usually welded from 9%-nickel steel because of expense considerations. This practice is well-established worldwide (Mokhatab et al. 2014).

3.5%-nickel steel was introduced into cryogenic applications in 1944 for construction of an LNG tank; stainless-steel alloys were scarce because of shortages resulting from World War II. Shortly after going into service, on 20 October 1944, the tank failed. In 1946, investigations by the US Bureau of Mines concluded that the incident was a result of the low-temperature embrittlement of the inner shell of the cylindrical tank. The 3.5%-nickel steel was not used further for cryogenic applications (Mannan 2005).

Since 1985, ADGAS has been operating three 80 000-m³, aboveground, double-containment-type tanks, designed according to *API Standard 620* (2013), that consist of an inner tank and an outer tank. The inner tank is made of 9%-nickel steel. The outer tank has a post-tensioned concrete wall with a reinforced concrete roof. A secondary bottom is connected to the outer-tank wall to provide a flexible liquid seal. The entire construction is made of 9%-nickel steel.

Between 2012 and 2013, a longevity study of the storage and export areas was conducted to ensure their fitness for service up to 2019, as a base case, and 2045, as an extended case. Recertification of “conventional” static equipment, piping, jetty, electrical components, instrumentation, rotating elements, structure, and concrete foundations are not addressed in this paper—only LNG tanks are covered. These tanks have never been inspected internally. The most-important outcome from this study is to advise whether to keep them running beyond their design life or to conduct an intrusive inspection to verify their condition.

In this paper, the focus will be given first to the 9%-nickel steel, its properties, and its use in LNG-storage tanks. The different LNG-tank design generations and their particularities will be described. A general overview of LNG-tank failures, as recorded in the industry, is presented. Finally, the approach adopted by ADGAS to recertify the LNG tanks is explained. Basically, it is a matter of whether to conduct an intrusive inspection or to keep the tanks operating on the basis of industry practice. For this, well-documented cases will be presented, mainly from Ishikawajima-Harima Heavy Industries, Brunei LNG, Gaz de France, and Malaysia LNG.

Background

Development of 9%-Nickel Steels for Refrigerated, Liquefied Gas Tanks: Key Dates. When the research that resulted in 9%-nickel steel was presented, its cryogenic toughness was evaluated with Charpy Testing with liquid nitrogen, and it was related to the 20-J minimum that is required in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code

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1944	Rupture of LNG storage tank at Cleveland, Ohio. The cause of the rupture is believed to have been the use of 3.5%-nickel steel, which was unsuitable for the low temperatures involved.
1946	9%-nickel steel was developed by the International Nickel Company.
1947	ASTM conducted different tests on the double-normalized and tempered 9%-nickel steel.
1952	ASTM approved the use of double-normalized and tempered 9%-nickel steel.
1963	<i>ASME Special Code Case 1308-4</i> was issued, setting allowable design stresses for both quenched and tempered plates and double-normalized and tempered plates and permitting the use of 9%-nickel steel in as-welded condition.
1970	9%-nickel-steel toughness enhanced and Charpy values averaged in the 50- to 70-J range.
1977	Incident at Umm Said in Qatar, where the plant was destroyed by the failure of a liquid-propane tank in a brittle manner.
1977	In reaction to the Umm Said incident, the <i>BS 7777</i> standard was originated, pushing the industry toward secondary containment, full-height hydrostatic testing, and in the case of 9%-nickel steels, increasing fracture toughness.
1978	Charpy values started to increase sharply (greater than 70 J).
1983	Charpy values reached 175 J. This is a result of improved steel-making processes.
1993	<i>BS 7777-4:1993</i> incorporated all of the major requirements outlined in <i>EEMUA Publication 147</i> (1986).

Table 1—9%-nickel-steel development for refrigerated tanks: key dates.

(2013) for pressure-vessel steels for cryogenic applications. Different successful tests were conducted on small, simulated pressure vessels by impacting them when filled with liquid nitrogen. This led to the American Society for Testing and Materials (ASTM) specification, and led ASME to approve the use of the double-normalized and tempered 9%-nickel steel.

Nine large cylindrical and rectangular vessels were tested to destruction in liquid nitrogen to provide the evidence that 9%-nickel-steel vessels, fabricated by field-erection practices and put into service without stress relief, would have a great resistance to over-stress, and would retain toughness at liquid-nitrogen temperatures. On the basis of the results of this demonstration, *ASME Special Code 1308-4* was issued in May 1963, setting allowable design stresses for both quenched and tempered plates and double-normalized and tempered plates, and permitting the use of 9%-nickel steel in as-welded conditions.

The Gas Research Institute consortium was able to survey 643 commercial 9%-nickel-steel samples made between 1970 and 1983, showing that all samples considerably exceeded the minimum Charpy value of 34 J at -196°C , and that Charpy values that averaged in the range of 50 to 70 J in the early 1970s started to increase sharply in 1978 to reach an average much greater than 175 J by 1983.

The Engineering Equipment and Materials Users Association (EEMUA) formulated rules for refrigerated tanks with the assistance of major UK design/construction companies. These were published as *EEMUA Publication 147* (1986) and were widely adopted for application around the world. In the wake of the failure of the liquefied-petroleum-gas tank at the Qatar General Petroleum Corporation plant at Umm Said, Qatar, on 3 April 1977, which led to the complete destruction of the plant by fire and the loss of seven lives, requirements for refrigerated tanks have been developed by means of *EEMUA Publication 147* (1986), which has evolved into *BS 7777-4:1993* (1993). In these specifications, carbon steels are restricted to operation down to -35°C . Below this temperature, low-nickel, 9%-nickel, and austenitic steels are required for the inner tanks for liquid-propane (-50°C), -ethane (-105°C), and -methane/nitrogen (-196°C) operations, respectively.

Table 1 summarizes the key dates for the preceding developments.

Physical Metallurgy: Principles

- Alpha ferrite is an interstitial solid solution of carbon. It is stable over the temperature range of -273 to 912°C . Carbon solubility is extremely limited. The maximum solubility is 0.02 wt% at 727°C .
- Austenite is stable from 912 to $1,394^{\circ}\text{C}$. Carbon solubility is greater compared with ferrite. The maximum solubility is 2.1 wt% at $1,146^{\circ}\text{C}$.

- Delta ferrite is stable from $1,394$ to $1,539^{\circ}\text{C}$, the melting point of iron. The maximum solubility of carbon is 0.09 wt%.
- Cementite is an intermetallic compound with the formula Fe_3C . The atomic percent of carbon in Fe_3C is 25, and the weight percent is 6.67.

The effect of alloying elements on the Fe-C phase relationships is best understood by first considering the two types of phase diagrams obtained, when iron is alloyed with elements (some alloying elements tend to stabilize the ferrite phase in preference to austenite). Other alloying elements are austenizing elements. They enlarge the area of the austenite phase on the phase diagram, and austenite may be present at room temperature because the low-temperature reactions may be too slow to occur. The common austenite stabilizer elements are manganese and nickel.

When austenite is cooled rapidly, it transforms into an extremely fine nonlamellar mixture of ferrite and carbide known as bainite. Below the bainite-transformation range, the diffusion rate of carbon becomes so negligible that the austenite transforms without a change in composition to a new product called martensite. Martensite starts to form at a well-defined temperature called martensite start (M_s). The amount of martensite that forms is a function of the temperature to which the steel is cooled below M_s and not of the time of holding at that temperature. The transformation trails off again and is virtually complete at martensite-finish temperature.

The binary diagram depicts phases that form at extremely slow rates of cooling. In industrial practice, the cooling rates may not be very slow. More importantly, a cooling rate may be deliberately chosen to obtain a desired transformation product in steel. For understanding the effect of cooling rates, it is important to understand the relationship between the transformation and both temperature and time. This is why temperature/time/transformation diagrams (**Fig. 1**) are useful to depict the relationship between temperature and time.

In general, the steel is continuously cooled from the austenitizing temperature to room temperature at different cooling rates. Continuous-cooling transformation diagrams (**Fig. 2**) are developed to depict the transformation, temperature, and time relationship during continuous cooling.

9%-Nickel Steels: Cryogenic Applications and Industry Standards

The majority of import/export liquefied-natural-gas (LNG) -storage tanks are built with 9%-nickel steel as the primary containment barrier. It is a steel material with very high strength and toughness to limit thickness and ensure safe behavior at ultrachilled LNG temperatures (Nasr and Connor 2014). 9%-nickel steel was developed by

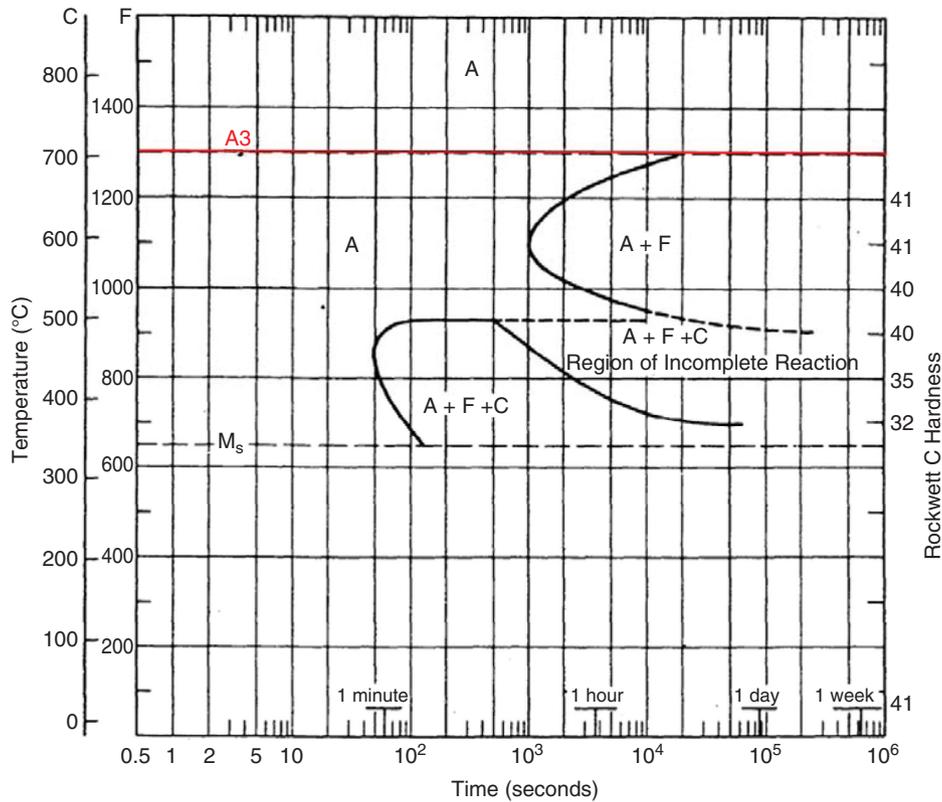


Fig. 1—9%-nickel-steel isothermal diagram (temperature/time/transformation) [modified from Pense and Stout (1975)].

the International Nickel Company (Inco) in 1946, and it has excellent low-temperature toughness at -196°C (Pense and Stout 1975).

The benefit of nickel as an alloying element in low-carbon steel to enhance low-temperature notch toughness has been recognized since the 1960s (Pense and Stout 1975). The use of low temperatures for processing and handling materials such as petroleum products and liquefied gases has increased in the cryogenic field. Inco developed the 9%-nickel steel, which provided tough, welded pressure vessels at -196°C without the need for post-weld heat treatment. Since then, investigations of cryogenic nickel steels have been intensified in connection with storage and transporting of LNG.

The effects of nickel as an alloying element in low-carbon steels are more readily understood by examination of the iron/nickel bi-

nary-equilibrium diagram. In fact, addition of nickel to iron lowers the transformation temperature of gamma- to alpha-iron progressively until it is eventually suppressed completely (Pense and Stout 1975) (Fig. 3). The A3 temperature in Fig. 3 widens to a range of temperatures as nickel is increased, so that at greater than 7% nickel, the alloys do not become completely ferritic at any temperature (Pense and Stout 1975).

A more-specific method of describing the behavior of the series of nickel steels is by way of the temperature/time/transformation diagrams (Pense and Stout 1975) or the continuous-cooling temperature diagrams. 9%-nickel steel has a tendency to retain some austenite at room temperature following the cooling in air from heat-treatment temperatures of even thick-plate sections.

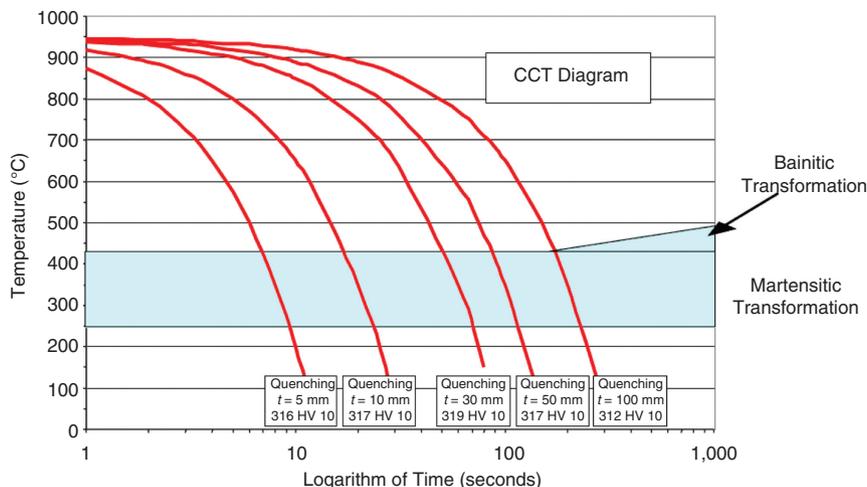


Fig. 2—9%-nickel-steel continuous-cooling transformation (CCT) diagram (Toussaint and Pillot 2007).

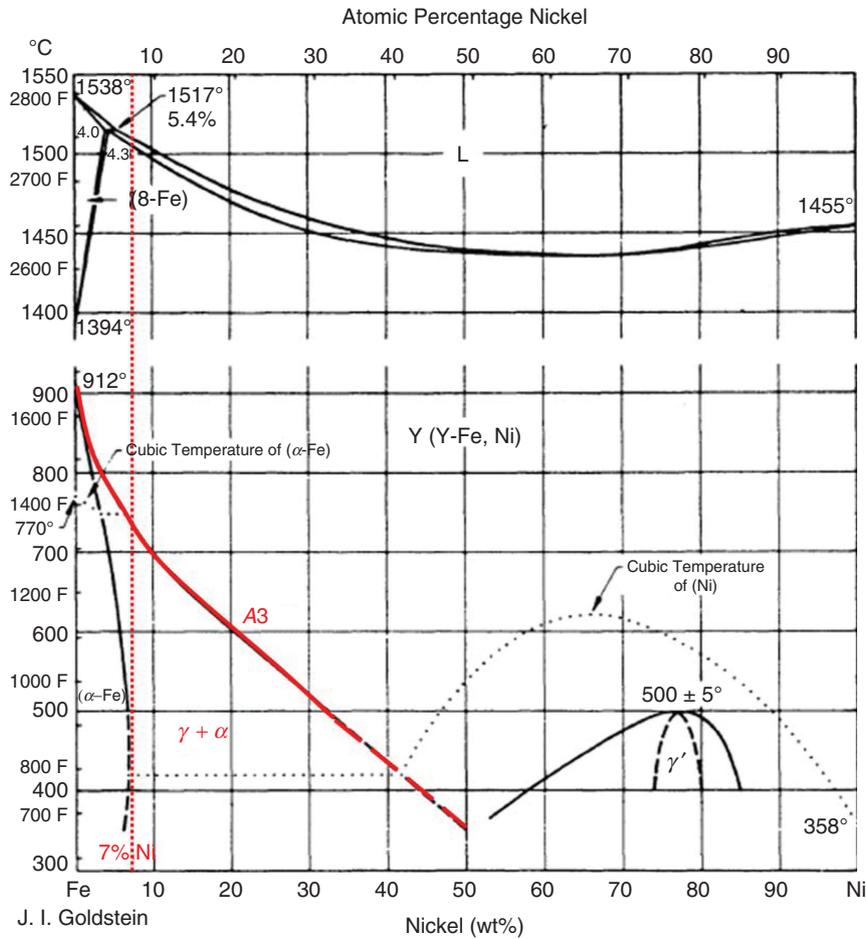


Fig. 3—Iron/nickel binary diagram [modified from Pense and Stout (1975)].

The 9%-nickel grades develop martensite over the full range of cooling rates, with at least traces of retained austenite and with bainite volumes increasing as the cooling rates are reduced. These microstructures are modified by further heat treatment for service applications (Toussaint and Pillot 2007). For cryogenic applications, the 9%-nickel steel is usually heat treated and either double normalized and tempered or quenched and tempered to meet the toughness requirements.

The double normalizing and tempering (*ASTM A353/A353M-09* 2014) for steel plates produces a fully homogeneous structure followed by a second treatment that results in a structure of low-carbon martensite and bainite. The first normalizing treatment at 900°C produces martensite and bainite. In the second cycle of the normalizing treatment at 750°C, fine-grained austenite forms and subsequent air cooling transforms the austenite to martensite and bainite. Tempering at 565 to 610°C causes reversion of metastable products to 10 to 15% austenite, which remains stable upon air or water cooling. This retained austenite contributes to high notch toughness down to liquid-nitrogen temperature (Bhadeshia and Honeycombe 2006).

The quenched and tempered steel, according to *ASTM A553/A553M-14* (2014), is obtained by heating the steel to a uniform temperature of 800 to 925°C, holding it at this temperature until uniform temperature is obtained throughout the plate thickness, and then quenching the steel in water. It is then reheated until the plate attains a uniform temperature of 565 to 605°C and is cooled in air or quenched in water. The microstructure of heat-treated steel consists of bainite, nickel-rich ferrite, and stable carbide-rich, retained austenite. The metallurgical, stable, retained austenite is very important in developing the superior cryogenic toughness of the steel

(Hashmi 2014). According to general practice, thinner plates (23.5 mm) were produced according to *ASTM A353/A353M-09* (2014), while thicker plates (30.5 mm) were produced according to *ASTM A553/A553M-14* (2014) (Hashmi 2014).

Mounce (1989) described the main results of a 5-year multinational study sponsored by the Gas Research Institute (GRI), showing in quantitative terms that 9%-nickel steel has very high resistance to the initiation and propagation of brittle fracture at LNG temperatures. The study provided reassurance that steels made by current modern steel-making practices meet the desired leak-before-failure criteria in LNG service and at even lower cryogenic temperatures. Mounce (1989) reviewed the practical significance of the GRI studies to the designers and owners of LNG facilities, and related them to the unblemished record that the steel has compiled since the early 1960s in ship and storage tanks. Currently, 9%-nickel steel has a track record of more than 50 years, and it has become one of the most-dominant materials for use in the inner tanks of aboveground LNG-storage tanks.

It is worth noting that the GRI consortium was able to survey 643 commercial 9%-nickel-steel samples made between 1970 and 1983, the period during which a majority of LNG storage and ship tanks were built (Stout et al. 1986). The only type of toughness data available for all of these samples was from the Charpy V-notched-bar impact test, a quality-acceptance test required in all specifications. The GRI survey showed clearly that

- All samples considerably exceeded the minimum Charpy value of 34 J at -196°C that is required for quenched and tempered plates manufactured to *ASTM A553/A553M-14* (2014) Type 1 and similar specifications.

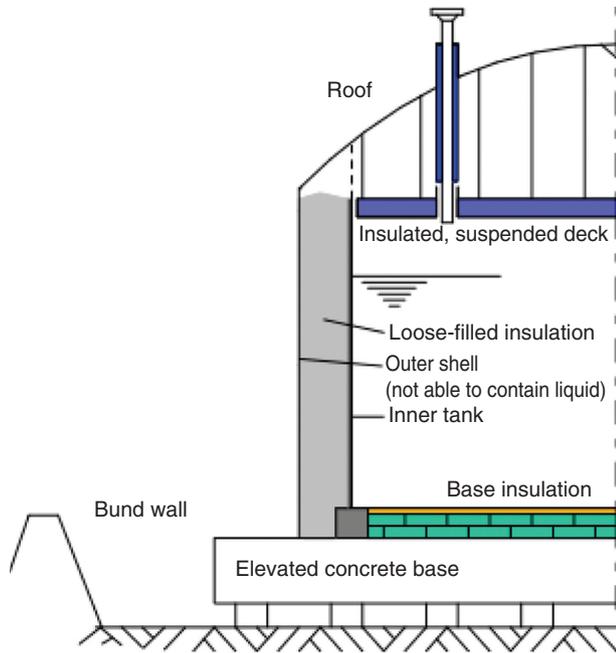


Fig. 4—Single-containment tank.

- Charpy values that averaged in the range of 50 to 70 J in the early 1970s started to increase sharply in 1978 to reach an average that was much greater than 175 J by 1983.

The study determined that this improvement in Charpy values was directly related to improved steel-making practices in which sulfur was reduced and other elements were more closely controlled (Stout et al. 1986).

In 1952, the American Society for Testing and Materials (ASTM) approved the use of double-normalized and tempered 9%-nickel steel on the basis of different tests conducted since 1947. Nine large cylindrical and rectangular vessels were tested to destruction in liquid nitrogen to provide the evidence that 9%-nickel vessels, fabricated by field-erection practices and put into service without stress relief, would have great resistance to overstress, and would retain toughness at liquid-nitrogen temperatures. On the basis of the results of this demonstration, *ASME Special Code Case 1308-4* was issued in May 1963, setting allowable design stresses for both quenched and tempered plates and double-normalized and tempered plates and permitting the use of 9%-nickel steel in as-welded condition (Mounce 1989).

The two most commonly used codes for the design of LNG tanks are *API Standard 620* (2013), Appendix Q, and *BS 7777-4:1993* (1993). *API Standard 620* (2013), Appendix Q was written for single-containment tanks and has served the industry well for many years.

BS 7777-4:1993 has its origins in *EEMUA Publication 147* (1986), which was in many ways a reaction to the incident in 1977 at Umm Said in Qatar, where the plant was destroyed by the failure of a liquid-propane tank in a brittle manner. The subsequent technical and legal processes served to throw little light on the real causes of this event. This was, however, a very influential event that, through *EEMUA Publication 147* (1986), pushed the industry toward secondary containment, full-height hydrostatic testing, and in the case of 9%-nickel steels, increased fracture toughness.

BS 7777-4:1993 incorporated all of the major requirements outlined in *EEMUA Publication 147*. Those most significant are the increased hydrostatic-testing level to the full product height (for all products), the increased minimum-thickness requirements for shell and bottom plates, and the increased allowable stress for the operating conditions.

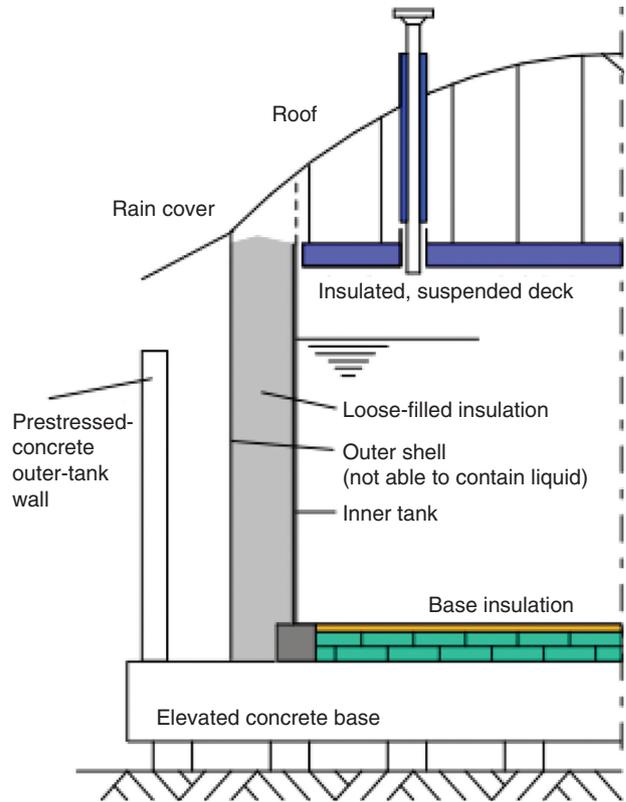


Fig. 5—Double-containment tank.

By contrast to the atmospheric storage tanks designed according to *API Standard 650* (2007), with a specific standard (*API Standard 653* 2014) addressing the recertification requirements to be considered, cryogenic tanks designed according to *API Standard 620* (2013) do not have any standard or practice covering their recertification.

Liquefied-Natural-Gas (LNG) Tanks: Types

According to *BS 7777-4:1993* (1993), LNG tanks are classified in three different types: single containment, double containment, and full containment.

Single Containment. A single-containment LNG tank is defined as a tank comprising an inner tank and an outer container designed and constructed so that only the inner tank is required to meet the low-temperature ductility requirements for the storage of the product. The outer container of a single-containment storage tank is primarily for the retention and the protection of the insulation and to constrain the vapor-purge gas pressure, but is not designed to contain the refrigerated liquid in the event of a leakage from the inner tank (i.e., it will collapse because of brittle fracture when coming into contact with the large quantity of cryogenic liquid leaking from the inner tank) (Fig. 4).

Therefore, a single-containment LNG tank needs to be surrounded by a bund wall or dike to prevent uncontrolled liquid spillage.

Double Containment. A double-containment LNG tank (Fig. 5) is designed and constructed so that both the inner self-supporting primary container and the secondary container are capable of independently containing the refrigerated liquid being stored. To minimize the pool surface of escaping liquid (and, thereby, the evaporation rate), the secondary container should be located at a distance not exceeding 6 m from the primary container.

The primary container contains the refrigerated liquid under normal operating conditions. The secondary container is intended to contain any leakage of the refrigerated liquid, but is not intended

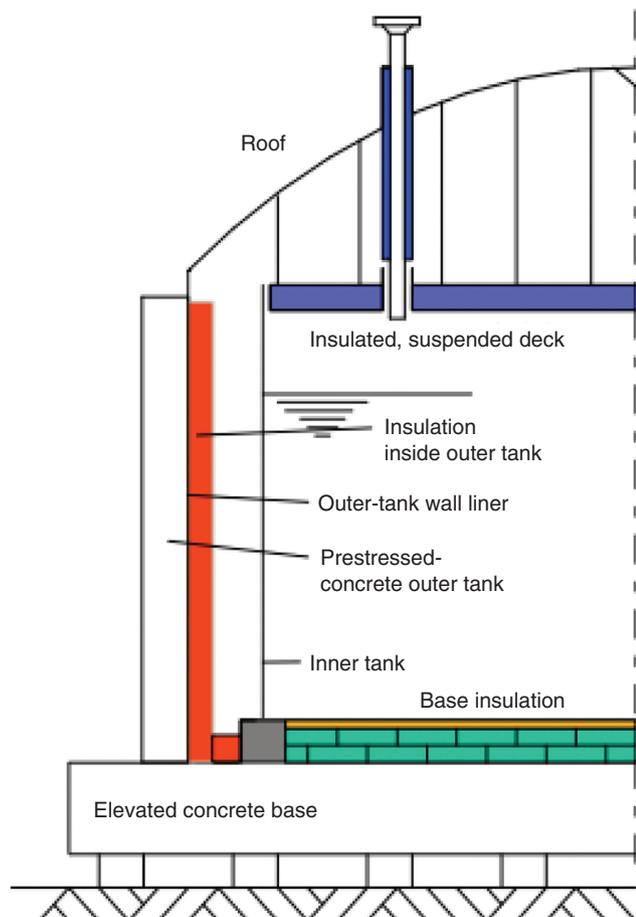


Fig. 6—Full-containment tank.

to contain any vapor resulting from this leakage. This configuration is sometimes referred to as a double-integrity tank.

Full Containment. A full-containment-tank design is defined as a double tank designed and constructed so that both the inner tank and the outer tank are capable of independently containing the refrigerated liquid being stored. The inner tank contains the refrigerated liquid under normal operating conditions. The outer tank is intended to be capable of containing the refrigerated liquid and of a controlled venting of the vapor resulting from a product leakage after a credible event. A full-containment tank is also known as a full-integrity LNG container (Fig. 6).

Among these three types of LNG tanks, the full-containment type is regarded as the most-advanced type. The tanks are also classified by the elevations from the ground level: aboveground type, inground type, and underground type.

Liquefied-Gas-Tank Incidents

One of the earliest process-industry disasters was the failure on 20 October 1944 of a liquefied-natural-gas (LNG) -storage tank in Cleveland, Ohio, USA. The cause of the rupture is believed to have been the use of 3.5%-nickel steel, which was unsuitable for the low temperatures involved. A vapor cloud of LNG formed and ignited in the plant, while LNG liquid flowed into storm sewers, where it mixed with air and caused a series of subsequent explosions. Some 128 people were killed (Kletz 2009; Melhem et al. 2005).

A rollover incident occurred on 21 August 1971 at the SNAM LNG terminal in La Spezia, Italy. A sudden increase in pressure occurred in the tank, causing a discharge from the tank safety valves and the tank vent. The release from the safety valves lasted for 75 minutes and that from the vent lasted 3 hours and 15 minutes.

A quite different case is the disaster at Staten Island, New York, USA, in 1973. Work was being performed inside an empty LNG-storage tank when flammable residues were ignited. Some 40 people died in the resultant fire (Kletz 2009).

In 1977, a major leak from a 20 000-m³ liquefied-propane tank in Qatar ignited and the resulting fire and explosion killed seven people and caused extensive damage to the rest of the plant (Mounce 1989). There had also been a leak before, but it had not ignited, and the tank had been repaired. The propane was stored at -42°C and atmospheric pressure. A member of the concerned company published several papers, which gave recommendations for the construction of tanks for refrigerated gas to be made from materials such as 9%-nickel steel, limiting the propagation of a crack if one should start (Kletz 2009).

In 1978, ADGAS experienced significant leakage trouble resulting from the failure of a bottom pipe connection on an LNG tank. The tank had a double wall (a 9%-nickel-steel inner wall and a carbon-steel outer wall). Vapor from the outer shell of the tank formed a large heavier-than-air cloud, which did not ignite. These tanks were modified with a top unloading system (Kletz 2009). This failure was attributed to the design. Later, these tanks were replaced by double-containment tanks.

ADGAS Liquefied-Natural-Gas (LNG) Tanks: Longevity Study

LNG Double-Containment Tanks: Description. Since 1985, ADGAS has been operating three 80 000-m³, aboveground, double-containment-type tanks, designed according to *API Standard 620* (2013), each of which consists of an inner tank and an outer tank. The inner tank is made of 9%-nickel steel. There is a suspended deck above the inner tank that is used to support a layer of perlite insulation. The outer tank has a post-tensioned concrete wall with a reinforced concrete roof. The concrete has a steel-lining plate that acts as a vapor barrier, keeping LNG vapors inside the tank and water vapor out. A secondary bottom is connected to the outer-tank wall to provide a flexible liquid seal. The entire construction is made of 9%-nickel steel (Fig. 7).

The insulation systems for these tanks are split into two sections called the primary and secondary. The primary comprises load-bearing foam glass beneath the inner tank, lightweight perlite concrete blocks that form an annular ring supporting the inner-tank wall, and an expanded perlite with a resilient glass-fiber blanket attached to the inner-tank wall at the 1100-mm annular space between the inner- and outer-tank walls. The blanket helps control compaction of the perlite during the expansion and contraction of the inner tank. The secondary insulation comprises sprayed polyurethane foam (PUF) applied 60-mm thick to the steel-liner plate of the outer-tank wall. The PUF is intended to reduce the rate of vapor production in the event of an LNG spill into the annular space. The insulation is completed with a 900-mm layer of loose, expanded perlite on the suspended deck.

To prevent freezing of the tank's foundation subsoil and possible movement problems, a foundation-heating system has been installed. This will control the foundation temperature between 3 and 10°C. A further check on the condition of the foundation is provided by settlement monitoring. The LNG tanks are provided with three nitrogen purging systems¹.

Between 2012 and 2013, a longevity study of the storage and expedition areas was conducted to ensure their fitness for service up to 2019, as a base case, and 2045, as an extended case. Recertification of "conventional" static equipment, piping, jetty, electrical components, instrumentation, rotating elements, structure, and concrete foundations are not addressed in this paper—only LNG tanks are covered. These tanks have never been inspected internally. The most-important outcome from this study is to advise whether to keep them running beyond their design life or to conduct an intrusive inspection to verify their condition.

¹ADGAS Operating Manual - Plant 27. 2007. Internal document.

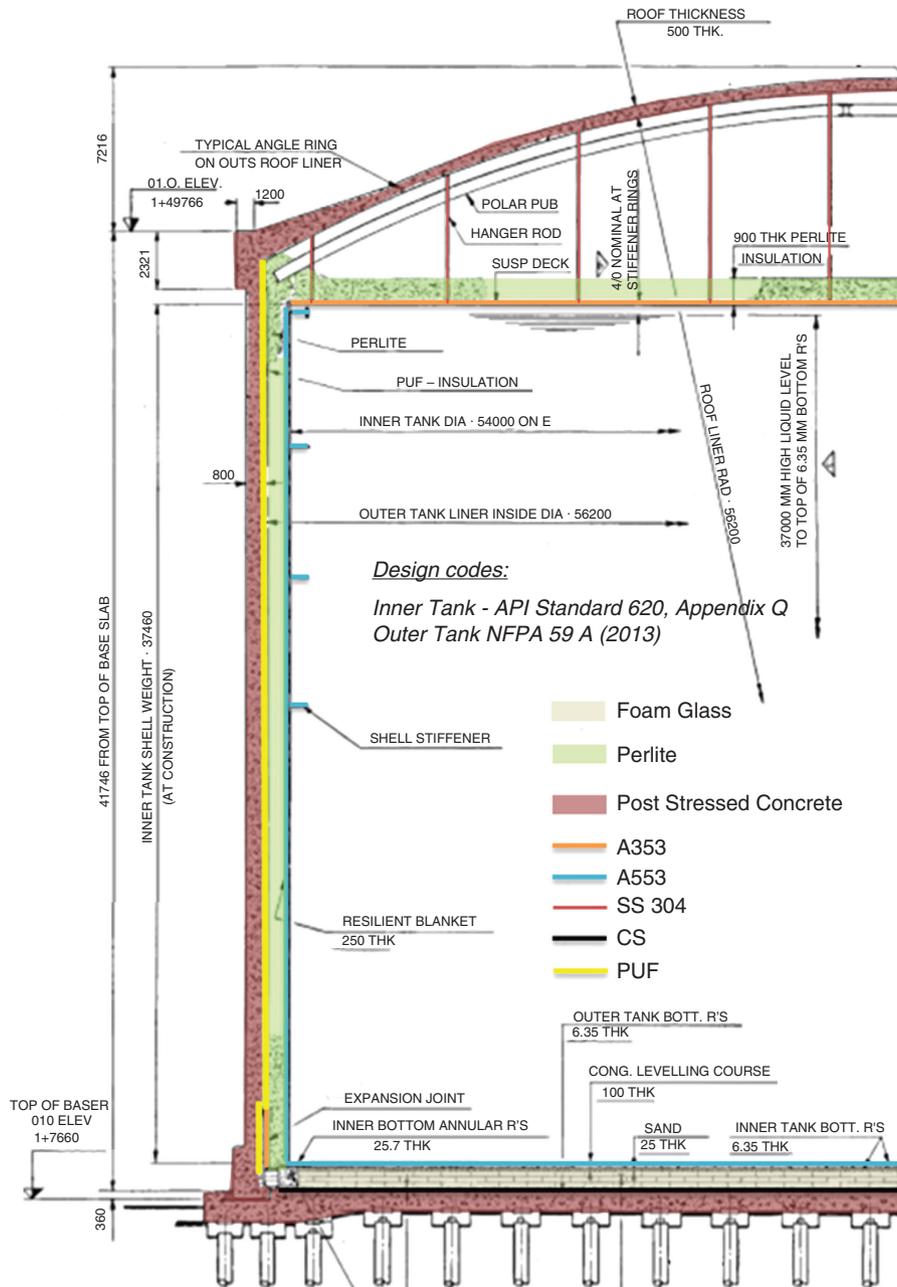


Fig. 7—ADGAS LNG tank: general configuration¹.

The following subsection describes the general longevity concept for the tanks.

Longevity-Study Approach for LNG Tanks. The approach undertaken to conduct the longevity study for the LNG tanks is based on the assessment of the actual conditions of the assets to evaluate the gaps between the “To Be” and “As Is” conditions (Fig. 8). To Be conditions can be defined as the ideal technical practice (international standards and best practices) to achieve trouble-free operation on both a short-term and a long-term basis for these tanks.

The integrity of the equipment is ensured when the maintenance and inspection activities suitable for current tank conditions are well-organized as a management system. The equipment condition varies according to the period of the equipment usage.

To evaluate the As Is condition, it is required to review the basic information, such as past inspection history, operating conditions, struc-

tures, and construction materials. In addition, it is required to review comprehensively the maintenance practice, policy, and methodologies, and the history of excursions from the operating window, if any.

Because the LNG tanks have never been inspected internally, a general overview of the service life of the LNG tanks in the industry is presented. The elements described in Fig. 9 were thoroughly checked:

1. Inspection strategy and condition monitoring for the tanks and associated piping
2. Foundation-settlement monitoring
3. Frozen-soil protection (electrical resistance)
4. Cathodic protection
5. Concrete condition (outer tank and foundation)
6. Insulation condition
7. Temperature monitoring (inner and outer tank, product temperature)

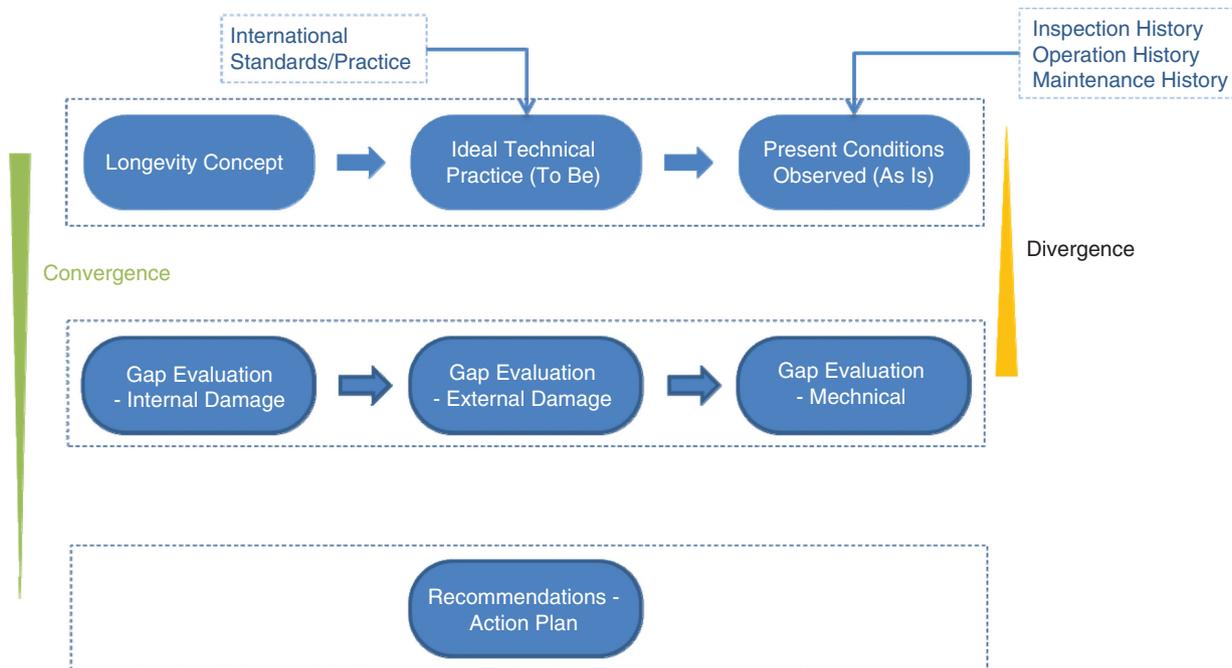


Fig. 8—Longevity-study concept overview.

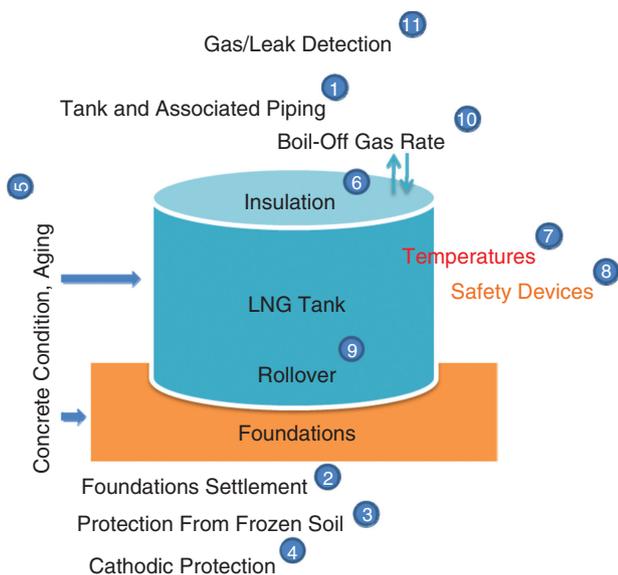


Fig. 9—ADGAS cryogenic tanks longevity study: scope of work.

8. Safety and protective devices inspection/maintenance strategy
9. Rollover² monitoring
10. Boil-off gas rate
11. Gas-leak-detection system

²“Rollover” is one of the major issues concerning the safety and mechanical stability of storage and transportation facilities for LNG. Addition of a new LNG mixture to an existing LNG without adequate mixing can result in the formation of separate strata with different densities caused by differences in temperature and composition within the storage tank. Heat leaks through the bottom and the wall of a storage tank because temperature changes in the stored LNG layers. Rollover refers to the rapid mixing of stratified LNG layers because of the equalization of their mass densities over time caused by heat and mass transfer between the layers. Rollover leads to the release of an abnormal amount of vapor into the storage tank, which endangers its mechanical stability and may result in a loss of valuable product through venting, with associated environmental pollution.

The following subsection describes the main outcomes of this study.

Current Condition and Gaps. The review concluded the following:

- No problem occurred in the tank safety operation during 30 years.
- No long-range variation of the tank internal condition was obtained by instrumentation system.
- Surface temperature shows stability.
- The insulation performance was found to be acceptable on the basis of the stability of the surface temperature, boil-off gas volume, and the frequency of the pressure safety valve/vacuum safety valve (PSV/VSV).
- Foundation settlement is monitored biannually, and no sign of deviation is noticed.
- No clear sign of deterioration was found on the outer surface of the concrete tank (i.e., chips, cracks, aging of concrete).
- Corrosion was found on the embedded steel band, which perhaps was provided for the seal for the pinned joint between the concrete wall and the bottom slab.
- The outer surface of the concrete dome roof has been repaired and repainted recently, and good condition has been maintained.
- Almost all pipe insulation is seriously damaged. The cladding plates are rusted and lost. Serious damage was found at the exposed PUF insulation. This was already captured by the inspection system, and corrective actions are identified and planned.
- No wet patch was found on the concrete wall and roof surface. The perlite refilling has not been performed for more than 30 years. It is highly possible that perlite settling occurred.
- The tank area is paved. Because no particular crack was found on the paving around the tanks, the tank foundation settlement is considered very small.
- The cathodic protection system operates adequately, and the potential coverage is checked twice per year.
- The liquid level in the tank is kept within the recommended limits by the designer, and no alarm was activated.
- No rollover issue has been recorded to date. Continuous recirculation is performed.
- No vibration/noise was noted during normal operation or loading.

- No steam/water hammers were experienced in the roof.
 - Vibration is monitored when the pump starts.
- The following opportunities for improvement were identified:
- Conduct a post-stressed concrete lifetime analysis.
 - Replace electrical cable, cable tray, and junction/connections.
 - Conduct a detailed check of the nitrogen purging system.
 - Perform a full PSV/VSV function check to ensure the integrity of safety.

LNG Tanks in the World. As part of this study, information of LNG tanks in the world was scrutinized to compare their service life and determine the practice undertaken for each operator in the industry.

DAS Island, UAE. Three LNG double-containment tanks were constructed in 1985, with continuous operation for 28 years. The original cryogenic tanks, with bottom-unloading configuration, were constructed because of the significant leakage trouble explained previously. The original tanks were replaced in 1985 with top-unloading-type cryogenic tanks, which ADGAS is now operating³.

Arun, Indonesia. Five single-containment tanks were constructed in 1978, each with a capacity of 125 000 m³. Three tanks out of five were operated continuously for 35 years. The other two tanks were decommissioned because of LNG-production decrease (Purba 2013; Chiyoda Corporation 2013).

Bontang, Indonesia. Six single-containment tanks were constructed in 1977, with total storage capacity of 630 000 m³. These tanks were operated continuously for 36 years (Chiyoda Corporation 2013).

Lummut, Brunei. Three LNG single-containment tanks were constructed in 1972, each with a capacity of 65 000 m³, and have been operated successfully for 20 years. Only normal external inspection and maintenance was carried out. No internal inspection was applied. A lifetime study was carried out to extend the asset lifetime, an outcome of which was a decision to upgrade the LNG tanks to full-containment type. The project was split into two phases: first was the construction of the two new tanks, including associated facilities, and second was the demolition of one existing tank and mothballing of two existing tanks. Brunei LNG (BLNG) took this opportunity to evaluate the tank integrity. The exercise covered the following:

- Visual inspection of the outer-tank steel, including roof, shell and floor plates, anchor bolts, piping, nozzles, steel structures, and accessories.
- Visual inspection of the suspended ceiling deck, including the deck plates and hangers.
- Visual inspection and nondestructive examinations of inner-tank steel, including shell and floor plates, shell stiffeners, and attachments.
- Thermal-conductivity check, density check, sieve analysis, and organic analysis of expanded, loose-perlite insulation material.
- Thermal-conductivity check of fiberglass blanket-insulation material.
- Visual inspection and compressive-strength test of perlite concrete block and foam-glass-insulation materials.
- Chemical analysis of 9%-nickel steel and welds.
- Mechanical tests of 9%-nickel steel and welds, including tension tests and Charpy impact tests.
- Brittle-fracture (crack initiation and arresting) -resistance tests of 9%-nickel steel and weld metal, including crack-tip-opening-displacement (CTOD) tests, wells notched welded wide-plate tests, Naval Research Laboratory drop-weight tests, and duplex Esso tests.

Uittenbroek et al. (1998) described the inspection and test results showing that the steel inner and outer tanks, including insulation materials, are in good condition. Other corroded details need improvements. BLNG is actually planning to reuse one of the mothballed tanks, with modifications.

Kenai, Alaska, USA. Two single-containment tanks have been operated since 1969, with 555,000-bbl storage capacity each (approximately 65 000 m³). These tanks were operated continuously for 44 years. ConocoPhillips planned to decommission the plant in 2014 (Chiyoda Corporation 2013; FERC 1978).

Compagnie Algérienne du Méthane Liquéfié (CAMEL), Arzew, Algeria. Three single-containment tanks, each with a storage capacity of 33 000 m³, were constructed in 1964. These tanks were operated until 2007 without internal inspection. In 1990, the outer tanks, made with carbon steel, were replaced because of severe external corrosion and excessive boil-off gas (Chiyoda Corporation 2013; Benazzouz and Abbou 1986).

Ishikawajima-Harima Heavy Industries (IHI), Osaka, Japan. Two single-containment tanks were constructed in 1972, with a storage capacity of 45 000 m³ each. The tanks were operated successfully without any trouble for 40 years. Because of a capacity issue, IHI started building a new, large full-containment tank with a storage capacity of 230 000 m³. Two old tanks were dismantled (one made with 9%-nickel steel and the other with aluminum), were subjected to a full characterization against aging, and their integrity was assessed thoroughly. Nishigami et al. (2013) described the investigation scope:

- Base-metal mechanical properties (chemical composition/macro- and microstructure/tensile strength/Charpy absorbed energy/retained austenite)
- Weld-metal mechanical properties (chemical composition/macro- and microstructure/tensile strength/Charpy absorbed energy)
- Fracture-toughness properties (CTOD test/duplex Esso test/wide-plate test)
- Corrosion of foundation piles (steel-pipe piles)
- Deterioration of concrete
- Deterioration of instrumentation devices
- Deterioration of thermal-insulation material

With this investigation, Nishigami et al. (2013) proved the high integrity of the LNG-storage tanks on the basis of the mechanical properties for both 9%-nickel steel and aluminum in terms of chemical composition, tensile strength, and Charpy absorbed energy, which satisfied a sufficient level. Also, thermal-insulation material, steel-pipe piles, and instrumentation devices have no significant deterioration.

Gaz de France (GDF), Nantes, France. A 500-m³ single-containment tank has been operated for more than 40 years in the Liquefied Natural Gas Testing Station in Nantes, France, by GDF since 1959. At the end of 2001, this LNG-testing station was dismantled. The operator (GDF) took this opportunity, jointly with different industrial partners (BP, Kogas, Osaka Gas, Tractebel Gas Engineering, Fluxys, and Total), to investigate the effect of aging on a LNG tank by use of both destructive and nondestructive techniques:

- Visual inspection of the outer-tank wall
- Visual and paint-dye-penetrant tests of 9%-nickel walls
- Radiographic examinations of 9%-nickel walls
- Destructive examinations of the 500-m³ tank: chemical composition, microhardness, tensile test, impact tests, and CTOD test
- Microstructure analysis of base metal and welds
- Examination of concrete base slab

The results were presented by Uznanski et al. (2004). No significant defects were revealed during this investigation; in particular, no defects resulting from the aging of the tank. Further metallographic examinations of some of the main defects revealed by the radiographic examinations confirmed that all of the examined defects originated during the tank-construction period and were not caused by the aging process of the tank during its service life. These defects did not increase in size, despite the numerous thermal and mechanical cycles they endured, confirming the performance of the 9%-nickel steel.

Malaysia LNG (MLNG) Sdn. Bhd. Experience With Double-Wall Tanks. MLNG has adopted a risk-assessment (RA) approach for the double-wall tanks since 2010 and has used the results of the RA as the basis for decision making. The scopes of RA included data, information, compilation, review inspection, failure history,

³From ADGAS Inspection Operation Files - Records (inspection history dating from 1984).

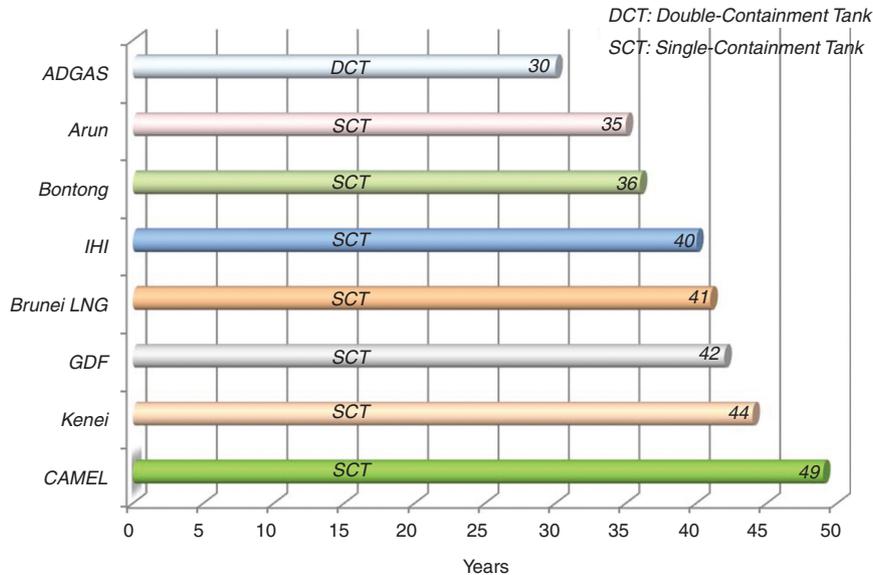


Fig. 10—LNG-tank service life: benchmarking.

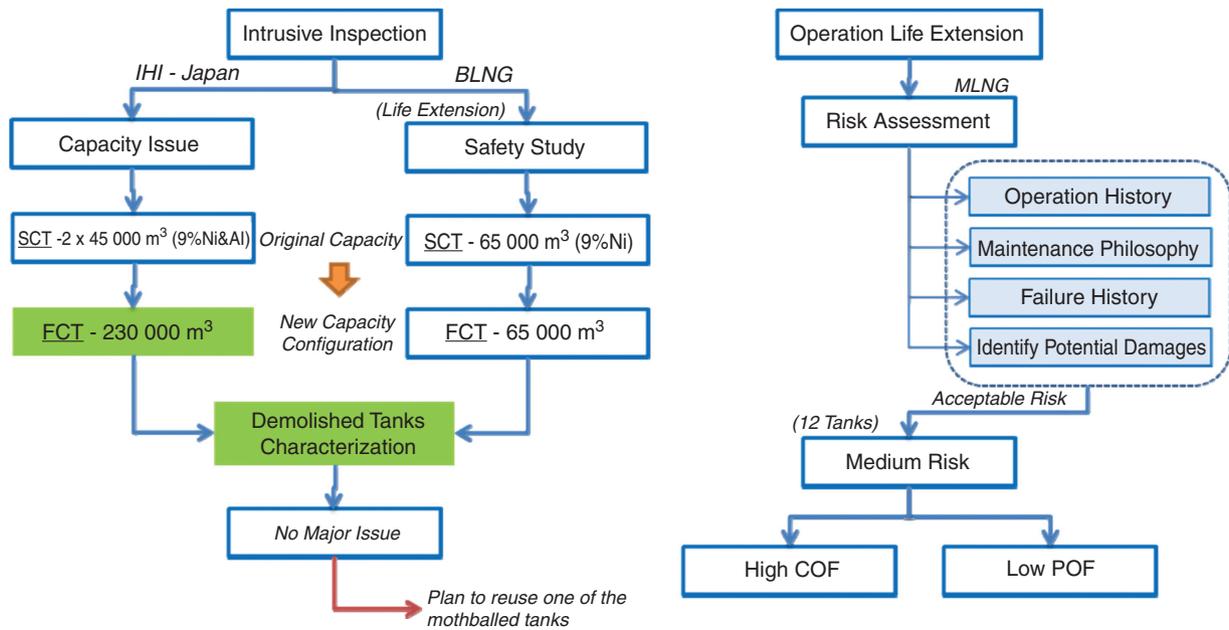


Fig. 11—Possible industry practices for LNG recertification.

operating, maintenance philosophy, and design data to identify expected damage mechanisms that may be present in these tanks. Damage mechanisms that had been identified and anticipated at all of these tanks include internal corrosion, stress-corrosion cracking, brittle fracture, overpressure/vacuum collapse, mechanical fatigue, vibration fatigue, and mechanical damage.

On the basis of the preceding analysis, all the double-wall tanks (12) fall into the medium-risk category. The medium-risk ratings for all 12 tanks are primarily driven by expected, relatively high consequence in the event of failure. However, the probability of failure (POF) for all tanks is found to be low. On the basis of these results, no intrusive inspection is envisaged⁴.

MLNG is willing to operate these tanks with an enhanced maintenance and inspection program. If any significant changes in operating parameters occur, the RA should be revisited.

Fig. 10 summarizes the different life services of the LNG tanks as described previously in the known cases in the LNG industry.

ADGAS LNG Tanks: Recertification. On the basis of the operation lifetime of the LNG tanks, two options may be identified (Fig. 11):

- Option 1: Tank-intrusive inspection with full characterization of the different components of the tank as per BLNG and IHI experience
- Option 2: Approach based on the RA, as per MLNG practice For ADGAS, the first option will imply
- One year of tank shutdown for the internal inspection. Including the long waiting period for heating up and degassing, 1 year is required to perform the tank internal inspection (Fig. 12).

⁴Email exchange between Malaysia LNG Sdn. Bhd. (Senior General Manager—Plant Division) and ADGAS (Vice President Integrity and Quality). ADGAS LNG/LPG Storex Facilities Longevity Study, September 2013.

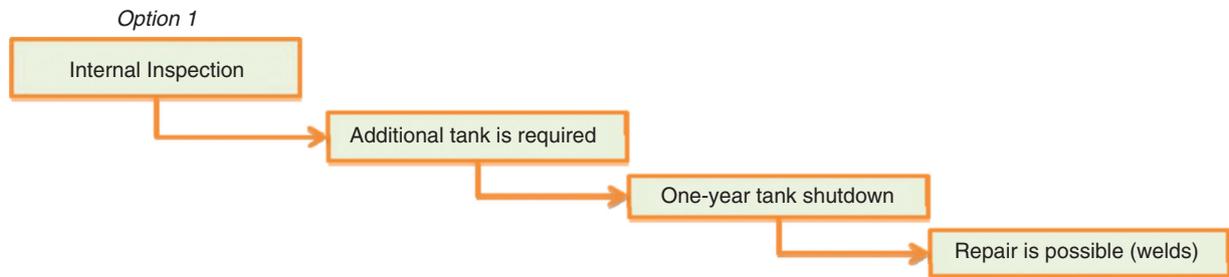


Fig. 12—Option 1: intrusive inspection and its requirements and estimated cost.

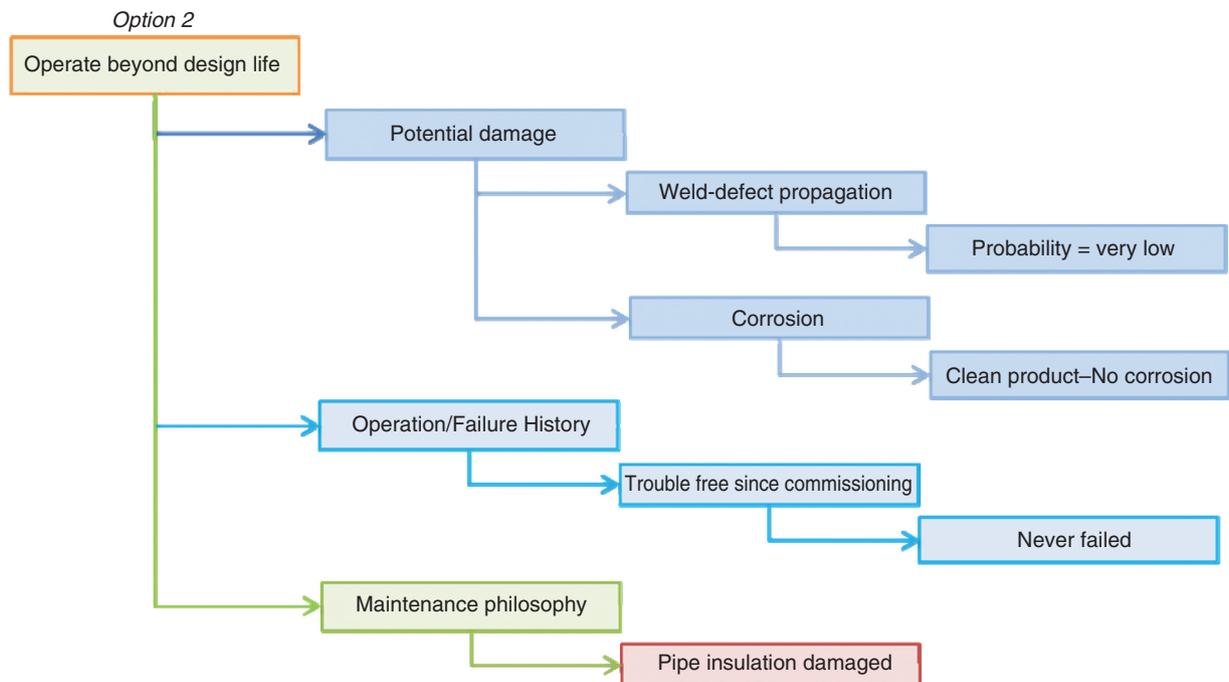


Fig. 13—Option 2: approach based on the RA.

- An additional tank to ensure the same LNG-production and -storage capacity. Because the LNG tanks are used fully to handle the required exporting of LNG, an additional LNG tank is required to ensure the same storage capacity when one tank will be shut down for the internal inspection.

For the second option [i.e., the RA approach (Fig. 13)], in case of a leak in the inner tank (9%-nickel steel), the double-containment tanks have a barrier for liquid gas only; vapor may be released to the atmosphere through the post-stressed concrete. The consequence should be high.

The probability of an event occurrence depends on the potential damage mechanism:

- Original welding defects (during construction finished in 1985). Because thorough internal inspection for the welding was performed during the construction, the possibility of the existence of welding defects should be very small. In addition, the 9%-nickel steel has shown a good crack arrestability with aged tanks, as discussed previously.
- The likelihood of corrosion with a clean product at very low temperature is low.

On the other hand, on the basis of the operation, maintenance, and inspection records, the tanks have operated trouble free since commissioning.

In Appendix F.5 of *EEMUA Publication 159* (2011), which addresses internal inspection of refrigerated-liquefied-gas tanks, the decommissioning and internal inspection of refrigerated-liquefied-gas tanks are potentially hazardous operations, especially for an open-topped inner tank, and there exists an associated risk of causing damage to the tank and insulation system. Corrosion is known not to occur in the dry, inert, low-temperature conditions inside the tank³.

If the product is known not to be dry, corrosion can occur. The foundation designs used for refrigerated-liquefied-gas tanks do not normally suffer unacceptable tank settlement. No technical justification for conducting routine internal inspections of refrigerated-liquefied-gas tanks can be provided so long as the tanks are operated within their design/operational limitations, which should be confirmed by the external inspection and the operating history. The environmental exposure to the outside of these tanks/systems does warrant a formal inspection protocol⁵.

Conclusions

Inspection, repair, and alteration of atmospheric tanks designed according to *API Standard 650* (2007) are well-covered under *API*

⁵Email exchange between CB&I (original tank designer) Europe, Africa, and Middle East and ADGAS (Senior Integrity Engineer). ADGAS Double-Walled Tanks, September 2013.

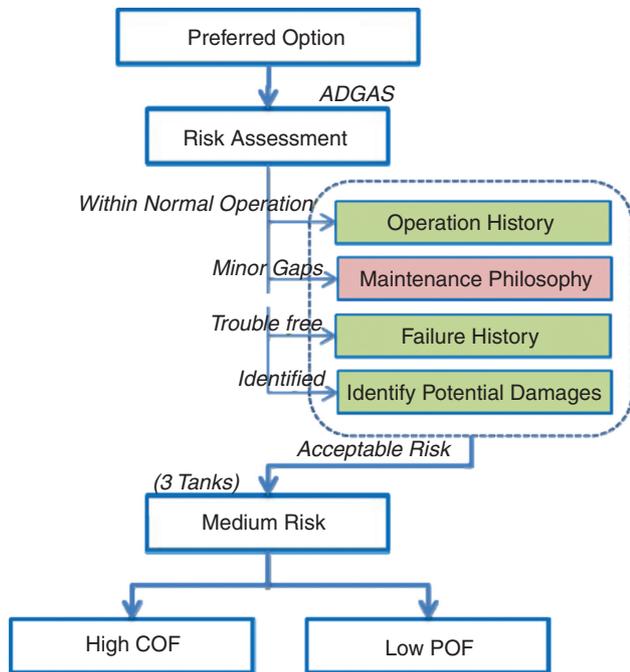


Fig. 14—ADGAS approach for LNG recertification.

Standard 653 (2014), unlike the cryogenic tanks generally designed according to *API Standard 620* (2013) or *BS 7777-4:1993* (1993); no standard exists to cover the inspection and repair/alteration requirements (when applicable) to recertify these tanks.

To extend the operational life of liquefied-natural-gas (LNG) storage tanks operated since 1985, ADGAS conducted a study covering the material-of-construction properties (9%-nickel steels) of material manufactured in the 1980s, focusing on its toughness and crack arrestability. Benchmarking was developed for different cryogenic tanks in terms of operation life and type of containment (single-containment vs. double-containment tanks) in the LNG industry.

Nickel steel, used commonly in the construction of refrigerated storage tanks, has a good performance in terms of mechanical properties at cryogenic temperatures, keeping enough toughness for crack arrestability. There have been no instances of leaks or rupture of inner-tank shells in the more than 40 years that such tanks have been used, which is a tribute to the quality of materials, fabricating practices, and the standards of design and inspection established by the international regulatory codes. Except when the adequate material was not selected or the design did not fulfill the loading/unloading requirements, such as with the old ADGAS tanks, this is well-reflected in the benchmarking undertaken within this study.

Several aging LNG tanks were dismantled by Brunei LNG, Ishikawajima-Harima Heavy Industries, and Gaz de France after 20, 40, and 42 years of continuous operation, respectively. Destructive and nondestructive techniques were used for the metal, concrete, and tank-components characterization. This exercise proved the high integrity of the LNG-storage tanks made with 9%-nickel steel or aluminum. A risk-assessment approach is adopted in the LNG industry as a basis for decision making. With this approach, all aspects relating to inspection, operation, and maintenance practices are scrutinized to ensure trouble-free operation of these tanks.

The risk-assessment approach adopted by ADGAS, with improvements in maintenance/inspection and operating systems and practices, will ensure LNG-tank operation to design life and beyond.

Recommendation and Path Forward

For all reasons explained in the preceding body of work, ADGAS opted for the risk-assessment approach. The following are the main

recommendations to use these tanks beyond their design life with some improvements (Fig. 14):

- To install a gas analyzer to improve the leak-detection system
- To refill the perlite to ensure better insulation and decrease the boil-off gas rate
- Concrete lifetime to be studied before 2019
- Associated piping insulation to be revamped

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