Development of large-scale precast, prestressed concrete liquefied natural gas storage tanks

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- Conventional technology for liquefied natural gas (LNG) tanks uses 9% nickel steel for the primary containment tank. This material is often in limited supply and is difficult to weld. Secondary containment tanks surrounding the primary tank are typically constructed using cast-in-place concrete.

- The composite concrete cryogenic tank incorporates integrated biaxially prestressed concrete tank walls and is one of the first cryogenic tanks designed to the provisions of the American Concrete Institute's *Code Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases*.

- This paper discusses the unique design and construction challenges encountered in the development of large-scale precast concrete cryogenic storage tanks, along with special considerations necessary when fabricating, handling, erecting, temporarily supporting, integrating, and posttensioning long and slender precast concrete wall elements.

- This concept takes advantage of the unique features of precast, prestressed concrete technology applied to a market currently held by cast-in-place concrete and welded steel.

World energy use is shifting from a primary focus on coal and oil to an increased emphasis on natural gas. With this shift, use of liquefied natural gas (LNG) has developed as a method to transport large quantities of gas via oceangoing LNG carrier vessels from producing countries to the major energy-using countries. The growth of this international business has resulted in an increased need for large (160,000 m^3 [5,700,000 ft^3] and larger) cryogenic-rated (-165°C [-265°F]) storage tanks at LNG export terminals in producing countries and at import terminals in the destination countries. **Figure 1** shows a typical LNG import terminal with two LNG storage tanks. A composite concrete cryogenic tank was designed to the provisions of the American Concrete Institute's ACI 376-10, *Code Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases and Commentary*.[1] This paper discusses the unique design and construction considerations encountered in the development of precast concrete cryogenic storage tanks of this scale. Also addressed is information regarding special considerations necessary when fabricating, handling, erecting, temporarily supporting, integrating, and posttensioning the long and slender precast concrete wall panels needed to produce a liquid- and gas-tight structure.

Figure 1. A typical liquefied natural gas (LNG) receiving terminal showing the marine berths for the LNG carriers and the LNG storage tanks and associated regasification equipment under construction. The secondary containment roof has not yet been constructed.

Background

Natural gas as a source of energy

Natural gas is cleaner burning than coal and is significantly more economical than oil on a relative energy basis. For example, in North America as of April 2012, 1 MMBtu (1,000,000 Btu) of energy from natural gas cost \$2.15 and from oil about \$20 (at \$105 per barrel). Even when including the costs of liquefaction, shipping, and regasification, the cost of gas delivered as LNG can be as low as \$6 per MMBtu, significantly less than the cost of energy from oil. Thus, for as long as these relative economic relationships exist, the demand for new large-scale LNG storage tanks is likely to persist. As with coal and oil, the source of natural gas is often in a different part of the world from the customers who need it.

Why the LNG industry has developed

With this continuing shift to natural gas as an energy source, the use of LNG has developed as a method to transport large quantities of gas from producing sources to the major energy-using destinations. These destinations are usually terminals where the LNG is subjected to a regasification process (warmed to the gaseous state) and transmitted at ambient temperature to the final user by natural gas pipelines. In some instances, LNG is moved from receiving terminals to user destinations in special insulated tanker trucks and converted to the gaseous state by the final user. The reason LNG is attractive for transportation is that 600 L (21 ft^3) of natural gas volume at ambient temperature and pressure can be reduced to 1 L (0.035 ft^3) of LNG at cryogenic temperature and ambient pressure. Careful handling of this material as LNG has also proved to be a safe and viable method of storage and transport.

Unique infrastructure associated with LNG

Over the past 10 years, significant investment has been made in plants and equipment to produce LNG from plentiful gas sources in the Middle East and Indonesia. Similarly, large investments in LNG production capability have been made in Russia and other countries, and new large-scale facilities are planned and are under construction for several locations in Australia. Each of these investments in production capability amounts to several billion dollars and is accompanied by similar large investments in special oceangoing LNG carriers and receiving terminals. Today the majority of new LNG carrier vessels under construction range from 120,000 to 140,000 m^3 (4,200,000 to 4,900,000 ft^3). The maximum capacity of LNG ships under order is up to 260,000 m^3 (9,200,000 ft^3). These carriers are designed with special thermally insulated containment systems to carry the -165°C (-265°F) LNG. The capacity of the LNG carrier vessels is significant in that it largely determines the capacity of the LNG storage tanks needed to support efficient ship loading and unloading.

Why large LNG storage tanks are needed

Because of the large volumes of LNG involved, storage tanks are needed in two places. The first is to store LNG at the production source before it is loaded into an LNG carrier for transport. This occurs typically over a 10- to 12-hour loading period. Tanks are also needed at the receiving terminal as the LNG is offloaded from the carrier into receiving storage tanks. The LNG is offloaded from the LNG carrier, usually over a 12- to 16-hour period. An LNG export facility may have two to twelve or more LNG storage tanks in the 160,000 m^3 (5,700,000 ft^3) size range, and a receiving terminal may have from two to six LNG storage tanks of this size, depending on the desired throughput capacity of the facility. The cost of an LNG tank of this size, using conventional construction, ranges from $100 million to reportedly over $300 million, depending on location and service conditions.

The owner's perspective: Why an alternative tank technology is needed

In recent years, cost increases of LNG facility–related construction have outpaced those of other types of industrial construction. In the face of rising costs to build LNG facilities, energy providers sought a lower-cost alternative to the 9% nickel steel LNG storage tanks that are the standard.

As the design was developed, it became clear that cost savings were not the only benefit to the composite concrete cryogenic storage tank alternative.

Reduced 9% nickel steel requirement

Today's conventional LNG tanks require large amounts of 9% nickel steel. Reducing the amount of this metal that is required for a tank decouples the tank from the sometimes volatile exotic metals market. This can allow for more predictable cost estimating, forecasting, and scheduling, which is essential in the development of plans to build LNG liquefaction facilities.

A reduction in the amount of 9% nickel steel used also translates to a reduction of the amount of 9% nickel steel welding required, thereby reducing the demand for specialized welders at the construction site.

Increased number of contractors who can build LNG storage tanks

Today, there are only a handful of contractors around the world that build conventional 9% nickel steel tanks. Adding a new tank technology based on precast concrete opens up the field to contractors experienced in large-scale precast concrete construction. The added competition will both provide a lower-cost storage tank alternative and also serve to pressure the conventional tank fabricators to control their costs, thus helping to keep tank prices competitive.

Faster construction schedule

For LNG liquefaction projects, the tanks are not usually on the critical path. The shorter construction schedule of the composite concrete cryogenic tank allows for completing the tanks more quickly, thus providing the opportunity to optimize project labor requirements. This can be important for projects that have limits on the maximum allowable on-site labor force. Such limits are often the result of environmental permit requirements for projects built in sensitive locations. For liquefaction facility expansions, LNG regasification terminals, and other projects where the tanks are on the critical path, the shorter construction time may also allow earlier start-up of the project. In most cases, because of the large investment involved, earlier start-up provides facility owners with important advantages associated with earlier revenue generation.

Ability to fabricate wall panels either on- or off-site

The ability to fabricate the precast concrete wall panels either on- or off-site allows greater flexibility to reduce the on-site workforce and increase the use of local unskilled labor. Because many large LNG facilities are built in remote locations, a construction worker camp is often required. The cost of on-site labor in such instances makes off-site prefabrication of wall panels economically attractive. In addition, improved quality is available through the use of off-site prefabrication of wall elements in an established manufacturing environment.

Ability to build larger tanks

The current upper limit on the feasible/economical size of conventional 9% nickel steel LNG storage tank results from difficulties in achieving the necessary high-quality welds of thick plates of 9% nickel steel. As LNG liquefaction plants are built larger and larger, the amount of LNG storage required increases as well. To keep up with the future new plant designs with capacities of 8 to 10 million tonnes per annum of LNG output, an alternative to the 9% nickel steel tanks will be needed.

LNG storage tanks: Basis of design

Governing codes

The governing standards and codes for design of LNG storage tanks used in the United States are the Code of Federal Regulations 49 CFR part 193 (2011), "Liquefied Natural Gas Facilities: Federal Safety Standards,"[2] National Fire Protection Association (NFPA) 59A (2001), *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*;[3] American Petroleum Institute (API) 620, *Design and Construction of Large, Welded, Low-Pressure Storage Tanks*;[4] and ACI 318-11, *Building Code Requirements for Structural Concrete and Commentary*.[5] The provisions of 49 CFR part 193 and NFPA 59A set the overall requirements for safety, LNG plant siting requirements, process equipment, vaporization facilities, piping, instrumentation, design, construction, operations, maintenance, and personnel qualifications. NFPA 59A (2001) section 4.2 refers to API 620 for welded container design. NFPA 59A (2001) Section 4.3 refers to ACI 318 for the design of concrete structures. Because ACI 318 primarily addresses design of general concrete building structures, in 2004, NFPA Committee 59A requested that ACI write a code that directly applies to the containment of refrigerated gas. In 2005, ACI created Committee 376, Concrete Structures for Refrigerated Liquefied Gas Containment, which published the provisional code[1] for public hearing in April 2010. The public comments have been addressed, and the code is currently available from ACI in electronic format and will be available in hard copy in late 2013. The recently printed NFPA 59A (2013) now refers to ACI 376 in lieu of ACI 318, and it is expected that ACI 376 will soon become the governing code for design of LNG concrete storage tanks in the United States. In the following paragraphs, unless otherwise noted, ACI 376 is referred to, not ACI 318.

Degree of LNG containment defined

Determination of the site layout for a facility with large-scale LNG storage is significantly dependent on the degree of containment chosen for the project storage. There are three degrees of containment systems: single containment, double containment, and full containment. Each has a different requirement for the tank setback from the boundaries of the facility related to the potential for accidental uncontrolled release of LNG vapor. The definitions of containment systems per NFPA 59A are shown schematically in **Fig. 2** and are described as follows.

Single containment A single-walled container or a double-walled tank in which only the self-standing primary or inner container is designed to contain LNG (Fig. 2).

Double containment A single-walled container surrounded by and within 6 m (20 ft) of a containment wall (secondary container) that is open to the atmosphere and designed to contain LNG in the event of a spill from the primary or inner container (Fig. 2).

Full containment A container in which the inner (primary) container is self-standing and is surrounded by a separate self-standing secondary container designed to contain LNG in the event of a spill from the inner container and in which the secondary containment is enclosed by a steel or concrete roof designed such that excess vapor caused by a spill of LNG from the primary container will discharge from the tank only through relief valves. Full containment allows for more-compact site arrangements than single or double containment. There has been a shift in the United States from the use of single containment toward full containment as an element of overall LNG facility risk management (Fig. 2).

Material strength at cryogenic temperatures

Concrete and posttensioning steel, as used in the typical building industry, can be considered suitable for cryogenic service because the posttensioning steel tensile strength and the concrete compressive strength are not reduced, but rather increased, at cryogenic temperatures.[6] Typically, the increased strength is not taken into account in design. Carbon steel reinforcing bar, on the other hand, behaves in a brittle manner at cryogenic temperatures. Because of this, the allowable tensile strength must be limited to 83 MPa (12 ksi) for no. 3 (10M) and no. 4 (13M) reinforcing bars; 69 MPa (10 ksi) for no. 5 (16M), no. 6 (19M), and no. 7 (22M) reinforcing bars; and 55 MPa (8 ksi) for no. 8 (25M) and larger reinforcing bars per ACI 376 and NFPA 59A. Structural metal liners and nonstructural metallic barriers incorporated into and functioning compositely with prestressed concrete are to be designed per API 620. Typically, 9% nickel steel (ASTM A553)[7] is used for structural metal liners, and carbon steel (ASTM A516)[8] is used for nonstructural metal liners.

Thermal motion effects: Ambient to cryogenic temperatures

An important consideration when designing composite structures subjected to wide temperature ranges (from ambient temperatures to cryogenic temperatures) is the difference in coefficient of thermal expansion between steel and concrete. Carbon steel and 9% nickel steel have similar coefficients of thermal expansion, which average 9.9 × 10^{-6}/°C (5.5 × 10^{-6}/°F) over the range from ambient to cryogenic temperature. The coefficient of thermal expansion for concrete, however, depends on a number of variables, the most important of which is the aggregate type. In

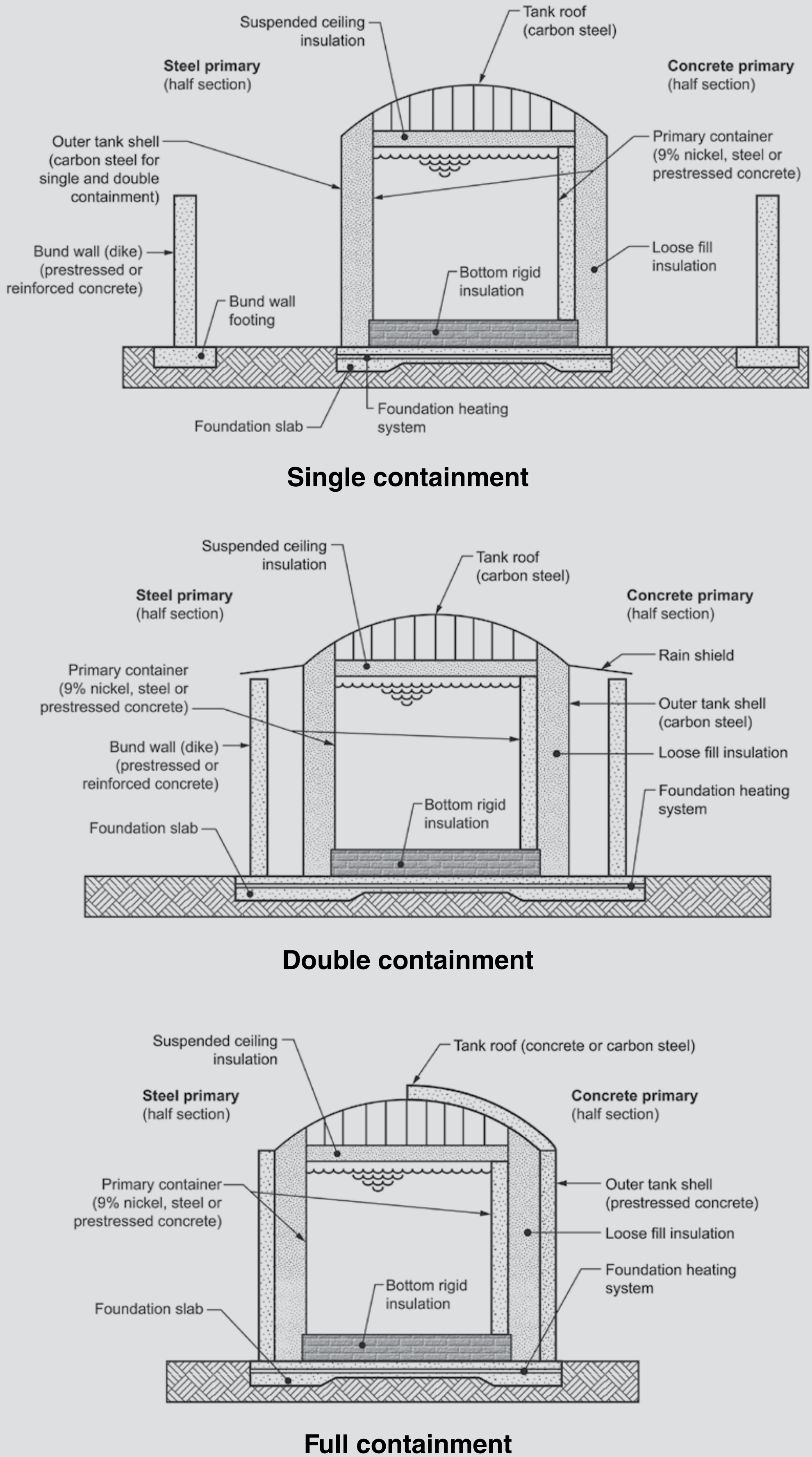

Figure 2. Tank systems for either steel or concrete structures.

addition, the water-cementitious materials ratio, presence of compressive stresses, and degree of water saturation of the concrete will influence the coefficient of thermal expansion as discussed by Neven Krstulovic-Opara.[6] For purposes of design, concrete coefficients of thermal expansion ranging from 7.9×10^{-6} to 9.4×10^{-6}/°C (4.4×10^{-6} to 5.3×10^{-6}/°F) were considered. When designing containment structures, the stresses and strains resulting from differences in coefficients of thermal expansion between steel and concrete must be taken into account. ACI 376 requires the coefficient of thermal expansion of the concrete to be confirmed by testing using the actual mixture proportions over the range of operational temperatures. For example, as the tank wall is cooled from ambient to cryogenic temperature, a drop of 188°C (338°F), it contracts, causing the composite concrete wall of a 160,000 m^3 (5,700,000 ft^3) capacity tank to move approximately 64 mm (2.5 in.) inward. As it cools, the 9% nickel steel tank bottom, which is attached to the tank wall at its base, also contracts. The more similar the coefficients of thermal expansion are for the tank wall and bottom materials, the less tension developed in the tank bottom plating. The effects of the differences in average coefficient of expansion for the two materials over this temperature range must be considered in design.

Conventional LNG storage tank technology defined

The development of conventional LNG storage tank technology

LNG storage tank design (**Fig. 2**) has evolved partly as the result of safety-related incidents. Initially, single containment tanks were the norm. Following an incident involving major failure of a welded steel primary containment, the design of secondary containment bund walls was revised to consider the high dynamic fluid pressures resulting from a major primary tank rupture. As steel materials and welding technology for cryogenic structures have improved, designing the secondary containment wall for the high dynamic fluid pressure associated with a major primary containment rupture is no longer required. Should the primary containment of a single or double containment tank leak, the resulting potentially flammable LNG vapor cloud could extend horizontally and vertically beyond the open top bund wall. Concern about this possibility has led to the incorporation of a vapor-tight roof on the secondary containment, resulting in a full containment tank system.

The conventional tank most often used today is a full containment tank. This type of tank is composed of a primary LNG containment enclosed within a secondary LNG containment. Typical dimensions for a 160,000 m^3 (5,700,000 ft^3) storage tank are 79 m (259 ft) diameter by 34 m (112 ft) high for the primary containment wall and 82 m (269 ft) diameter by 38 m (125 ft) high for the secondary containment wall. The height to the top of the domed roof of the secondary containment is typically 48 m (160 ft). The primary containment is designed to contain the LNG under normal operation. The secondary containment is designed to contain an LNG spill from the primary containment and resist the associated increased vapor pressure that develops in the event of an accidental leak or spill from the primary containment. The composite concrete cryogenic tank design qualifies as a full containment tank.

The primary containment in conventional tank technology is composed of an open-top steel containment tank constructed from welded 9% nickel steel (ASTM A553[7]) plate. The secondary tank is typically constructed of cast-in-place concrete with internal circumferential posttensioning. The secondary tank typically has cast-in-place concrete base slab, walls, and roof. The secondary tank usually has a steel plate liner attached to the interior surface of the secondary containment wall and roof with a bottom liner supported on the tank bottom concrete slab. The roof liner is also used as formwork for the cast-in-place concrete dome. The wall liner is welded to the floor plate of the secondary containment, providing a gas- and liquid-tight enclosure. The overall secondary containment is typically designed for a small vacuum pressure of about -15 mbarg (-0.22 psig) and larger outward pressure of about 290 mbarg (4.29 psig). The typical storage capacity of conventional LNG storage tanks is 160,000 m^3 (5,700,000 ft^3), but tanks up to 190,000 m^3 (6,709,787 ft^3) have been constructed. The size of conventional LNG storage tanks is limited by the economical aspect ratio for the primary containment and by the strength of the undertank structural insulation, which must support the weight of the full height of stored LNG.

Because of the low temperature of the LNG, it is necessary to thermally insulate the bottom, walls, and top of the primary containment to limit inflow of heat and the associated boiloff of the stored LNG. There is typically a 1 m (3 ft) annulus between the exterior of the primary containment wall and the interior of the secondary containment wall. This space is typically filled with expanded loose perlite insulation. There is a suspended deck over the open top of the primary containment upon which 1 m (3 ft) or more of fiberglass insulation is provided. Below the primary containment, there is typically about 0.7 m (2.3 ft) of structural insulation, which is composed of stacked structural insulating blocks with felt material between block courses to prevent convection currents from forming in the small spaces between the blocks.

Constraints associated with conventional technology

Conventional technology LNG storage tanks require large quantities of high-quality 9% nickel steel, available from only one mill in the world. Limited availability and delivery schedule for this material may adversely affect both schedule and cost of these tanks. The criticality of high-quality welding of the 9% nickel steel primary containment necessitates the secondary tank being constructed first to allow the welding of the primary tank plating in a protected environment free of wind and rain. This sequence constrains the construction schedule for the primary containment. The conventional technology secondary tank wall is constructed by placing a succession of lifts of cast-in-place concrete, much of it high above ground level.

The secondary wall of the conventional tank system is fixed at the base. The secondary wall tends to contract with posttensioning and the cooling caused by accidental LNG spills from the primary containment. The consequent shear stresses and moments at the base of the wall are significant and must be designed for. This necessitates heavy reinforcement and prestressing of the secondary containment wall–to–foundation slab joint.

Design and fabrication of larger storage tanks

To increase the size of the LNG tank beyond that used previously, we evaluated the behavior of each tank element both at ambient temperature and during the transition from 20°C (68°F) to the operating temperature of -165°C (-265°F). The movements due to circumferential posttensioning at ambient temperature and thermal contraction associated with cooling the tank were significant. The construction sequence and the relative thermal strains of the various materials were carefully considered.

Exploiting advances in construction technology

The availability of large cranes has expanded the capability to handle large, heavy precast concrete elements. In the concept development, the largest precast concrete elements that could safely be handled and erected with a 300-ton crane were considered. These cranes can position large elements within close tolerances. The design of the large elements was modified as necessary to permit highway transport to the site from the fabrication plant.

Similarly, advances in concrete mixture proportioning and pumping equipment make it possible to reliably construct panel-to-panel joints that result in monolithic behavior of the tank wall after the panel joints have been concreted. Wrap prestressing equipment, used to circumferentially posttension the tank walls, has been developed to provide good control of the applied prestressing force and produces a continuous quality assurance record of the applied force.

Requirements for technology qualification

Precast concrete LNG storage tanks are key elements in both production facilities and receiving terminals. They must be first proven both safe and reliable before the associated savings in cost and schedule with the tanks can be considered. Because of the critical role played by the LNG tank in both the safety and operations of an LNG facility, any deviation from conventional technology requires that the technology be qualified as mature enough to be adopted as a low-risk alternative in terms of safety, operations, construction schedule, and cost.

Approach to technology qualification

Most major energy companies have formal technology qualification processes. These processes include a business case for the introduction of the new technology to confirm the benefits of deployment and a comprehensive risk analysis, considering design, material, construction, and operational risks. For each identified risk, the corresponding likelihood and consequence of occurrence are identified and risk mitigation methods consistent with each identified risk are defined. These risk mitigation methods may comprise analysis and design requirements to address design uncertainties, test programs to qualify materials for service or to confirm the behavior of design details, and procedures to mitigate operational risk. The new technology is generally not adopted for deployment until all of the identified risks have been appropriately mitigated and an overall low level of risk is achieved for all of the new technology elements working together as a system. For a critical element, such as an LNG storage tank, the threshold of proof for adoption and acceptance is necessarily high.

In the case of the composite concrete cryogenic tank, this risk assessment process was first undertaken by the design team and then extended to include subject matter experts in LNG safety, materials, tank design, and operation. The extended risk analysis was facilitated by a classification society, which also performed a detailed third-party review of the tank design and provided a conditional fitness-for-service approval. The conditions to be satisfied for the full fitness-for-service designation involve the completion of several planned detail confirmation and material tests, which will be completed in 2013.

Extending proven technology to meet new needs

The design team elected to adapt the proven aspects of previous technology to address some of the risks and design uncertainties identified in the design and confirmation testing. Previously deployed concrete LNG tank technology with potential safety, cost, and schedule benefits could be adapted to larger tanks constructed using modern precast concrete fabrication, construction methods, and equipment.

The design team was aware of smaller LNG storage tanks that had been constructed using precast concrete wall elements for both primary and secondary containment. As an initial element of the development work, the designers, constructors, and operators of these tanks were interviewed to confirm that the tanks were performing successfully. The literature regarding details, including material tests and qualification tests, and previous design calculations were assembled and reviewed to verify the viability of concepts developed for extending this technology to larger LNG storage tanks. This information was also used to define and plan the tank analytical and design program and to define the necessary material and detail testing program to provide confirmation test data in areas of uncertainty.

Composite concrete cryogenic tank technology

As discussed, the composite concrete cryogenic tank is a full-containment LNG storage system that incorporates two prestressed concrete containment structures **(Fig. 3)**. The primary and secondary containment walls are constructed using full-height precast, vertically pretensioned concrete panels that are integrated with cast-in-place concrete panel-to-panel joints. The panels include a steel liner on the exterior surface (between the wrap prestressing and the wall concrete) that is cast compositely with the precast concrete panels. Most of the liner is made from mild carbon steel. The lower portion of the wall liner (near the wall base) is made from 9% nickel steel. The bottom of the primary containment is also fabricated from 9% nickel steel plate that extends beneath the primary containment wall and is welded to the wall liner to form a fluid-tight, hinged connection at the wall base. As a result of this hinge, the shear stresses and moments to be designed for at this location are significantly lower than those typical for a conventional concrete secondary containment. The primary containment bottom plating is supported on structural insulation (Fig. 3).

Tank design conditions

After the tank wall panels have been erected and joined and the primary and secondary tanks have been circumferentially posttensioned, the floor plates are welded to the annular plates that extend beneath the tank walls, and the primary tank is subjected to hydrostatic testing. The tank system is then purged with nitrogen, cooled to cryogenic temperature, and filled with LNG. During operation, the primary tank may be subjected to seismic loads or accidental fire. The secondary tank may be subjected to pressure and vacuum testing, accidental hydrostatic spill effects, and wind. These tests represent conditions to be considered in tank design. The design of the secondary tank is similar to that of the primary tank, which will be discussed here.

Shrinkage and creep

Shrinkage- and creep-induced loads must be accounted for when designing the primary tank. An advantage of precast concrete is that much of the vertical shrinkage and creep of the panel has taken place before integration into the tank wall. Although both shrinkage and creep essentially stop when the tank is at operating temperature, the tank is designed assuming that ambient temperature creep and shrinkage continue throughout its service life. This is necessary because of the possibility that the initial commissioning of a tank could be delayed for months or even years or the tank could be taken out of service for an extended period.

Hydrostatic effects and testing

After the primary and secondary tanks are circumferentially posttensioned, the annular plates are welded to the primary and secondary floor plates. This creates liquid-tight inner and outer containers. The primary tank is then filled with water to a height corresponding to 1.25 times the product load. The test load induces circumferential tensile stresses in the primary tank and vertical bending stresses in the opposite direction of that caused by wall base friction due to circumferential posttensioning discussed later. The behavior of the tank at cryogenic temperatures and the loading caused by the LNG are generally similar to that of the hydrostatic water testing pressure at ambient temperatures.

Thermal effects during cooldown

After completion of hydrostatic testing, both the inner tank and the annular perlite insulation surrounding the primary tank are purged with nitrogen to a final oxygen level of 8% or less by volume (to ensure safe operation). All standing water is removed from the tank interior. The tank is cooled by controlled introduction of liquid nitrogen to the primary tank interior. For a concrete primary tank, a rate of temperature drop from 0.6°C/hr to 1.3°C/hr (1.1°F/hr to 2.3°F/hr) is sufficiently slow to avoid overstressing the primary tank. At the completion of cooldown, the temperature in the primary tank has been reduced to cryogenic temperatures, with the outside of the tank wall about 0.6°C to 1.1°C (1°F to 2°F) warmer than the inside, causing small permanent stresses in the tank. The difference in coefficient of thermal expansion between steel and concrete also causes permanent stresses due to the large temperature change the materials go through while being cooled to -165°C (-265°F). This is accounted for in the design.

Seismic effects

The primary tank and the secondary tank are designed for an operating basis earthquake and a safe shutdown earthquake. The operating basis earthquake is the maximum earthquake the structure is expected to withstand with

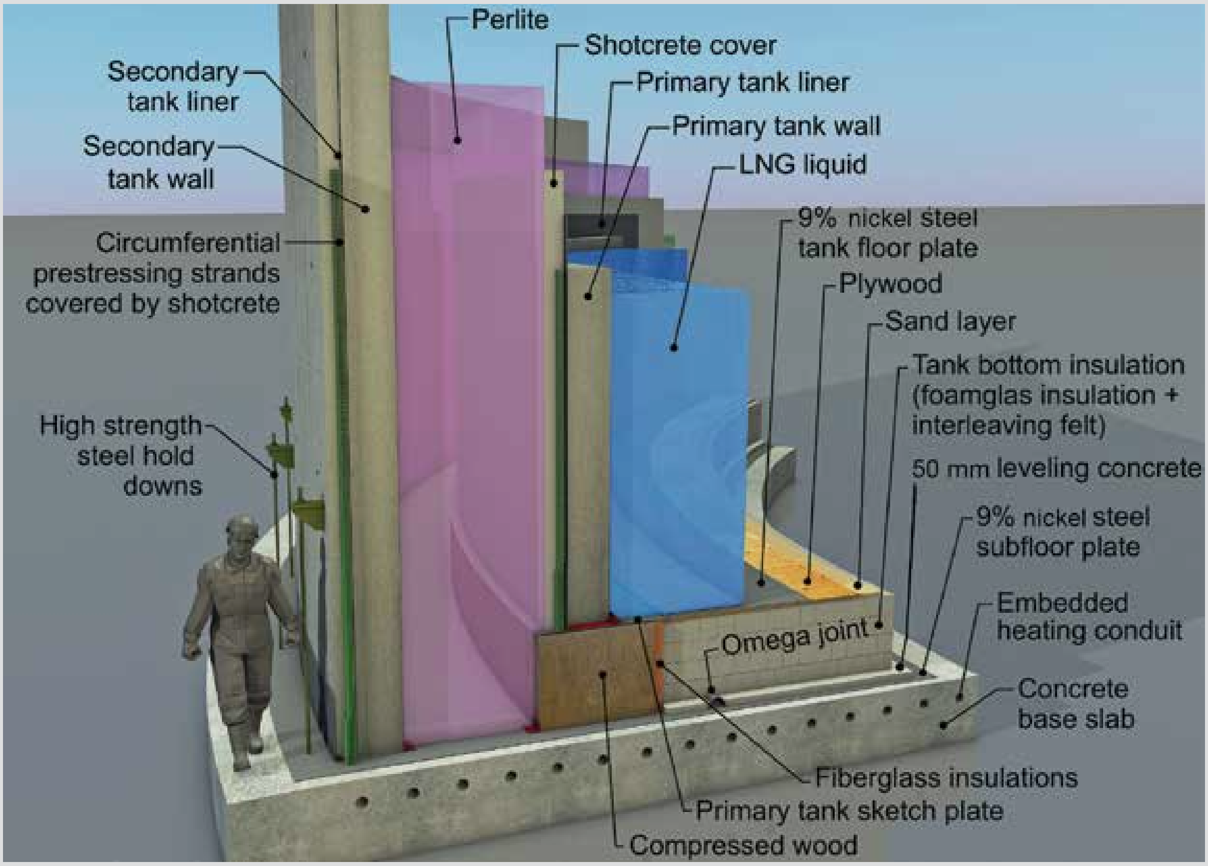

Figure 3. Cutaway section at the base of the composite concrete cryogenic LNG storage system. Precast concrete walls are used for both the primary and secondary containment. The annular space between the primary and secondary containment walls is filled with loose perlite insulation. Figure courtesy of BergerABAM.
Note: LNG = liquefied natural gas. 1 mm = 0.0394 in.

no damage and remain operable. The probabilistic return period for an operating basis earthquake is 475 years. The safe shutdown earthquake is the maximum earthquake the structure is expected to withstand with permanent damage requiring repair but without loss of overall integrity or containment. The probabilistic return period for a safe shutdown earthquake is 2475 years.

Effects of fire

The primary tank must be designed for internal fire effects (fire within the tank) as required by project and regulatory requirements. For a full containment tank, the primary tank is not affected significantly by an external fire. The secondary tank must be designed for external fire effects as required by project and regulatory requirements.

Use of biaxially prestressed, precast concrete wall elements

The individual tank wall panels are pretensioned vertically. The tank wall system is then posttensioned circumferentially after erection and integration by strand or wire wrapping that is coated with shotcrete as the layers of posttensioning steel are applied. Important for its cryogenic behavior, the biaxial prestressing maintains both the wall concrete and the composite steel liner in compression under operating conditions.

The secondary containment is similar to the primary containment in principle, except that the secondary containment also supports the roof structure (**Fig. 4**) and incorporates exterior hold-downs connecting the wall to the foundation to resist the net uplift created by internal tank pressure and wind loading. This internal tank pressure results from LNG vaporization, which can occur due to leakage from the primary containment into the secondary containment. The bottom plating of the secondary containment is welded to the wall liner plate and is directly supported on the tank foundation slab. The foundation slab contains heating elements that prevent freezing of the foundation subgrade soil.

Carbon steel liner material

The use of thin carbon steel plating for most of the wall liner is unique because carbon steel is not rated by most

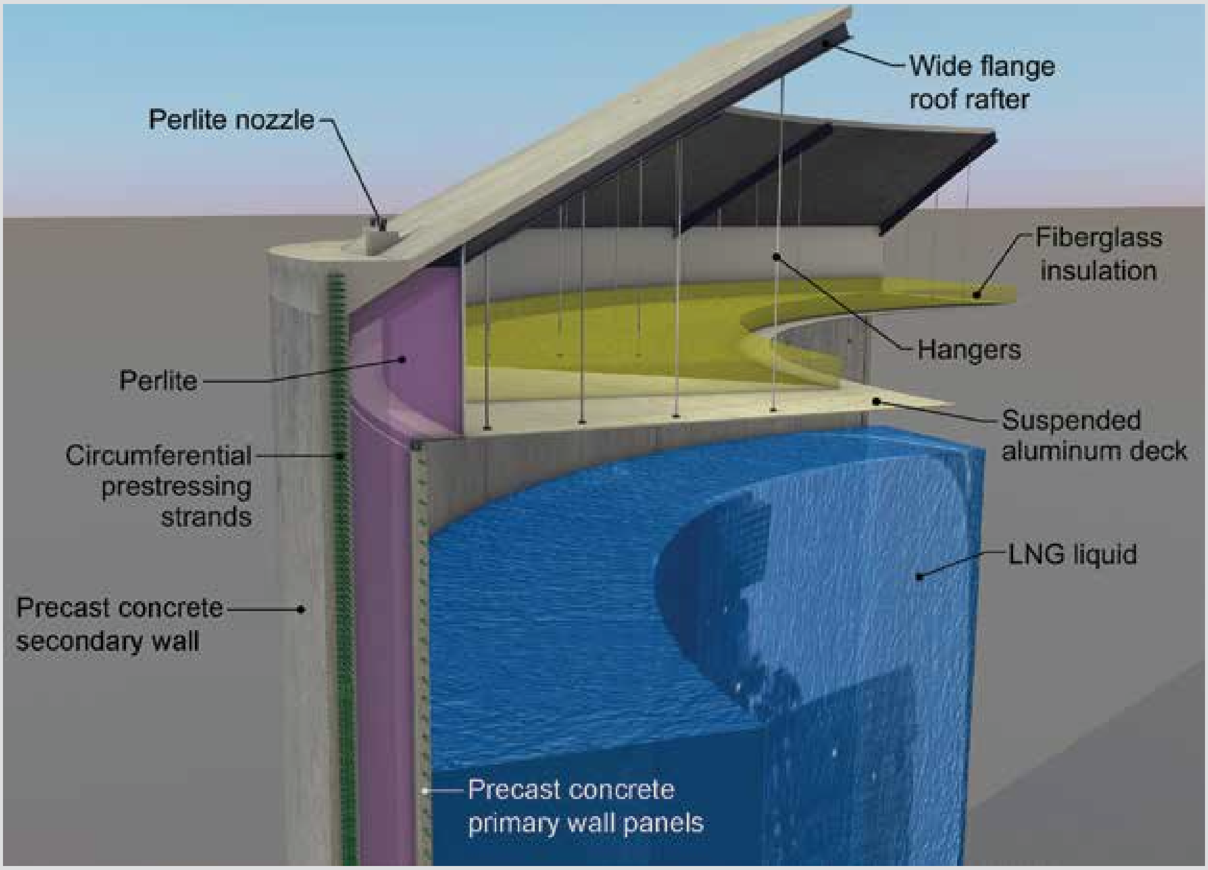

Figure 4. Cutaway section at the top of the composite concrete cryogenic LNG storage system. The concrete roof is part of the secondary containment and the suspended deck supports the thermal insulation over the stored LNG in the primary containment. Figure courtesy of BergerABAM. Note: LNG = liquefied natural gas.

codes for performance at cryogenic temperatures. It has been proven in practice and by testing that prestressing to maintain compression or low tension enables thin (5 mm [0.197 in.]) liner steel plating to perform acceptably as a supplemental liquid barrier to the concrete wall at the loading rates typical for LNG tank elements.[10] The concrete wall itself is in direct contact with the stored LNG and is designed to be liquid tight.

Behavior of long, slender precast concrete wall panel elements

Although a metallic liner is provided, the design philosophy for the primary containment is that the containment walls must remain gas tight throughout operation. Internal stresses due to restraint of volume changes, such as thermal contraction during cool-down, typically do not affect the overall strength of the structure but combine with stresses from external loads during operation. Prescribed fabrication and site construction procedures must be followed to limit these stresses to allowable levels. With regard to the tank, stresses in the steel liner and its welds that could lead either to brittle rupture or buckling of the liner membrane are of greatest concern. Similarly, the stresses in the carbon steel reinforcement and the concrete must be limited to control crack widths and depths.

Internal stresses are a design concern for concrete slabs and beams that can crack due to restraint of volume changes. For structures with large precast concrete elements, such as the wall elements of the tank, internal stresses can result not only from the differential thermal and mechanical characteristics of its components but also from external forces applied during construction. Hence, construction procedures, such as the panel production methods, handling, storage, transportation, erection procedure, wall integration, and posttensioning sequencing, become significant design considerations.

During the wall integration, adjacent panel edges have to be aligned relative to one another within millimeters to allow welding the liners together from two adjacent panels. A kink in the liner would cause a local stress concentration and predispose the liner to buckling during circumferential posttensioning. Although the panels seem easy to adjust as a result of their aspect ratio of over 100:1, an uncontrolled adjustment could introduce unwanted stresses. To minimize these stresses, the panels must be fabricated and handled so that, once erected, adjacent wall panels show minimal differential deformations. If the wall panels need to be adjusted, the adjustment procedure must be carefully controlled.

Differential panel deformation

Prestressing, posttensioning, creep, and shrinkage all have the potential to deform the wall panel. Due to variation in construction tolerances and material variations, individual panels will deform differently even if they were formed in the same bed. The wall panels for the composite concrete cryogenic tank are prone to differential camber because their center of stiffness, and thus curvature, is sensitive to the ratio of stiffness provided by the concrete versus that provided by the composite steel liner.

Although the liner is not considered in the ultimate strength calculations, it contributes to the stiffness of the panel. The liner on one side shifts the center of stiffness away from the centerline of the wall. Any change of stiffness of the composite section can introduce a small local curvature, which can add up to a significant camber over the length of the wall. Change of composite section stiffness can arise from variations in construction tolerances, variations in material characteristics, or construction conditions.

Construction tolerances that could affect the curvature of the section are variations in the location of the prestressing steel or the mild steel reinforcement, the thickness of the concrete section, the thickness of the steel liner, and the prestressing force. Variations in concrete strength and stiffness also influence curvature. Variations in the concrete age at form stripping and transfer of prestress, the duration and condition of concrete curing, and the concrete age at wall panel integration all affect creep and shrinkage.

Thermal gradients can introduce unanticipated curvature. For example, concrete curing temperatures above the allowable introduce a residual tension in the steel liner once the wall panel has cooled. A thermal gradient through the wall section due to sun exposure during wall installation can induce curvature.

Differential deformations of panels can also be caused by different storage conditions for individual panels. For example, panels bunked lying on their side will deform differently over time than panels lying flat with similarly spaced bunk supports. Thus it is essential that the construction parameters are understood, considered in design, and controlled on-site to minimize differential wall deformations and thus the potential for unwanted and potentially significant internal stresses.

To understand the significance of small variations in section properties and material properties on the behavior of these panels, a series of parametric studies was performed. **Figure 5** shows the result of one combination of fabrication and erection procedures on the wall panel moment capacity versus moment demand. This background was used in determining allowable construction tolerances for dimensions and material mechanical properties and for the development of the handling and erection shoring procedures.

Panel camber adjustment during wall integration

The alignment of a wall panel in its erected position can be adjusted to match the adjacent panel. The most common method would be to jack the edges of the adjacent panels against each other, forcing them into the same plane. However, correcting the wall panel camber at only a few discrete points can induce localized stresses. On the other hand, correction of camber at too many locations along the wall height is difficult to control, and overcorrection could also lead to high internal stresses.

At a length of over 34 m (112 ft), the individual tank panels need intermediate supports over their height to be sufficiently secured against wind during construction. Multiple temporary support points make the wall panel statically indeterminate and may lead to higher than desired internal stresses and large support reactions. Once the erection shoring is removed, the reaction forces disappear but the internal stresses, though at a new equilibrium, remain. Too many intermediate support points also make it difficult to align adjacent wall panels relative to each other. It may be more appropriate to adjust the panels individually against the shoring system. During the adjustment of the wall panels, other external effects such as wind and sun exposure must be considered. They can introduce significant reaction forces and thus higher than desired stresses in the panel.

The wall shoring, camber adjustment, and wall integration procedures must be considered during shop drawing design and also influence tank behavior during operation. Therefore, the effects of these procedures must be quantified during the design of the structure.

Controlling unintended internal stresses

The differential camber of the panels can be addressed by defining clear limits for construction tolerances and material property variations. Parameters that are most influential may require tighter tolerances than the industry standard. For example, the maximum allowable camber for the wall might have to be limited to $^{l}/_{700}$ instead of the PCI-recommended $^{l}/_{360}$[9] for the wall panels. Similarly, variations in material characteristics can be addressed by design, but their limits for construction should be specified. Additional requirements to control differential camber include maximum allowable concrete curing temperatures, curing cycles and methods, bunking locations during panel storage, and dimensional tolerances. Critical parameters

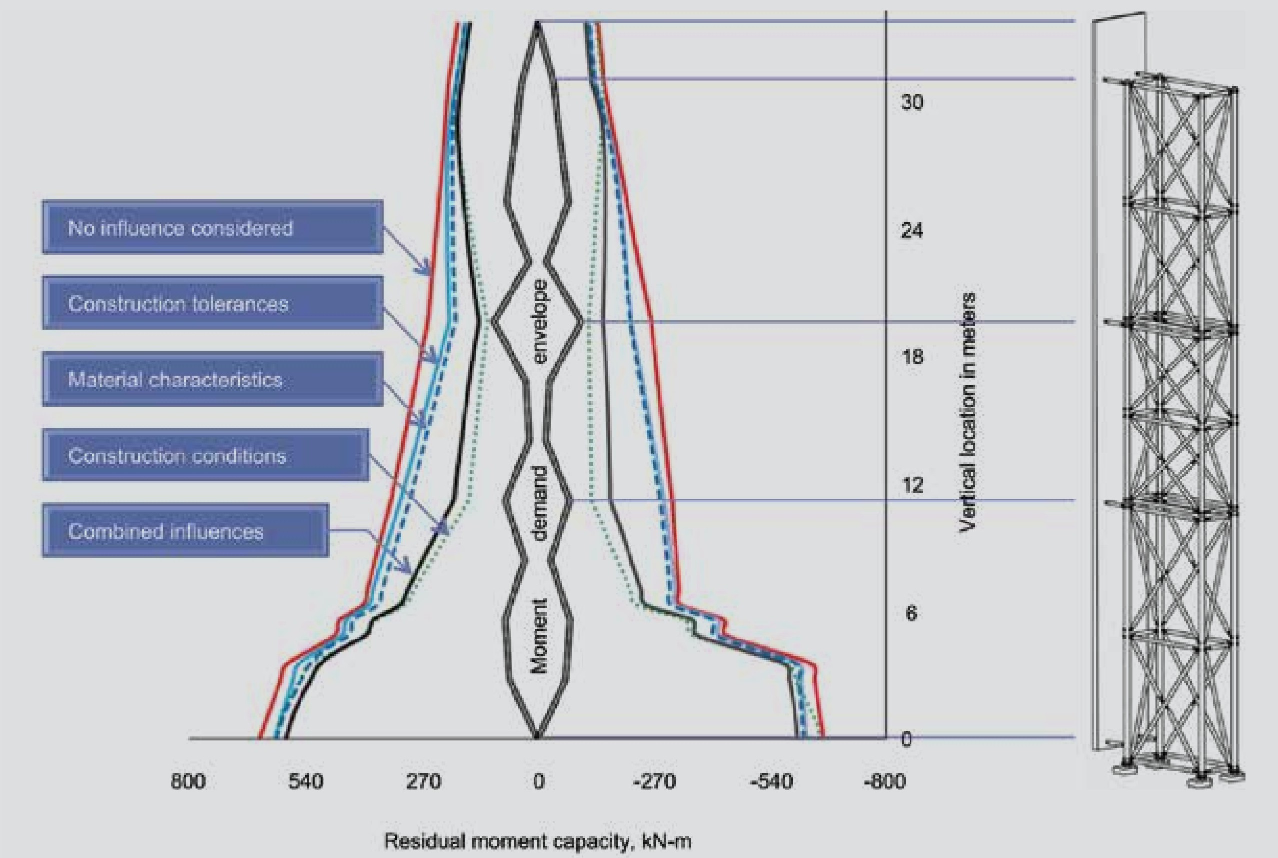

Figure 5. Variations in individual material and geometric parameters can reduce the residual cracking moment capacity of a shored wall panel. Due to internal stresses, the cracking moment capacity can potentially be reduced by up to 50%. Note: 1 m = 3.28 ft; 1 kN = 0.225 kip .

are specifically addressed in the panel fabrication and erection quality control programs.

The control of internal stresses from panel camber adjustment can be addressed by either a performance specification that limits the additional stresses due to adjustment or by specifying an adjustment procedure.

Design of wall panels for construction loading

The length and slenderness of the panels necessitate careful handling, transport, and erection procedures to avoid cracking and excessive internal stresses. The wall panel formwork must produce panels within tight dimensional and alignment tolerances. Hence, the formwork must be stiff and not subject to deformations from differential settlement, thermal exposure, or prestressing. At a length of more than 34 m (112 ft), even the prestressing strands must be supported at intermediate points to avoid draping that will affect camber. The formwork must allow the panel to shorten during prestress transfer and form stripping.

It is difficult to accurately measure the as-built camber of the flexible panels until they are positioned vertically. Thus the processes that induce camber must be controlled to avoid construction of a panel that might not be recognized to be out of camber tolerance until it is in its erected position.

Supports for the panels in storage must be the same for each panel because they are prone to creep or possible cracking under differential settlement of the storage bunks unless they are stored on their sides. Sun exposure can induce thermal gradients leading to cracking of the panels.

Multiple-panel support positions cannot effectively be provided during transport of full-height panels unless a strong-back is mounted to the panel. However, panels can be transported in an appropriate tilted position to provide horizontal stiffness without a strong-back. Stability and potential vibration during transport have to be considered to avoid panel cracking.

The panel tilting and erection procedures are sensitive to wind, which must be considered in handling procedures and monitored on-site. The panels can be tilted from horizontal to vertical with the use of a tilting table or by a crane with an equalizing pulley system or a strong-back attached to the panel. The strong-back can be part of the shoring system of the panel in erected position. A large crawler crane is used to walk the panels from their pick-up location to their erection location. Cracking due to a combination of wind and self-weight when the panel is tilted must be addressed. Preliminary analysis suggests that a set-down panel not yet connected to the shoring points could sustain wind speeds up to 40 km/h (25 mph) if plumb. However, even at low winds, to avoid the possibility of panel cracking, the tilt during erection must be controlled to allow no more than 2 degrees. Thus the erection procedure must control panel tilt to maintain the top and the bottom of the wall panel within the same vertical plane within a tolerance of 1.2 m (3.9 ft).

As discussed, the panel must be attached to the shoring to maintain the panel within erection tolerances, prevent cracking due to wind or sun exposure, and limit internal stresses. Once multiple panels are erected and adjusted, they can be connected. As the integrated wall evolves into a cylindrical shell and gains stability, the shoring towers can be removed except at the corner panels. After all panels have been connected, the shoring can be removed and the wall circumferentially posttensioned. For the erection of the secondary containment wall, the panels can be shored against the finished primary containment wall.

Circumferential posttensioning of tank walls

The primary tank will be circumferentially posttensioned so that the wall remains in compression when the tank is subjected to hydrostatic pressure during hydrostatic testing or in operation. Circumferential posttensioning causes the tank wall to shorten in circumference. This results in an inward radial translation of 20 mm (0.8 in.) for a 160,000 m^3 (5,700,000 ft^3) tank. The annular plate is not welded to the tank interior floor plate until after posttensioning of the wall to avoid buckling of the floor plate and the floor plate single fillet welded joints as the wall moves inward. A low-friction sliding surface is provided above the compressed wood structural insulation supporting the primary containment wall to accommodate this motion (Fig. 3).

It is also important to account for friction between the primary tank wall base and the low-friction surface. This friction is developed as the primary tank wall base slides radially toward the center of the tank during circumferential posttensioning. The friction reduces the effects of the circumferential posttensioning and introduces a bending moment in the lower portion of the wall, inducing vertical tension on the inside of the wall and compression in the carbon steel liner that must be considered in design.

Achieving construction quality

Achieving the necessary constructed quality is a challenge in a conventional technology LNG storage tank. The primary containment involves the inherently difficult welding of thick 9% nickel steel plate. The cast-in-place concrete secondary containment of a conventional technology tank is placed in typically 3 m (10 ft) lifts or by slipforming and contains significant amounts of reinforcement and posttensioning ducts, making placement and consolidation of the concrete difficult.

In contrast, the composite concrete cryogenic tank wall panels are lightly reinforced; contain primarily pretensioning strands; and are cast flat, near ground level, and using the steel liner as the bottom of the wall panel form. Achieving the necessary concrete placement and consolidation in elements cast in this manner is a reliable operation. The primary containment wall elements are 360 mm (14 in.) thick at the base, tapering uniformly to 180 mm (7 in.) at the top. The secondary containment wall elements are a constant 460 mm (18 in.) in thickness. The element width was selected to maintain the full-height panel weights at approximately 100 tonnes (220 kip). All welding is of thin plates, typically 5 mm (0.2 in.) thick, and most welding is fillet welding of mild steel (ASTM A516,[8] Grade 65 [450 MPa]) to mild steel.

A challenge in the design of such large and slender wall elements is to develop handling and erection support methods to ensure that the temporary handling, transport, erection, and erection support conditions do not control the design.

Conclusion

The work done to develop and qualify the composite concrete cryogenic LNG storage tank technology has shown that the concept will provide a safe and robust LNG storage facility. The structural behavior of the tank system is well understood and will provide reliable performance. Modern precast, prestressed concrete fabrication and erection techniques to produce and integrate the precast concrete tank wall elements provide the potential to more economically achieve the high quality and reliable performance necessary for these facilities.

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Abstract

The growing use of liquefied natural gas (LNG) has necessitated large (160,000 m^3 [5,700,000 ft^3]), cryogenic-rated (-165°C [-265°F]) storage tanks. Conventional technology uses primary containment tanks fabricated of 9% nickel steel, which is in limited supply and difficult to weld, and cast-in-place concrete secondary containment tanks. Composite concrete cryogenic tank design incorporates integrated precast, biaxially prestressed concrete tank wall panels for both primary and secondary containment. The wall panels weigh 100 tonnes (220 kip) and are up to 38 m (125 ft) tall. This LNG storage tank is one of the first cryogenic tanks designed to the provisions of ACI 376-10.

This paper discusses the unique design and construction challenges encountered in the development of large-scale precast, prestressed concrete cryogenic storage tanks, along with special considerations necessary when fabricating, handling, erecting, temporarily supporting, integrating, and posttensioning the long and slender precast concrete wall panels needed to produce a liquid- and gas-tight structure.

Keywords

Cryogenic temperatures, storage, tank, wall panel.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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