DEVELOPMENT OF LARGE-SCALE PRECAST, PRESTRESSED CONCRETE LIQUID NATURAL GAS STORAGE TANKS

Kåre Hjorteset, PE, SE, BergerABAM, Houston, TX
Markus Wernli, PhD, PE, LEED AP, BergerABAM, Seattle, WA
Michael W. LaNier, PE, BergerABAM, Federal Way, WA
Kimberly A. Hoyle, Chevron Energy Technology Company, Houston, TX
William H. Oliver, PE, ConocoPhillips, Houston, TX

ABSTRACT

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 liquid natural gas (LNG) has developed as a method to transport large quantities of gas 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 cubic meters and larger) cryogenic rated (-165°C) [-265°F] storage tanks at both LNG export terminals in producing countries and at import terminals in the destination countries. Conventional technology uses primary containment tanks fabricated of 9 percent nickel steel. The supply of this material is often constrained and it is difficult to weld the thick plates required for large tanks. Conventional secondary containment tanks, surrounding the primary tank, are constructed using cast-in-place concrete technology. Developed under the sponsorship of major energy companies, the Composite Concrete Cryogenic Tank (C^3T) design draws on previous experience and takes advantage of current construction technology by incorporating integrated precast biaxially prestressed tank wall panels that weigh 100 tonnes and are up to 37 meters (121 feet) tall. The C^3T LNG storage tank system is one of the first cryogenic tanks designed to the provisions of the new ACI 376 "Code Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases."

This paper includes a discussion of the unique design and construction issues encountered in the development of precast concrete cryogenic storage tanks of this scale. Also to be addressed is information regarding special considerations necessary when fabricating, handling, erecting, temporarily supporting, integrating, and post-tensioning the very long and slender precast wall panels needed to produce a fluid and gas tight structure.

Keywords: Precast Walls, Cryogenic Temperatures, Biaxial Prestressing

BACKGROUND

NATURAL GAS AS A SOURCE OF ENERGY

World energy use is shifting from a primary focus on coal and oil to an increased emphasis on natural gas. Natural gas is cleaner burning than coal and is significantly more economical than oil on a relative energy basis. For example, as of this writing, MMBtu (1,000,000 Btu) of energy from natural gas costs $4.35 U.S. (Nymex Henry Hub Future) and from oil about $21 (at $113 per barrel). Even when including the cost of liquefaction, shipping, and regasification, the cost of gas delivered as liquefied natural gas (LNG) can be as low as $6 per MMBtu, which is still significantly less than the cost of oil per MMBtu. As with coal and oil, the source of natural gas is often in a different part of the world than the customers who have the energy need.

WHY LNG INDUSTRY HAS DEVELOPED

With this continuing shift to natural gas as an energy source, 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 as LNG over the highway system in special trucks and converted to the gaseous state by the final user. The reason LNG is attractive for transportation is that 600 liters of natural gas volume at ambient temperature and pressure can be reduced to 1 liter of LNG volume at cryogenic temperature and ambient pressure. Careful handling of this material as LNG has also proven 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 plant 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 currently planned and under construction for several locations in Australia. Each of these investments in production capability amounts to several billion U.S. dollars and are accompanied by similar large investments in special oceangoing LNG carriers and receiving terminals at the points of destination. Today the majority of the new ships under construction are in the size of 120,000 m^3 to 140,000 m^3 (32.7 to 37.0 million gallons). The maximum capacity of LNG ships under order is up to 260,000 m^3 (68.7 million gallons). These carriers are special in that they are designed with special thermally insulated containments systems to carry the cold (-165^{o}C) [-265^{o}F] LNG.

WHY LARGE LNG STORAGE TANKS ARE NEEDED

Because of the large volumes of LNG involved, storage tanks are needed to store LNG both at the production source, in advance of loading it from a production storage tank into an LNG carrier, over a typically 10- to 12-hour loading period, for transport and at the LNG receiving terminal as it is offloaded from the carrier, usually over a 12- to 16-hour period, into receiving storage tanks. An LNG export facility may have from 2 to 12 or more LNG storage tanks in the 160,000 m^3 (42.3 million gallons) size range and a receiving terminal may have from 2 to 6 LNG storage tanks of this size. The cost of LNG tanks of this size using conventional construction ranges from \$100 million to reportedly over \$300 million each, depending on the locations and circumstances where they are built.

Fig. 1, A typical LNG receiving terminal showing both the marine berths for the LNG carriers and the LNG storage tanks and associated regasification equipment under construction. *Photo courtesy of Baker Concrete.*

THE OWNER'S PERSPECTIVE – WHY AN ALTERNATIVE TANK TECHNOLOGY IS NEEDED

In the face of rising costs to build LNG facilities, Chevron and ConocoPhillips, like the other partners of the C^3T Joint Industry Program (JIP), originally joined the JIP in order to find a lower-cost alternative to the 9 percent nickel steel LNG storage tanks, which are currently the standard.

As the C^3T design was developed, it became clear that cost savings were not the only benefit to this LNG storage tank alternative. Some of the beneficial aspects of an alternative tank technology are shown below.

REDUCED 9 PERCENT NICKEL STEEL REQUIREMENT

Today's conventional LNG tanks require large amounts of 9 percent 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 percent nickel steel used also equates to a reduction of the number of 9 percent nickel steel welds required; therefore, reducing the demand for specialized highly skilled welders.

INCREASED NUMBER IN CONTRACTORS WHO CAN BUILD LNG STORAGE TANKS

Today, there are only a handful of contractors around the world that are used to build conventional 9 percent nickel steel tanks. By adding a new tank technology based on concrete, it opens up the field to contractors with concrete tank experience. The added competition will help to keep tank prices competitive and add pressure to the conventional tank fabricators to control their costs and provide more attractive prices to LNG projects.

FASTER CONSTRUCTION SCHEDULE

For grassroots LNG liquefaction projects where the tanks are not usually on the critical path, allowing for the tanks to be completed faster allows for labor time to be optimized by having laborers work on other aspects of the plant. For liquefaction facility expansions, LNG regasification terminals, and other projects where the tanks are on the critical path, the shorter construction time may allow earlier startup of the project and the associated revenue.

ABILITY TO FABRICATE THE PRECAST WALL PANELS EITHER ON SITE OR OFF SITE

The ability to fabricate the precast wall panels either on site or off site allows greater flexibility to either (1) reduce the on-site workforce or (2) increase the use of local nonskilled labor.

ABILITY TO BUILD LARGER TANKS

As it currently stands, there is likely an upper limit on the feasible size of a conventional 9 percent nickel steel LNG storage tank. As LNG liquefaction plants are built larger and larger, the amount of LNG storage required increases as well. In order to keep up with the future 8 to 10 million tonnes per annum of LNG output new plant designs, a new alternative to the 9 percent 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 “Liquefied Natural Gas Facilities: Federal Safety Standards,” National Fire Protection Association (NFPA) 59A “Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG),” American

Petroleum Institute (API) 620 “Design and Construction of Large, Welded, Low-Pressure Storage Tanks,” American Concrete Institute (ACI) 318 “Building Code Requirements for Structural Concrete and Commentary,” and ACI 376 “Code Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases and Commentary.” The 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 Section 7.4 refers to API 620 for welded container design. NFPA 59A Section 7.5 refers to ACI 318 for the design of concrete structures. ACI 318 is written to address design of general concrete building structures. In 2004, NFPA contacted ACI with the request that ACI write a code that directly applies to the containment of refrigerated gas. In 2005, ACI created the Committee ACI 376 Concrete Structures for Refrigerated Liquefied Gas Containment that published a provisional code “Code Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases and Commentary” for public hearing in April 2010. The public comments are currently being addressed and it is expected that the final code will be published late 2011 or early 2012. In the next revision of NFPA 59A, it is expected that Section 7.5 will reference to ACI 376 in lieu of ACI 318. In the following, ACI 376 is referred to, not ACI 318.

LEVEL OF CONTAINMENT

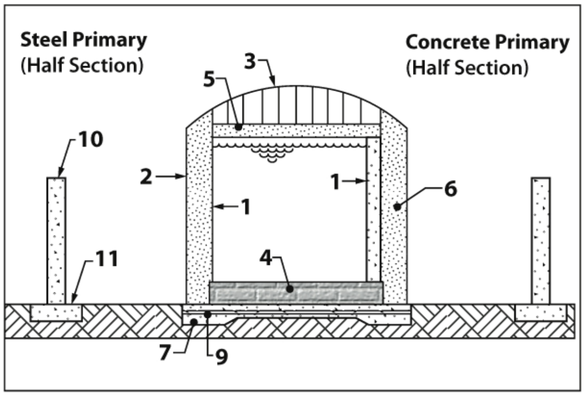
Determination of the site layout for a facility with LNG storage is significantly dependent on the level of containment chosen for the project storage. There are three levels of containment systems; single containment, double containment, and full containment. The definitions of containment systems per NFPA 59A are as follows.

- Single-Containment Container – A single wall container or a double wall tank where only the self-supporting primary or inner container is designed to contain LNG.

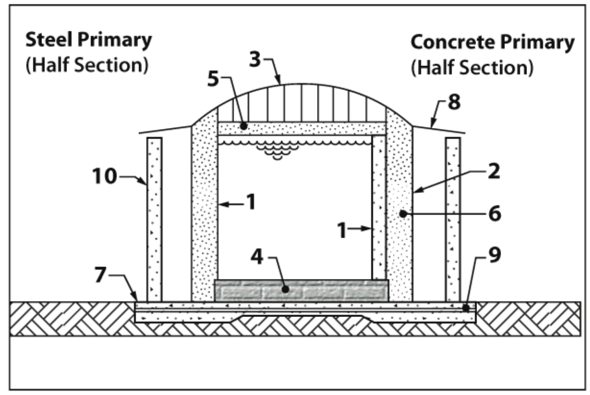
- Double-Containment Container – A single-containment container surrounded by and within 6 m (20 ft) of a containment wall (secondary container) that is open to the atmosphere and designed to contain LNG in the event of a spill from the primary or inner container.

- Full-Containment Container – 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 where 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 only through relief valves.

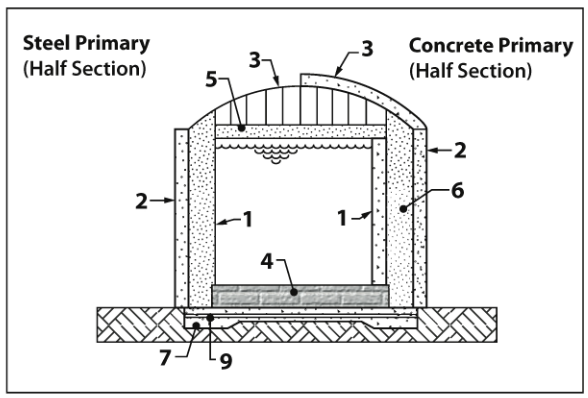
Full-containment containers can be placed in more compact site arrangements than single containment containers. Further, there has been a shift in the United States from use of single containment towards full containment. Figure 2 shows the three containment systems for either steel or concrete structures.



Single-containment tank system



Double-containment tank system



Full-containment tank system

Fig. 2, Containment Tank Systems

LEGEND

1 Primary container (9 percent nickel steel or prestressed concrete)
2 Outer tank shell (carbon steel for single- and double-containment and prestressed concrete for full-containment)
3 Tank roof (carbon steel or concrete)
4 Bottom rigid insulation
5 Suspended ceiling insulation
6 Loose fill insulation
7 Foundation slab
8 Rain shield
9 Foundation heating system
10 Bund wall (dike) – prestressed or reinforced concrete
11 Bund wall footing

MATERIAL STRENGTH AT CRYOGENIC TEMPERATURES

Concrete and post-tensioning steel as used in the typical building industry can be considered to be suited for cryogenic service, as the post-tensioning tensile strength and the concrete compressive strength are not reduced, but rather are increased at cryogenic temperatures. Typically, no benefit of the increased strength is used while designing using these materials. Carbon steel rebar on the other hand behaves in a brittle manner in cryogenic temperatures, and thus if carbon rebar is used to resist loads, the allowable tensile strength must be limited to 83 MPa (12 ksi) for #3 and #4 rebars; to 69 MPa (10 ksi) for #5, #6, and #7 rebars; and to 55 MPa (8 ksi) for #8 and larger rebars per ACI 376 and NFPA 59A. Structural metal liners and nonstructural metallic barriers incorporated in and functioning compositely with prestressed concrete are to be designed per API 620. Typically, 9 percent nickel steel is used for structural metal liners and carbon steel is used for nonstructural metal liners.

THERMAL MOTION EFFECTS – AMBIENT TO CRYOGENIC TEMPERATURE

An important consideration when designing composite structures subjected to large temperature ranges from ambient temperatures to cryogenic temperatures is the difference in temperature-thermal strain relationship between steel and concrete. Carbon steel and 9 percent nickel steel have similar temperature-thermal strain relationship. The temperature-thermal strain relationship for concrete depends on a number of variables. The most important variable is the aggregate type. In addition to aggregate type, the water/cement ratio, presence of compressive stresses, and degree of water saturation of the concrete will influence the temperature-thermal strain relationship as discussed in the *ACI Journal*, May-June 2007 technical paper, "Liquefied Natural Gas Storage: Material Behavior of Concrete at Cryogenic Temperatures," by Neven Krstulovic-Opera. When designing the containment structures, the loads resulting from the different temperature-thermal strain relationship between steel and concrete must be accounted for. ACI 376 requires that the coefficient of thermal contraction of the concrete shall be confirmed by testing the actual mix proportion over the range of the operational temperatures.

CONVENTIONAL LNG STORAGE TANK TECHNOLOGY DEFINED

THE DEVELOPMENT OF CONVENTIONAL LNG STORAGE TANK TECHNOLOGY

LNG storage tank design has evolved over time and as the result of several safety-related incidents to the conventional practice in tank design today. Initially single-containment tanks were the norm. Following an incident involving major failure of a primary containment, the design of bund walls for a time considered very high dynamic fluid pressure forces resulting from such a major primary tank rupture. As steel material and welding technology for cryogenic structures has improved over the years, the requirement to design the secondary containments for the high dynamic fluid pressure associated with a major primary containment rupture is no longer required. The recognized potential for an LNG vapor cloud, developed as result in a leak in the primary containment, to extend beyond the limits of the open top bund wall lead to the incorporation of a vapor-tight roof on the secondary containment resulting in a full-containment tank.

The conventional tank most often used today is designated as 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 (42.3 million gallons) storage tank are 79 m in diameter by 34 m high (259 ft x 112 ft) for the primary containment and 82 m diameter by 38 m high (269 ft x 125 ft) for the secondary containment. Height to the top of the domed roof of the secondary containment is typically 48 m (157 ft). The primary containment is designed to contain the LNG under normal operation. The secondary containment is designed to contain the LNG and associated increased vapor pressure under accidental conditions in the event of a leak or a spill from the primary containment. The C^3T design qualifies as a full-containment tank.

Figure 3. Conventional LNG storage tank under construction. The secondary containment roof has not yet been constructed in this photo. *Photo courtesy of Baker Concrete.*

The primary containment in the conventional tank technology is composed of an open top steel containment tank constructed from welded 9 percent nickel steel (ASTM A553) plate. The secondary tank is typically constructed of cast-in-place concrete, post-tensioned with circumferential internal post-tensioning tendons. The secondary tank typically has a cast-in-place concrete roof. The secondary tank usually has an interior steel plate liner attached to the secondary containment walls, roof, and floor plate. The overall secondary containment is typically designed for a small vacuum pressure of about -0.22 psig (-15 mbarg) and larger outward pressure of about 4.29 psig (290 mbarg). Typical size of conventional LNG storage tanks is 160,000 m^3 (42.3 million gallons). Lately, tanks up to 180,000 m^3 (47.6 million gallons) 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 under tank 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 primary containment to limit inflow of heat and the associated boil off of the stored LNG. There is typically a 1-m (3 ft) annular space between the exterior of the primary-containment walls 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 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. This insulation is built up of stacked structural insulating blocks and includes interleaving felt material between block courses to prevent convection currents forming in the small spaces between the blocks.

CONSTRAINTS ASSOCIATED WITH CONVENTIONAL TECHNOLOGY

Conventional technology LNG storage tanks rely on the availability of large quantities of high-quality 9 percent nickel steel, primarily available from only one mill in Belgium. At times, the availability and delivery schedule for this material adversely affect the construction schedule and the cost of these tanks. The criticality of welding of the ASTM A553 9 percent nickel steel results in the secondary tank being constructed first to provide a necessary enclosure to allow the welding of the primary tank plating in a protected environment–free of wind and rain. This sequence results in schedule constraints for the construction of the primary containment. The conventional technology secondary tank is constructed by placing a succession of lifts of cast-in-place concrete, much of it placed high above the ground level. The conventional technology tank secondary wall is configured with a fixed condition at the intersection of the base of the concrete wall and the tank foundation slab. This fixity results in significant shears and moments that must be designed for as result of the restraint provided by this intersection as the secondary wall shortens both as a result of post-tensioning and as a result of the cooling as result of an LNG spill from the primary containment.

ADAPTING PROVEN TECHNOLOGY TO TAKE ADVANTAGE OF ADVANCES IN CONSTRUCTION TECHNOLOGY

LNG storage tanks are key elements in both LNG production facilities and LNG receiving terminals. Because of this, they must be shown to be both safe and reliable and these two essential qualities must be satisfied before the cost and construction schedule associated with the tanks can be considered.

REQUIREMENTS FOR TECHNOLOGY QUALIFICATION

Because of the critical role played by the LNG tank in both the safety and the operations of an LNG facility the introduction of a change from conventional technology to a different “new” technology of LNG, tank construction requires that the “new” technology be qualified as mature enough to be adopted as a low-risk alternative to currently used conventional technology. Low risk in this case means low safety, operational, construction schedule, and cost risk.

APPROACH TO TECHNOLOGY QUALIFICATION

Most major energy companies have formal technology qualification processes that they apply to their consideration of new technologies of various types. These processes include the development of a business case for the introduction of the new technology to confirm the benefits of deployment and a comprehensive risk analysis of all aspects of the new technology, considering design, material construction, and operational risks. For each identified risk, the corresponding likelihood and consequence of occurrence is identified and risk mitigation methods consistent with each identified risk are defined. These risk mitigation methods may address analysis and design requirements to address design uncertainties, test programs to qualify materials for service or to confirm the behavior of design details, and operational procedures that may be needed to mitigate operational risk. The new technology is generally not adopted for company project deployment until all of the identified risks have been shown to 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, like an LNG storage tank, the threshold of proof of fitness for service for adoption and acceptance by the energy companies is necessarily very high.

In the case of the C^3T, this risk assessment process was first undertaken by our design team and then extended to include energy company subject matter experts in LNG safety, materials, tank design, and operation. The extended risk analysis was facilitated by a classification society who also performed a detailed third-party design review of the C^3T design and provided a conditional "fitness for service" approval. The conditions to be satisfied for the full fitness for service involve the completion of several planned detail confirmation and material tests.

APPROACH TO EXTENDING PROVEN TECHNOLOGY TO MEET NEW NEEDS

Because of the need to assure reliability of the overall LNG storage tank system, our design team determined that the most viable approach to the development of a "new" LNG tank concept was to adapt the proven aspects of previously used technology. We were aware of previously deployed concrete LNG tank technology with potential safety, cost, and schedule benefits that we felt could be adapted to larger tanks constructed using modern precasting, construction methods, and equipment. By taking this approach, previous successful operating experience could be used in addressing some of the risks and design uncertainties identified to be mitigated as result of the design and confirmation testing process.

Our design team was aware of smaller LNG storage tanks that had been constructed in the past using precast concrete wall elements for both the primary and secondary containments. As an initial element of our development work, we interviewed the designers, constructors, and operators of these tanks to confirm that they were providing successful performance. We also assembled and reviewed all of the relevant literature, including material tests and qualification tests for details, reviewed previous design calculations to confirm that our concepts for extending this technology to larger LNG storage tanks was likely viable. We also used this information to define and plan the C^3T analytical and design program and to define the necessary material and detail testing program to provide confirmation test data in areas of uncertainty.

ADVANCEMENTS IN PRECASTING TECHNOLOGY - KEY TO MEETING LARGER STORAGE REQUIREMENTS

Our approach to increasing the size of the LNG tank was to evaluate the consequence of increasing the size of the tank to the various major elements and features of the tank. This effort is complicated by the fact that one must consider the behavior of the tank elements both at ambient temperature and as the various elements interact during the transition from ambient 20°C (68°F) to the cryogenic operating temperature of -168°C (-270°F). Because of the significant movements that result both from radial translation due to circumferential post-tensioning at ambient temperature and from the large temperature range involved with cool down of the tank, the sequence of construction and the relative thermal strain behavior of the various materials must be carefully considered.

As a general principle in our concept development, we considered construction using the largest on-site precast elements that could safely be handled and erected using a 300-ton crane and then considered how to modify these large elements so that they could also alternatively be highway transported to the site from a remote plant precasting location.

COMPOSITE CONCRETE CRYOGENIC TANK TECHNOLOGY

As discussed, the C^3T is a full-containment LNG storage system that incorporates two prestressed concrete containment structures as shown in Figure 4. The primary and secondary containments are constructed using full-height precast vertically pretensioned concrete panels that are integrated with cast-in-place, 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 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 percent nickel steel. The bottom of the primary containment is fabricated from 9 percent 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 result of this hinge, the shears and moments to be designed for at this location are significantly lower than those typical for a conventional secondary containment. The primary containment bottom plating is supported on structural insulation as shown.

USE OF BIAXIALLY PRESTRESSED PRECAST CONCRETE WALL ELEMENTS

The tank wall system is prestressed circumferentially after erection and integration by strand or wire wrapping that is coated with shotcrete as the layers of prestressing steel are applied. The combination of the vertical pretensioning and the circumferential post-tensioning in the wall elements result in a beneficial biaxial prestressing of the wall elements. Importantly for its cryogenic behavior, the prestressing maintains the composite steel liner in compression for operating conditions.

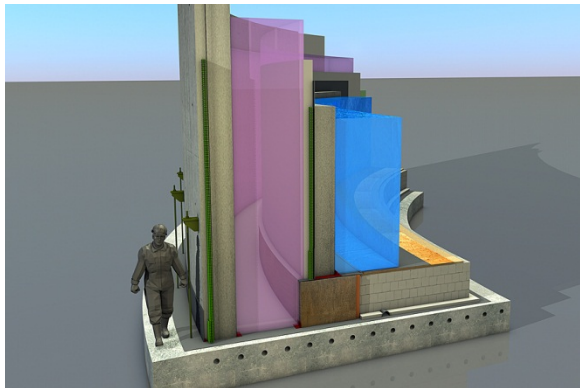


Fig. 4, Cut-away section at the base of the C^3T LNG storage system. Note the precast concrete walls used for both the primary and secondary containments. The annular space between the primary and secondary containment walls is filled with loose perlite insulation.

The secondary containment is similar to the primary containment in principle, except that the secondary containment supports the roof structure as shown in Figure 5 and incorporates exterior hold downs connecting the wall to the foundation to resist the uplift created by internal tank pressure. The bottom plating of the secondary containment is directly supported on the tank foundation slab. The foundation slab contains heating elements that are used to heat the slab to a level that prevents freezing of the foundation subgrade soil over time.

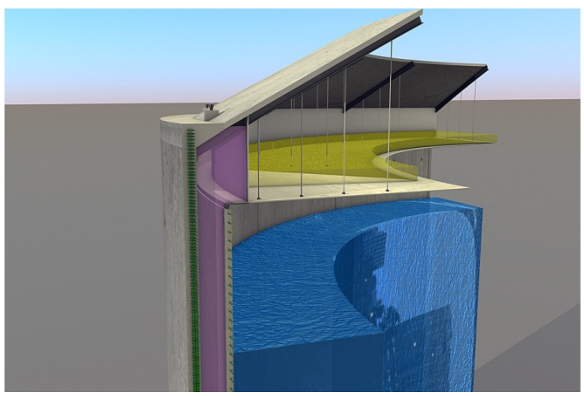


Fig. 5, Cut-away section at the top of the C^3T LNG storage system. Note the concrete roof structure that is part of the secondary containment and the suspended deck that supports the thermal insulation over the stored LNG in the primary containment.

UNIQUE APPLICATION OF CARBON STEEL LINER MATERIAL

The use of thin carbon steel plating for most of the wall liner material, especially for the primary containment, which operates at LNG temperatures, is unique as carbon steel is not rated by most codes for performance at cryogenic temperatures. It has been proven in practice and by test that by prestressing this thin (5 mm) [0.197 in.] liner steel plating to maintain it in compression for operating conditions, it will provide the necessary performance as a supplemental liquid barrier to the concrete wall. The concrete wall itself is in direct contact with the stored LNG and is designed to be liquid tight.

APPROACH TO ACHIEVING CONSTRUCTION QUALITY

Achieving the necessary constructed quality is always a challenge in a conventional technology LNG storage tank. The primary containment involves the welding of very thick 9 percent nickel steel plating, which is inherently difficult to weld. The cast-in-place 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 post-tensioning ducts, making successful placement and consolidation of the concrete difficult.

In contrast, the C^3T wall panels are relatively lightly reinforced, contain primarily pretensioning strands, and are cast flat, using the composite steel liner as the bottom form for casting the wall elements. Achieving the necessary concrete placement and consolidation in elements cast in this manner is a reliable operation. The primary containment wall elements are 356 mm (14 in.) thick at the base, tapering uniformly to 178 mm (7 in.) at the top. The secondary containment wall elements are a constant 457 mm (18 in.) in thickness. The element width was selected to maintain the full-height panel weights at approximately 100 tonnes. All C^3T welding is of thin plates, typically 5 mm (0.197 in.) thick and most welding is fillet welding of mild carbon steel (ASTM A516, Grade 65) to mild carbon steel.

A challenge in the design of such large and slender wall elements is to develop handling and erection support methods to assure that the temporary handling, transport, erection, and erection support conditions do not become the controlling design condition for the elements. The approach to these issues is discussed in some detail below.

UNIQUE BEHAVIOR OF LONG SLENDER PRECAST CONCRETE WALL PANEL ELEMENTS

The tank design has stringent requirements on the containment walls under operational loading to maintain gas-tightness throughout operations. Internal stresses that are built up during construction are caused by constraints, such as during cool-down of the structure, typically does not affect the global strength of the structure, but superposes directly to the stresses from external loads at the operational level. Procedures must be followed to assure that this does not lead to stresses in excess of the allowable levels. In regards to the tank, the issues of highest concern are potential excessive stresses in the steel liner and its welds that could lead to brittle rupture or buckling of the liner membrane. Similarly, limiting the stress level of the carbon steel reinforcement to below that which can rupture the reinforcement and compromise its function to control crack widths, and control of high-tensile stresses in concrete that can cause premature cracking is required.

Internal stresses are a typical design concern for the construction industry that battles to control the behavior of concrete slabs and beams that can crack due to concrete shrinkage and thermal contraction. For structures with large precast elements, such as the wall elements used in the C^3T, internal stresses not only can build up from the differential thermal and mechanical characteristics of its components, but it can also be built into the elements through external forces applied during construction. Hence, construction procedures, such as the panel production method, handling, storage transportation, erection procedure, wall integration method, and post-tensioning sequencing become design considerations.

The key issue for the precast wall panels is that during the wall integration, adjacent panels have to be aligned relative to one another within millimeters in order to weld the liner from two adjacent panels. A kink in the liner would cause a local stress concentration and could cause the thin liner plate to be prone to local buckling during the circumferential post-tensioning operation. Though the panels are flexible at their large height/thickness aspect ratio of over 100:1 and seem easy to adjust, an uncontrolled adjustment could introduce unwanted stresses that remain within the structure as internal stress state. To minimize these stresses, the panels must be fabricated and handled so that, once erected, adjacent wall panels show minimum differential deformations and that, if panels need to be adjusted, the adjustment procedure is well controlled and designed to only burden the panel with acceptable stress levels.

DIFFERENTIAL PANEL DEFORMATION

Prestressing, post-tensioning, creep, and shrinkage deform the wall panel from its original shape given by the prestress bed to the final shape once the panel is in its installed position ready to be integrated. Due to construction tolerances and material variations, individual panels will deform differently, even if they were manufactured in the same prestress bed. The wall panels for the C^3T are prone to differential camber as 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.

Even though in the C^3T design, the liner is not considered to be structural for the ultimate strength calculations, the liner contributes to the stiffness of the wall panel section. The one-sided liner shifts the center of stiffness away from the centerline of the wall, so that any change of material/section stiffness can introduce a small local curvature in the section, which can add up to a significant camber over the length of the wall element. This change of material/section stiffness can be due to construction tolerances, variations in material characteristic, or variations in construction conditions.

Construction tolerances that are most likely affecting the curvature of the section are for variations in the location of the prestress steel, the thickness of the concrete section, the thickness of the liner, the prestress force, and the location of the mild reinforcement. Variations in material characteristics that influence the curvature relate in particular to variations in concrete strength and stiffness. Variations in construction conditions relate primarily to the creep and shrinkage behavior of the wall concrete and thus depend on the concrete age at form stripping, the duration and condition of concrete curing, and the concrete age at wall integration.

Furthermore, thermal gradients can introduce unanticipated curvature, such as a high concrete setting temperature that introduces a residual tension in the steel liner, once the wall panel has cooled off, or a high thermal gradient through the wall section due to sun exposure during wall installation.

Differential deformations of panels can also be caused by different handling of individual panels. For example, if some panels are bunked laying on their side or with bunk supports that impose a different creep or shrinkage deformation on a panel compared with others.

It is essential that the construction parameters discussed above are understood, considered in the design, and controlled on the construction site to minimize differential wall deformations and thus the potential for unwanted and potentially significant internal stresses.

In order to understand the significance of small variations in construction tolerances and variations of material properties on the behavior of these panels, a series of parametric studies were performed to determine stresses caused by these variations. This background was used in developing allowable construction tolerances for both dimensional tolerances 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 simply jack the edges of the adjacent panels against each other to force them into the same plane. However, if the camber is corrected at only a few discrete points, the correction can introduce unwanted localized stresses that may lead to concrete cracking or high-internal stresses. On the other hand, if the correction is done at too many locations along the wall height, then the process becomes difficult to control and the panels might be overcorrected, which again could lead to high-internal stresses.

At a length of over 30 m (100 ft), the individual tank panels will need intermediate supports over their height to be sufficiently secured against wind during construction. The use of multiple temporary support points will make their support statically indeterminate and introduces the potential that internal stresses can build up to large reaction forces. Once the erection shoring is removed, the reaction forces disappear but the internal stresses, through at a new equilibrium, remain in the panel. Too many intermediate support points also make it difficult to align adjacent wall panels relative to each other as discussed above, and it becomes more appropriate to adjust the panels individually against the shoring system. During the adjustment of the wall panels, the effects of other, external forces have to be considered, such as wind and thermal gradient, across the wall thickness due to sun exposure that can introduce significant reaction forces and thus high stresses in the panel.

It is clear that the wall shoring, camber adjustment, and wall integration procedure does not only represent an independent construction condition to be considered during shop drawing design but also has an inherent influence on the tank behavior during operation. Therefore, these procedures have to be quantified during the design of the fully integrated structure.

METHODS TO PREVENT AND CONTROL INTERNAL STRESSES

The differential camber of the panels can be addressed by defining clear limits for construction tolerances and material property variations, which are considered in the design process and met on the construction site. Parameters that are most influential may need to be specified at a higher than industry standard tolerance. For example, while most geometric tolerances can be considered in the design to be within the acceptable values per codes and standards, the maximum allowable camber for the wall might have to be limited to l/700 instead of the Prestressed Concrete Institute (PCI) recommended l/360. Similarly, variations in material characteristics can be addressed by design, but their limits for construction should be stated in the specification. Additional requirements that have to be addressed in a specification in order to control differential camber would refer to concrete setting temperatures, curing cycles and methods, and bunking locations and dimensional tolerances. Critical parameters are specifically addressed in the panel fabrication and erection quality control programs.

The control of the internal stresses from panel camber adjustment can be addressed by either a performance specification that limits the additional stresses due to the adjustment forces or by including an adjustment procedure in the tank design and specifying the procedure with its requirements and limitations.

DESIGN FOR CONSTRUCTION PERIOD LOADING

The length and slenderness of the panels creates the requirement to carefully plan handling, transportation, and erection procedures to avoid cracking of the panels and the above-discussed build-up of internal stresses. The formwork has to be designed to produce panels within tight camber and levelness tolerances. Hence, the formwork has to be stiff and not subject to deformations from differential settlement, thermal exposure, or the prestressing procedure. At a length of more than 30 m (100 ft), even the prestress strands will have to be supported at intermediate points in order not to drape significantly in spite of the high prestress load in the strands. The formwork has to allow the panel to shorten during the prestress release and form stripping process.

It is difficult to accurately measure the as-built camber of the flexible panels until the panels are positioned vertically. Thus, early as-built camber measurements are necessary and the processes that create camber must be carefully controlled, to avoid a panel that might not be recognized to be out of camber tolerance until it is in its erected position.

The flexible panels need multiple bunking positions during storage and are prone to long-term deformation or cracking under differential settlement of the bunks, unless the panels are stored on their sides. The influence of sun exposure has to be understood or reduced as thermal gradients could lead to cracking of the panels.

Multiple panel support positions cannot be provided during transport unless a strong-back is mounted to the panel. But panels can be transported in a tilted position to provide horizontal stiffness without a strong-back. Stability and potential vibration have to be carefully considered during the transportation planning in order to avoid cracking.

The panel tilting and erection procedure are sensitive to wind. Construction winds, thus, have to be considered in the planning of all handling procedures and monitored on the site. The panels can be tilted with the use of a tilting table or by a crane with the use of an equalizing pulley system or a strong-back. 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, is a concern. Preliminary analysis suggests that a set-down panel not connected to the shoring points yet could sustain winds up to 40 km/h, (25 mph) if plumb. However, even at low winds, the panel might crack if tilted more than 2 degrees, thus the erection procedure must control the extent of panel tilt.

As discussed above, the panel has to be attached to the shoring in a way so that the panel is within the erection tolerances, does not crack due to wind or sun exposure, and does not build up excessive internal stresses. Once multiple panels are erected and adjusted, the panels can be joined. As the integrated wall evolves into a cylindrical shell and gains stability, the shoring towers, except at the corner panels, can be removed. After all panels have been joined, the shoring can be removed entirely and the wall is ready to be prestressed horizontally. For the erection of the secondary-containment wall, the panels can be directly shored against the finished primary-containment wall.

DESIGN OF PRIMARY TANK

After the tank has been erected as described above, the primary tank will be circumferential prestressed, the floor plate will be welded to the annular plate, the primary tank will be subjected to hydrostatic testing, purged and cooled down, and filled with LNG. Further, during operation, the primary tank may be subjected to seismic loads and accidental fire. The secondary tank may in addition be subjected to pressure and vacuum testing, accidental hydrostatic spill effects, and wind. The design of secondary tank is similar to that for the primary tank and not addressed herein.

CIRCUMFERENTIAL PRESTRESSING

The primary tank will be circumferential prestressed to provide sufficient circumferential precompression such that when the tank later is subjected to hydrostatic pressure from testing water or LNG, the initial precompression is larger than the later applied tension loads. When performing the design, it is important to account for the friction load occurring between the primary tank wall base and the low-friction sliding surface above the compressed wood structural insulation supporting the wall (see Figure 4). This friction force is developed when the primary tank wall base slides towards the center of the tank while being circumferential prestressed. The annular plate is not welded to the floor plate at this stage to avoid introducing compression stresses and potential buckling of the floor plate and floor plate single welded joints. The friction loading reduces the circumferential prestressing in the lower portion of the wall and introduces bending moment in the lower portion of the tank wall that causes vertical tensile stresses on the inside of the tank wall and vertical compressive stresses on the outside of the tank wall (in the carbon steel liner).

SHRINKAGE AND CREEP

Shrinkage and creep induced loads must be accounted for when designing the primary tank. While both shrinkage and creep essentially stop when the tank is at operating cryogenic temperature, the tank is designed assuming that ambient temperature creep and shrinkage continue throughout its entire service life.

HYDROSTATIC TESTING

After the tanks are circumferentially prestressed, the annular plate is welded to the floor plate creating a watertight inner container. The primary tank is then subjected to hydrostatic testing where test water corresponding to 1.25 times the product load is applied to the primary tank. The test load causes circumferential tensile stresses in the primary tank and vertical bending stresses in opposite direction of that caused by wall base friction due to circumferential prestressing. The hydrostatic pressure caused by the LNG is similar to that of the hydrostatic water testing pressure.

THERMAL EFFECTS DURING COOL-DOWN

After completion of hydrostatic testing, both the inner tank and the annular perlite insulation space surrounding the primary tank is purged to a final oxygen level of 8 percent or less by volume, and dried such that all standing water is removed. Thereafter, the tank is cooled down in preparation to fill the tank with LNG. For a concrete primary tank, a temperature drop between 0.6°C/hr to 1.3°C/hr (1.1°F/hr and 2.3°F/hr) is sufficiently slow to avoid overstressing the primary tank due to the transient temperature differences in the tank wall during the cool-down period. At the completion of the cool-down, the temperature in the primary tank has been reduced from ambient temperatures to cryogenic temperatures with the outside of the primary tank being about 0.6°C to 1.1°C (1°F to 2°F) warmer than the inside of the primary tank causing small permanent stresses in the tank. The difference in thermal expansion coefficients between steel and concrete also causes permanent stresses due to the large temperature change the materials go through while being cooled down from ambient to cryogenic temperatures. This is accounted for in the design.

SEISMIC EFFECTS

The primary tank and the secondary tank are designed for Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE). The OBE is the maximum earthquake level a structure is expected to withstand with no damage and remain in an operable condition during and after an OBE event. The probabilistic return period for an OBE event is 475 years. The SSE is the maximum earthquake level a structure is expected to withstand with permanent damage but without a loss of overall integrity or containment during and after the SSE event. The probabilistic return period for an SSE event is 2475 years.

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 very much affected by an external fire. The secondary tank will need to be designed for external fire effects as required by project and regulatory requirements.

CONCLUSIONS

The work done to develop and qualify the C^3T concept LNG storage tank 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. The use of modern precasting techniques and prestressing methods to produce and integrate the tank wall elements provides the potential to more economically achieve the high levels of constructed quality necessary for these facilities.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Chevron Energy Technology and ConocoPhillips for their support of the overall C^3T development program.

REFERENCES

American Concrete Institute (ACI) 318 “Building Code Requirements for Structural Concrete and Commentary”

ACI 376 “Code Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases and Commentary”

ACI Journal May-June 2007 technical paper “Liquefied Natural Gas Storage: Material Behavior of Concrete at Cryogenic Temperatures” by Neven Krstulovic-Opera

American Petroleum Institute (API) 620 “Design and Construction of Large, Welded, Low-Pressure Storage Tanks”

Code of Federal Regulations 49 CFR Part 193 “Liquefied Natural Gas Facilities: Federal Safety Standards”

National Fire Protection Association (NFPA) 59A “Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)”