

Design and Construction of a Cryogenic LNG Tank on Permafrost

Precast concrete panels provide an enclosure for steel tank construction

by Sanjay S. Mehta and Eric T. Reaman

Fairbanks, AK, has a unique geology of discontinuous permafrost with an active layer. While permafrost can extend to a depth of 275 ft (84 m), it may also be absent near or under water bodies. Further, the upper few feet (top meter) of soil, known as the active layer, may thaw and refreeze each year. The associated variability creates challenges for civil engineering structures, as is evident from the roller coaster ride one experiences while driving the region's roads during summer months—some road segments subside due to thawing, while other segments remain relatively stable.

Fairbank's arctic climate creates additional challenges for residents and businesses. Many residents burn wood/coal to stay warm, and this results in some of the worst air quality in the United States. As part of a greater effort to improve the air quality, more than 1100 residential and commercial customers in Fairbanks now use natural gas for heating. The gas is distributed by local utility Fairbanks Natural Gas (FNG) through about 70 miles (113 km) of an underground distribution piping system.

But that system comprises only the final leg of the journey for the natural gas. The Fairbanks region lacks a proven source of natural gas, and there is no gas pipeline to supply gas from producing areas. Therefore, FNG purchases natural gas from the Cook Inlet area. There, the gas is condensed into liquefied natural gas (LNG), and the LNG is trucked to two temporary storage sites in Fairbanks before being heated to reconvert it to gas for distribution. Until recently, the storage facilities in Fairbanks had a total storage capacity of only about 340,000 gal. (1,290,000 L) of LNG—enough to provide for 5 days of supply during peak

demand. In December 2017, after many years of planning to increase the gas supply, FNG awarded an engineering, procurement, and construction contract to Preload Cryogenics for construction of a 5,250,000 gal. (19,900,000 L) full-containment LNG tank.

The region's very limited construction season, combined with permafrost conditions, ruled out traditional LNG tank design and construction methods. The selected solution by FNG was to construct a 109 ft (33.2 m) diameter and 82 ft 9 in. (25.2 m) high inner steel container with a precast, prestressed concrete outer container (115 ft 5 in. [35.2 m] in diameter and 88 ft 3 in. [26.9 m] high) supporting a structural steel roof dome. Both the steel and precast containers were designed to be founded on a common cast-in-place concrete mat slab supported on structural fill. The contract was awarded to Preload Cryogenics, which, in turn, coordinated with American Tank & Vessel (AT&V) for construction of the inner container and steel dome. Global Engineering Services served as the Structural Engineer of record for the project and sought professional services of other firms for steel work as required to meet the project deadline.

This article describes the unique challenges encountered during design and construction of the concrete foundation and outer wall as well as the team efforts used to arrive at solutions to each challenge. It is noteworthy that this is the second precast, prestressed outer concrete full-containment LNG tank with a sliding base constructed since publication of the first edition of ACI 376 in 2011.¹ The first such structure, also built by Preload Cryogenics (as a subcontractor to AT&V) and designed by Global Engineering, was completed in 2017.

Foundation Options

Historic climate data for the Fairbanks area show that the average air temperatures have increased over the past 60 years. They are projected to continue to increase, albeit at a slower rate, for the next 30 years. The impact of this trend on ground temperatures and permafrost conditions played a major role in the selection and construction of a foundation system. Three foundation systems were evaluated during the initial phase of the project by Global Engineering.

Elevated slab

One option was an elevated concrete slab supported on helical piles, providing an air gap below the slab. This is a simple yet effective and proven method of isolating a cryogenic heat sink from the ground surface, and it provides the advantage of eliminating the need for an underfloor heating system. Even in cold regions, the thermal gradient from the soil to the tank will result in water vapor migration from deep soil layers. Water vapor will freeze, causing frost heave unless a sufficient air gap is provided to prevent cold LNG temperatures from penetrating the soil surface. This can be exacerbated during summer months due to thawing of the active layer and the availability of surface runoff water.

As per the recommendations developed by the project's geotechnical engineer, Golder Associates, installation of helical piles required predrilling of an oversized hole in the ground, installing the piles to the specified depth, and filling the holes with a sand slurry. After installation of the piles and slurry, it would be necessary to ensure that the piles were maintained within the design tolerances until "freezeback" of the bond between the slurry and the pile. The construction of the concrete slab could start only after achieving adequate freezeback of the bond to ensure that the tank settlement would be within the specified limits during the operating life.

Like all other options, this option would require installing an active, as well as a passive, cooling system to ensure that the ground temperature remained within the specified range to prevent formation of a talik—an area of unfrozen ground surrounded by permafrost. In the final analysis, it was realized that this option would extend the construction schedule to another construction season (including another winter) because the piles could be adequately installed only during warm periods and freezeback could be adequately achieved only during cold temperatures. Furthermore, it was necessary to avoid lateral movement generated by the active layer before freezeback bond was achieved. Lastly, for the air space to remain effective during the operating life of the tank, it would be necessary to maintain the perimeter of the elevated slab free of snow and ice buildup. In the arctic weather of Fairbanks, snow buildup of 4 to 6 ft (1.2 to 1.8 m) is very normal. Thus, removal of snow and ice from the tank foundation (at about 6 ft aboveground) on a regular basis during winter months would add maintenance costs that would need to be included in the final analysis.

Separated concrete slabs

A second option was to construct two concrete slabs separated by 3 ft (1 m) tall concrete columns. Because the upper slab supporting the LNG tank would be separated from the bottom slab on grade by an air gap, this option would also avoid the need for a foundation heating system. All frost-susceptible silty sands near the surface would need to be replaced with compacted, non-frost-susceptible (NFS) gravel prior to construction of the bottom slab-on-ground.

Although schedule-effective, this option was not found to be cost-effective. Furthermore, removal of column forms posed a challenge, unless the columns were constructed and allowed to achieve the required strength prior to top slab placement. Like the first option, this option would also require removal of snow and ice buildup around the periphery of the tank during winter periods. Most importantly, short and stubby columns are prone to brittle shear failure in a seismic event, and Fairbanks is in a zone with high seismic risk and with frequent small-magnitude earthquakes. The site-specific response spectra based on a probabilistic seismic hazard analysis specified a short period acceleration of 1.0 g for a safe shutdown event. The risk of brittle shear failure in the short and stubby columns was deemed unacceptable.

Mat slab

The third option considered was the construction of a mat slab-on-ground. This option would require installing a foundation heating system within the slab to prevent the development of very cold temperatures within the subgrade. However, the cost of a foundation heating system would be partially offset by the elimination of the need for snow and ice removal around the tank periphery. Furthermore, the owner's engineer, CHI Engineering, was able to design a cost-effective system that would make use of boil-off gas from the tank to provide the heat energy necessary for the foundation heating system.

To eliminate the potential for settlement and frost heave in the active layer, Golder Associates recommended the replacement of the upper 14 to 17 ft (4.3 to 5.2 m) of ice-rich silty sand with NFS gravel. The excavation of this soil would also facilitate installation of an active, flat-loop thermosyphon system (which could be converted to a passive system in the future) designed by Arctic Foundation, Inc. (at two different levels), along with the installation of an insulation system during the fill process. Most importantly, it was possible to carry out the excavation and fill work during the winter months, thereby allowing construction of the concrete slab in early spring. In the final analysis, this option was found acceptable to all parties involved and resulted in significant cost and schedule advantages. Modeling of the ground temperature and design and construction of the subgrade and the active/passive cooling system are discussed in References 2 through 5. Design and construction of the concrete slab-on-ground is discussed in the following paragraphs.

Mat Design and Construction

Several design iterations were required to arrive at an optimum thickness of the ring footing and mat slab. Important design variables considered included control of cracking during an LNG spill event, reducing flexural tension during normal tank operation based on steady-state temperature distribution of the tank-foundation system and vertical loads; control of thermal and shrinkage stresses during and after the concrete placement; stability of the foundation system during specified operating-basis earthquake, safe-shutdown earthquake, and aftershock earthquake events; and near uniform load transfer to subgrade during operating conditions.

ACI 376-11 was used as the basis for design and analysis of the foundation system. Soil-structure interaction effects were included in the foundation model and seismic analysis. Stability of the foundation system was also checked per the requirements of API 620.⁶ Because construction efforts of the entire project were in lockstep with design efforts, it was possible to estimate the ambient temperature conditions during the concrete placement. Hence, the entire thermal time-history starting from concrete placement up to various design cases was considered in the foundation design. Figure 1 shows the typical cross section of the mat slab. The top layer of reinforcement would be subjected to cryogenic temperatures in case of an LNG spill and, hence, reinforcing steel rated for cryogenic temperature was specified for those bars. Optimum design resulted in a 3 ft (0.9 m) thick concrete floor cast monolithically with a roughly 5 ft (1.5 m) thick ring footing. Minimum floor reinforcement was provided as required by ACI 376.

Foundation design was based on a 28-day concrete strength of 4500 psi (31 MPa). To control shrinkage stresses, shrinkage tests of concrete mixtures were performed as per ASTM C157/C157M, “Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete,” to ensure that drying shrinkage strain in the laboratory was less than 0.035%. Polymer microfibers (3/4 in. [19 mm] long) were also included in the concrete mixture to help reduce shrinkage. Air entrainment of 6% was specified to improve

resistance to cyclic freezing and thawing, and a maximum water-cement ratio (*w/c*) of 0.42 was specified.

The slab was placed in April 2018, after 3 months of excavation and replacement of the subgrade soils, installation of the flat-loop thermosyphon system, and placement of the formwork and reinforcing bars. Although April is typically the start of spring in Fairbanks, it was necessary to implement the cold weather concrete recommendations of ACI 306R-16⁷ because temperatures were expected to be below 40°F (4°C) for the entire month. The process was further complicated by the fact that it was necessary to heat the top of the prepared subgrade before starting the placement while also ensuring that this heat did not travel too far down into the subgrade to disturb the permafrost. Hence, heat was supplied to the top surface for 12 hours prior to concrete placement while the flat-loop thermosyphon system was used to supply cold temperatures continuously at the bottom. Prior to starting the concrete placement at 4:30 a.m., the temperature of the subgrade was measured at several points. The temperature of the concrete from each ready mixed concrete truck was also recorded to make sure that concrete temperature at the time of placement did not exceed 45°F (7°C).

Based on availability of concrete, it was decided to place the 1800 yd³ (1380 m³) concrete mat in one continuous operation, thereby eliminating the need for a construction joint. The concrete was sourced from the three major concrete producers in Fairbanks to ensure an uninterrupted supply. Two spare concrete pumps were also provided to account for unforeseen pump issues. The placement was divided into six sections, with one concrete pump for two adjacent sections. This method avoided cold joints.

Because of the fast pace of this design-build project, design engineers, the flatwork concrete contractor, the testing laboratory, the concrete producers, and the owner’s quality assurance team coordinated and effectively communicated with each other prior to and during the concrete placement to ensure that the design concepts were correctly implemented. The entire concrete placement operation, including finishing

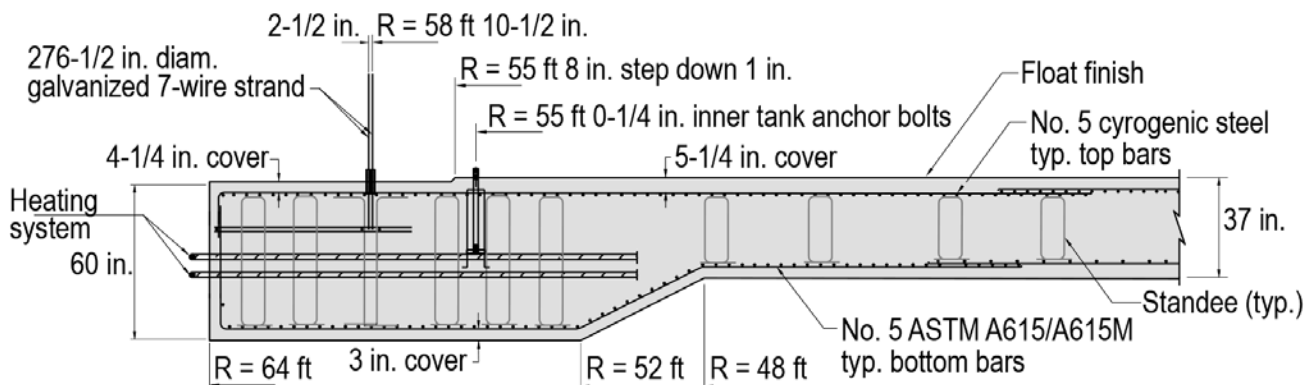


Fig. 1: Typical cross section, showing floor-footing transition and reinforcement (Note: 1 in. = 25 mm; 1 ft = 0.3 m)

to the specified tolerance, was completed in about 22 hours.

The entire surface was covered with insulating blankets immediately after finishing operations were completed. Heat of hydration, especially within the 5 ft thick section, was an important construction consideration because the temperature at both the top and bottom surfaces would be much lower than the maximum anticipated temperature at the center of the slab. A maximum permissible thermal gradient of 45°F was assumed in the design process. To ensure compliance with this design assumption, cooling pipes were installed in the 5 ft thick circumferential section. Thermal sensors were installed at the top, bottom, and center at four locations, and temperature was continuously monitored. Water trucks were made available to circulate cold water if it became necessary to cool the concrete.

Figure 2 shows the thermal history during the first 16 days after placement. Figures 3 through 6 show concrete placement and finishing operations. Insulating blankets were kept on the surface for 21 days to avoid thermal shock.

Precast Concrete Panel Design, Transport, and Erection

The contract documents required substantial completion of

the project in less than 18 months after the awarding of the contract. This period included all of the engineering design; approval of drawings by the Alaska Fire Marshall; and construction time for the full-containment tank, including excavation work. To meet the substantial completion date, it was necessary to complete the excavation and fill work, place the active and passive cooling systems, place the floor and foundation, and construct the outer concrete tank within 7 months of receiving the notice to proceed.

The uncertain weather conditions in the Fairbanks area made it necessary to minimize field concreting activities, so the only feasible option for the outer wall construction was to use precast concrete panels produced off-site, transported to the project site, tilted to the vertical position, and set on the prepared concrete foundation at predetermined locations. Once all panels were erected and partially prestressed in the circumferential direction, the completed enclosure allowed construction of the inner steel tank in a protected and heated space.

The precast panels included steel liner on the outer face, and they were longitudinally pretensioned. To our knowledge, the design of such a system is not fully covered in any design construction code; however, ACI 376-11 and NFPA 59A⁸

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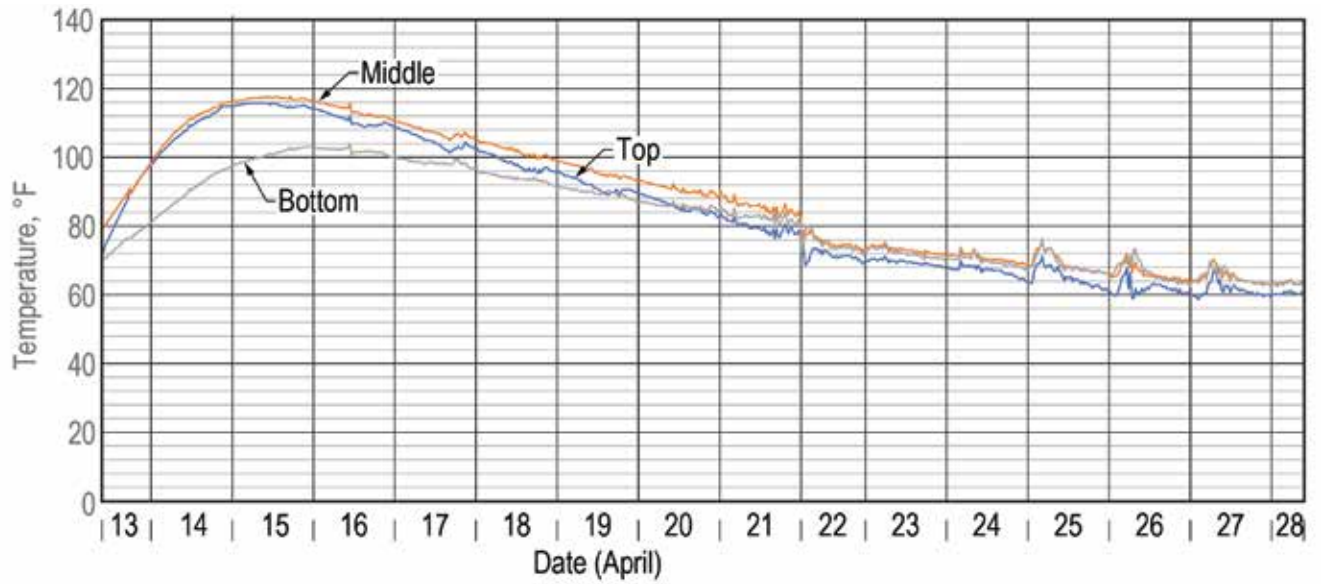


Fig. 2: Footing temperature variation for 16 days after slab placement (Note: °C = (°F – 32) / 1.8)



Fig. 3: View of floor-footing reinforcement



Fig. 4: Heating of reinforcement and top of subgrade 12 hours prior to placement

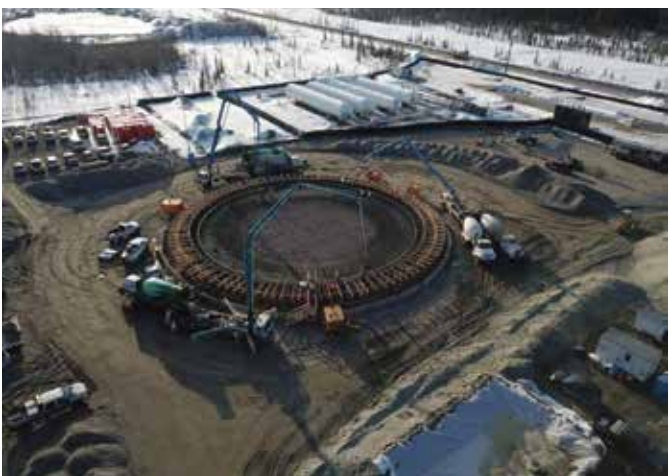


Fig. 5: Arrangement of three concrete pumps during placement



Fig. 6: Placing, vibrating, and finishing of concrete slab

specify performance criteria for this type of construction.

Important design considerations include evaluating creep and shrinkage of the concrete relative to the steel liner; ensuring strain compatibility at the interface between the concrete and the steel; transferring of prestress from the concrete section to the steel plate to ensure that the liner is loaded in compression; buckling of the steel liner; treating joints between the precast panels; controlling the depth of concrete cracks in response to a sudden thermal shock in case of an LNG spill; and developing the strength required to resist internal pressure plus LNG static/dynamic load in case of LNG spill and subsequent aftershock earthquake event.

It is also very important to consider stresses and deflections induced in the precast panels during transport, tilt up, erection, and bracing. Construction sequence considerations played a critical role in the precast panel design and controlled some aspects of the final design.

The construction sequence included the installation of the skirt-sketch plate assembly with slide bearings on a prepared concrete foundation as shown in Fig. 7. After the panels were tilted in vertical position and set in position on top of the skirt-sketch plate assembly, the outside face of the liner was welded to the top of the skirt plate. After setting the panels, the joints



Fig. 7: Installation of skirt-sketch plate assembly prior to precast panel erection

were shotcreted to complete the outer tank cylinder. The panels were then circumferentially prestressed with multiple layers of 0.192 in. (4.8 mm) high-strength ASTM A821/A821M wires, with each layer encapsulated in shotcrete prior to application of the next layer. This process of wire-winding is very well established and described in ANSI/AWWA D110-04⁹ and ACI 372R-13.¹⁰

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The project's 43 precast panels were fabricated by Alaska Sand and Gravel, Anchorage, AK. The steel liner plates were fabricated with a radius matching the enclosure radius, and the plates included headed studs to ensure composite behavior. Panels were 10 in. (250 mm) thick, 8 ft (2.4 m) wide, and 88 ft 3 in. (26.9 m) long. The concrete was specified to reach 7000 psi (48 MPa) at 28 days. Vertical prestressing was released as soon as the panel achieved a minimum strength of 4500 psi. Casting operations commenced in March 2018, and one panel was cast every day. The precaster used a heated tent to protect the panel concrete from cold weather and to provide steam curing for the panels. The precast panels were ready for transport and erection by the time the concrete foundation was cured. The simultaneous construction of precast panels and concrete foundation was instrumental in achieving the 18-month target schedule for substantial completion.

The panels were trucked from the precasting yard to the jobsite in early June 2018 (immediately after road restrictions

were lifted). The trailer beds were designed to control panel deflection and bowing during the 10-hour transport time. Once at the jobsite, the panels were inspected for cracking, excessive deflection, or any other kind of distress. The panels were lifted from the trailers upon arrival and set on the concrete foundation after performing the "tilt-up" operation. Typically, five to six panels were erected every day. All precast panels were set in position over 9 working days, starting from delivery of the first panel at the project site on June 11, 2018. Figures 8 through 11 show panel erection and shotcreting operations.

Joint welding and shotcreting, as well as circumferential prestressing, were completed over the following 75 days, and the site was handed over to AT&V for construction of the inner tank on September 4, 2018.

A steel dome and aluminum deck for roof insulation were fabricated by AT&V at the jobsite while precast panels were erected, and circumferential prestressing was performed. AT&V lifted and placed the dome with the aluminum



Fig. 8: Panel on trailer bed at jobsite



Fig. 9: Panel erection and bracing operations



Fig. 10: Shotcreting of joints between precast panels



Fig. 11: View of outer concrete tank after completion of circumferential prestressing

insulation deck immediately after circumferential prestressing was completed.

It was possible to complete this entire operation within 7 months due to close coordination between the owner, engineer, contractors, and quality assurance personnel. AT&V started construction of the 9% Ni steel inner tank in August 2018. The inner tank was successfully hydrotested in May 2019, and the outer tank was successfully pressure tested in June 2019. The inerting and purging operations were completed in August 2019. The tank cool down to cryogenic temperature was completed by the end of November 2019, thereby meeting the 18-month target of substantial completion. The tank is in operating condition and is holding the minimum amount of LNG until the balance of plant work is completed.

Final Thoughts

Publication of ACI 376 in 2011 has standardized the design and construction of precast, prestressed concrete walls with a sliding base for full-containment LNG tanks. This technology provides both cost- and schedule-effective alternatives to conventional cast-in-place concrete outer walls and cryogenic steel inner tanks. Indeed, it is possible to comply with a very restrictive design and construction schedule because precasting of the concrete walls can be done simultaneously with the placement of the concrete floor and foundation.

Lastly, the contributions of the following firms not specifically listed in this article are also acknowledged: Barter & Associates, Inc.; BBFM Engineers Inc.; Beckley Mechanical Company; Fullford Electric Inc.; Great Northwest, Inc.; Homestead Drilling Company; Rady Concrete Construction LLC; R.A. Hoffmann Engineering P.C.; and StrongMotions Inc.

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Note: Additional information on the ASTM standards discussed in this article can be found at www.astm.org.

Selected for reader interest by the editors.



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