COMPOSITE CONCRETE CRYOGENIC TANK (C³T): A PRECAST CONCRETE ALTERNATIVE FOR LNG STORAGE

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ABSTRACT

Traditional LNG storage tanks are built with significant amounts of 9 percent nickel steel and require extensive on-site welding of thick plating and a large construction area to assemble. Conventional tanks of 160,000m³ capacity can take over 34 months to construct and cost $130MM or more, depending on a variety of factors including the location of the plant. In Regasification plants and Liquefaction plant additions / expansions, the tanks can be a critical path item for commissioning.

The Composite Concrete Cryogenic Tank, C³T, is a modular design that replaces much of the 9 percent nickel steel with concrete, carbon steel, and wire wrapping, simplifying assembly, reducing material cost and speeding construction. It also introduces the ability to move a portion of the tank labor off-site. C³T was initially designed as part of a joint industry project (JIP), updating the design, construction, and application of concrete LNG tanks which were constructed without directly applicable design codes until the downturn in the LNG market in the 1980’s.

After the conclusion of the JIP, Chevron continued to develop the C³T concept. This work included evaluation using Chevron’s internal Technology Qualification Program (TQP), a constructability review, laboratory testing, and development of a construction demonstration plan. As a result of this work, Chevron is expected to receive endorsement from a third party accredited certification institution for Fitness for Service for C³T.

This presentation will offer Chevron’s perspective on C³T, explain the benefits and risks of this technology, and provide an update on the progress made after the conclusion of the JIP and introduction of the new American Concrete Institute (ACI) code for design and construction of concrete structures for containment of refrigerated fluids, ACI-376. Comparisons will be made between C³T and the traditional 9 percent nickel steel LNG storage tanks.

INTRODUCTION

The main objectives of this paper are to introduce the Composite Concrete Cryogenic Tank (C³T) as an advanced modular LNG storage tank technology, describe the technologies involved, document the development path, and discuss the benefits and risks of the technology. Some benefits discussed include cost and schedule savings, the ability to move labor off-site, and the flexibility to match the design of the tank to the needs of the specific project; and some of the risks discussed include the handling of the precast wall panels, and others related to the uncertainties associated with not having yet built the first C³T. This paper also serves to dispel some of the perceived risks such as questioning if concrete can function as a suitable containment material for LNG. Several examples of concrete tanks in service will also be given.
While this paper primarily provides a technical description of C\textsuperscript{3}T and discusses some of the technical benefits and risks, the lessons learned outlined in the paper may prove to be important not only to further the advancement of the C\textsuperscript{3}T concept, but may serve as lessons to help advance other potential improvements and technologies within the LNG industry.

A glossary has been provided at the end of this paper for readers who may not be familiar with some of the concrete industry terms used herein.

**THE COMPOSITE CONCRETE CRYOGENIC TANK - C\textsuperscript{3}T**

The C\textsuperscript{3}T technology represents the adaptation of LNG storage technology developed in the past to the needs of today – at a larger scale. The designs and construction methods involved differ somewhat from the LNG storage tank designs and construction methods in most common use today. Because of this, the C\textsuperscript{3}T technology has been the subject of design and analysis study to confirm desired behavior and is progressing through the Chevron Technology Qualification Process (TQP).

**The C\textsuperscript{3}T Technology**

C\textsuperscript{3}T is a new design for bulk LNG storage tanks. The C\textsuperscript{3}T approach is a full-containment design that reduces both the required amount of 9% nickel (9\%Ni) steel and the associated critical heavy plate field welding contained in the current best practice design by approximately 70%.

The C\textsuperscript{3}T design uses precast, vertically prestressed concrete panels to construct both the primary and secondary biaxially prestressed containment walls. The use of state-of-the-art concrete precasting technology was selected for C\textsuperscript{3}T for the following reasons.

- The worldwide precast industry is a unique sector of the heavy construction industry. While overall heavy construction industry productivity has remained flat or declined in recent years, the productivity of projects involving precast concrete continues to improve. Because of this it is judged that further improvements in quality, cost and schedule performance are more likely when employing precast technology than with the current on-site construction intensive approaches to tank construction.
- The precast concrete industry leads the heavy construction industry in its ability to produce large scale elements to high quality standards.
- The ability to cast the precast wall panels in the horizontal position onto a liquid/vapor tight carbon steel barrier as flat elements provides significant safety, quality, and overall cost benefits.

Both primary and secondary containment walls have a thin (5 mm) carbon steel liquid/vapor barrier on their outside surfaces. Using high strength steel wire or strand protected and anchored by layers of shotcrete, wrap prestressing is applied over the steel vapor barrier on the tank wall exterior to circumferentially prestress the concrete wall. The vapor barrier on the secondary wall connects with both the roof and floor vapor barriers to provide a reliable liquid and gas tight secondary containment. The tank floors are made with welded 9\%Ni steel plate extending under the wall panels and welded to a 9\%Ni steel skirt plate which is in turn welded to the wall panel liner, making the wall bottom joint both gas and liquid tight.

The primary structural elements of C\textsuperscript{3}T LNG storage containment are shown in Figures 1 and 2 below.
Figure 1. Section at Base of C³T LNG Containment
This illustration shows both the precast prestressed concrete primary containment and the precast prestressed secondary containment. Note the circumferential wrap prestressing of tank walls combined with vertical prestressing of the precast wall elements.

Figure 2. Section at the Intersection of the Secondary Containment Wall and the Roof
It is important to note that using concrete for primary LNG containment is not new; several precedents exist throughout LNG industry history. What is novel about the C$^3$T design is building both the primary and secondary tank walls with large precast, prestressed concrete panels incorporating a thin carbon steel liner with only a small amount of 9%Ni steel used in the wall construction. The panels are prestressed (to create a state of compression in the concrete) in the vertical direction by pretensioning during the panel precast fabrication process. This not only provides strength for handling the panels during transport and erection but also combines with the effects of the circumferential post tensioning (providing a state of compression in the horizontal direction) to provide the beneficial effects of biaxial compression in the concrete wall elements.

Only the structural aspects of the C$^3$T concept differ from “conventional” 9%Ni steel full containment LNG storage tanks. The roof, process and mechanical equipment, relief systems, safety systems and control instrumentation are fundamentally unchanged between the C$^3$T designs and the baseline 9%Ni steel design. It is the intent that best industry practice and project specific requirements will be followed in the development of the process, mechanical, electrical and controls systems for the C$^3$T.

THE HISTORY OF C$^3$T

C$^3$T Development History
The C$^3$T design originated as a Joint Industry Project (JIP) in 2006. Chevron, ExxonMobil, and ConocoPhillips were the JIP’s original majority sponsors, and Chevron and ConocoPhillips continued as majority sponsors for Phase 2 of the JIP. There are also numerous engineering and construction firms (both small and large) who were minority partners, and BergerABAM Engineers managed the JIP. Chevron continued to work with BergerABAM to further develop the concept after JIP closure upon completion of the preliminary design work.

Basis of the C$^3$T Concept
The JIP’s charter was to develop a more cost-effective LNG bulk storage tank. The escalating cost of 9%Ni steel, particularly since 2006, has exceeded the cost escalation experienced by the rest of the heavy construction industry and was the primary driver behind the JIP. Various sources indicate that the cumulative LNG specific construction cost escalation since 1996 has increased by a factor of about 2 and that the annual rate of escalation has been increasing each year since about 2004. Another important driver of the JIP efforts was reducing the tank construction schedule that is usually the critical-path of LNG regasification projects.

The concept development of the C$^3$T system was focused on reducing the required quantities of LNG industry specific premium materials (primarily 9%Ni steel) and taking advantage of construction equipment, construction methods and conventional construction materials advances to result in a best practice design that would not be so directly coupled with the higher LNG specific construction cost escalation.

Tanks which employ C$^3$T-like concepts for either the primary or secondary containments were first designed and constructed in the early 1950’s, and research indicates that 19 tanks of various sizes using C$^3$T-like concepts were built to store cryogenic liquids. All of the commissioned tanks have provided successful service. No concrete LNG storage tanks have been built after the 1980’s, primarily due to four factors: (1) at that time, 9%Ni Steel LNG storage tanks cost less to construct than the all-concrete LNG storage tanks, (2) a slowdown in the number of LNG Liquefaction plants being built between 1980 and 2000, (3) a preference for single containment systems until recently, and (4) a lack of design codes for concrete LNG storage structures until 2011 (design for 9%Ni steel tanks has been addressed in much of the world by the combined use of National Fire Protection...
Association standard NFPA 59A and American Petroleum Institute standard API 620 for many years).

Members of the C³T design team visited the sites listed in Table 1 below and interviewed the current operators to confirm successful in-service operation of these LNG storage facilities.

Table 1. Tank Installations Using Technology Similar to C³T

<table>
<thead>
<tr>
<th>Location</th>
<th>Year Built</th>
<th>Original Owner</th>
<th>Product Stored</th>
<th>Size m³</th>
<th>Currently In Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barcelona, Spain</td>
<td>1968</td>
<td>Esso Research (ENAGAS)</td>
<td>LNG</td>
<td>40,000</td>
<td>No*</td>
</tr>
<tr>
<td>Barcelona, Spain</td>
<td>1968</td>
<td>Gas Natural (ENAGAS)</td>
<td>LNG</td>
<td>40,000</td>
<td>No*</td>
</tr>
<tr>
<td>Philadelphia, PA, USA</td>
<td>1972</td>
<td>Philadelphia Electric Co.</td>
<td>LNG</td>
<td>63,000</td>
<td>Yes</td>
</tr>
<tr>
<td>Philadelphia, PA, USA</td>
<td>1974</td>
<td>Philadelphia Gas Works</td>
<td>LNG</td>
<td>94,000</td>
<td>Yes</td>
</tr>
<tr>
<td>Philadelphia, PA, USA</td>
<td>1974</td>
<td>Philadelphia Gas Works</td>
<td>LNG</td>
<td>94,000</td>
<td>Yes</td>
</tr>
<tr>
<td>Barcelona, Spain</td>
<td>1980</td>
<td>ENAGAS</td>
<td>LNG</td>
<td>80,000</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*Enagas’ two 40,000m³ tanks have only recently been taken out of storage, but have not yet been decommissioned.

All of the listed Enagas tanks have precast concrete primary containments similar to C³T, and the 80,000 m³ Enagas tank has both precast concrete primary and secondary containments similar to C³T. The 94,000 m³ Philadelphia Gas Works tanks have precast concrete primary and secondary containments similar to C³T. The 63,000 m³ Philadelphia Electric Company tank is a hybrid tank with a secondary containment similar to the C³T Hybrid concept.

PROGRESS MADE BY CHEVRON POST-JIP

Chevron continued to work on C³T after the JIP preliminary design was completed. Since that time the project team has initiated and followed the Chevron TQP to determine what laboratory tests would be required to mitigate the perceived risks of this new technology, initial construction procedures have been developed, and laboratory testing has started and the results will be used to complete the C³T certification by Det Norske Veritas (DNV).

Chevron’s Technology Qualification Process - TQP

Within Chevron, the C³T team followed Chevron’s TQP to assess the risks and uncertainties in C³T’s civil/structural design and construction methods, and prepare a forward plan to eliminate or mitigate those risks.

Chevron’s TQP is a formal process to assess new technology and existing technology in new applications. It is used to enable the high quality, risk-informed decisions regarding the technology’s further development or deployment and utilization on projects. It was developed in conjunction with DNV, based on DNV’s A203, and is an iterative process depicted in the following graphic, Figure 3.
Chevron also employs a scale which is applied by the development team in conjunction with potential internal clients to determine the Technology Development Stage (TDS) of the technology. Presently, C³T is at TDS 3. This qualification program will advance it to TDS 6, which is likely the optimal ranking to be achieved before C³T’s first internal commercial deployment. The progression from TDS 3 to TDS 6 will occur in two steps:

<table>
<thead>
<tr>
<th>Step 1</th>
<th>TDS 3 → TDS 4</th>
<th>Validate critical design parameters in controlled laboratory environments.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 2</td>
<td>TDS 4 → TDS 6</td>
<td>Demonstrate constructability of full-size tank components</td>
</tr>
</tbody>
</table>

For reference, the TDS definitions are shown below.
### Initial construction procedures

The C3T team has also advanced the construction procedures since the close of the JIP. Construction of the tank foundation and floor insulation follows conventional construction procedures. The construction of the primary containment tank wall occurs in three steps: (1) Fabrication of the precast panels, (2) erection and temporary shoring of the wall panels, and (3) integration of wall panels to form a monolithic wall. This process is repeated for the secondary containment wall erection. While the construction of the dome roof is similar to the traditional roof construction for double walled LNG tanks, it can begin earlier in the schedule when compared to traditional 9Ni steel tanks because the primary containment walls are completed before the secondary containment walls.

The precast concrete wall panels are cast in horizontal position by directly pouring the concrete on the carbon steel liner segments that function as a portion of the formwork. Casting in horizontal position is not only safer and more efficient but also reliably increases the concrete quality. Dependent on the site conditions and remoteness of the construction site, the precast panels are either cast in a precast plant and shipped to the site or cast directly at the site. The off-site panel fabrication can largely reduce the required workforce at the site. The panels are designed to be shipped by truck, rail, or barge, and can be fabricated by splicing two half height panels together on-

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**Table 2. Technology Development Stage (TDS) Designations**

<table>
<thead>
<tr>
<th>Operating Condition</th>
<th>Technology Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proven</td>
</tr>
<tr>
<td></td>
<td>Limited Field History/Not Used by Chevron</td>
</tr>
<tr>
<td></td>
<td>New or Unproven</td>
</tr>
<tr>
<td>Previous Experience</td>
<td>Low Uncertainty</td>
</tr>
<tr>
<td></td>
<td>Moderate Uncertainty</td>
</tr>
<tr>
<td></td>
<td>High Uncertainty</td>
</tr>
<tr>
<td>No Experience in Chevron</td>
<td>Moderate Uncertainty</td>
</tr>
<tr>
<td></td>
<td>High Uncertainty</td>
</tr>
<tr>
<td></td>
<td>Very High Uncertainty</td>
</tr>
<tr>
<td>No Industry Experience</td>
<td>High Uncertainty</td>
</tr>
<tr>
<td></td>
<td>Very High Uncertainty</td>
</tr>
<tr>
<td></td>
<td>Very High Uncertainty</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TDS</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initiation</td>
<td>Basic principles observed and reported</td>
</tr>
<tr>
<td>2</td>
<td>Concept</td>
<td>Technology concept and/or application formulated</td>
</tr>
<tr>
<td>3</td>
<td>Proof of Concept</td>
<td>Analytical and experimental critical functions and/or characteristic proof of concept</td>
</tr>
<tr>
<td>4</td>
<td>Integration</td>
<td>Component and/or bench configured sub-system validation in laboratory environment</td>
</tr>
<tr>
<td>5</td>
<td>Demonstration</td>
<td>Component and/or bench configured sub-system validation in relevant “real world” environment</td>
</tr>
<tr>
<td>6</td>
<td>Prototype</td>
<td>System/sub-system model or prototype demonstration in a relevant environment</td>
</tr>
<tr>
<td>7</td>
<td>Pre-production</td>
<td>System prototype or system demonstration in the intended operating conditions and environment</td>
</tr>
<tr>
<td>8</td>
<td>Production</td>
<td>Actual system completed and qualified through test and demonstration in realistic operating environments</td>
</tr>
<tr>
<td>9</td>
<td>Field Proven</td>
<td>Actual system(s) proven through successful field operations</td>
</tr>
</tbody>
</table>
site if the transportation of the 125 feet long panels is challenged by narrow and winding road conditions.

In parallel with the wall panel precasting, shoring towers are erected at the construction site along the internal perimeter of the tank to shore the precast panels before they get integrated to form the internal tank wall. At the same time, all necessary supplies (bottom plating, and bottom insulation) are placed inside the tank and fabrication of the structural steel portion of the roof structure is started. Once all wall panels are available on-site and the shoring towers are ready, the panels for the internal wall are one-by-one lifted into a vertical position with means of a lifting table or pulley system and installed against the shoring towers by a large crane. This construction step occurs very quickly with a relatively small crew as it does not involve much welding or concreting. Once erected, the wall panels are integrated by first welding the carbon steel liner splices and then pumping concrete into the closure pours between the panels.

At this point, the removal of the shoring towers can take place and the fabrication of the dome roof, floor plating, and suspended ceiling can be continued protected from wind and weather within the primary container wall. Access to the tank interior is provided by a short access tunnel that runs under the primary and secondary walls at one location. The integration of the primary wall is complete once the walls are wrapped with prestress wires or strands and covered with a shotcrete layer. This entire final integration is performed by an automated wrapping machine involving very little labor. The automated wrapping technology has been developed and perfected over the past 50 years and is in common use in the construction of large scale water tanks (Figure 4 and 5).

The secondary containment wall is installed and integrated similarly to the primary wall but can be temporarily shored directly to the primary wall. The steel roof structure is raised by air pressure and connected to the exterior wall with a strong ring beam. The roof is finally topped with a concrete pour before the roof top mechanical equipment is installed.

Figure 4. Strand Wrapping and Shotcreting of Walls with Means of an Automated Wrapping Machine
Photo courtesy of DN Tanks, Inc.
DNV Endorsement

On 20 August 2010 DNV issued a statement of endorsement of the C3T LNG Storage Tank Concept. DNV also made a general assessment of any review steps that may be required for a full qualification of the C3T new technology that will lead to a statement of fitness for service. The next steps required in order to obtain a fitness for service statement included a number of laboratory tests described in the next section.

Laboratory Tests
The laboratory material qualification tests required in order to obtain DNV fitness for service statement were developed in 2011 and Westmoreland Mechanical Testing & Research Inc. (WMT&R) was contracted to perform the tests in the Fall of 2011. WMT&R started the testing program shortly thereafter. The testing program includes a total of 402 tests (at temperatures varying from ambient to cryogenic) of the carbon steel liner used as liquid/vapor barrier and the 9%Ni steel floor plate used in the C3T system. It is expected to be completed early in calendar year 2013. The amount of reduction in 9%Ni steel used in the C3T system depends on the outcome of the testing results. As of the date of this paper (November 2012) the initial testing results have been favorable for the C3T system.

BENEFITS AND RISKS OF C3T / COMPARISON OF C3T TO 9%NI STEEL TANKS

The current version of the C3T design is a notional design based upon United States Gulf Coast (USGC) conditions.

C3T should reduce the on-site labor and on-site concrete production requirements as compared to the 9%Ni steel tank by use of offshore precasting of the C3T wall elements. A 160,000 m³ sized C3T is estimated to
require between 70,000 and 90,000 fewer on-site labor hours when compared to a conventional 9%Ni steel full containment tank.

C³T also appears to offer an improvement in project capital costs. The cost savings are estimated to be at least 10-15% as a reduction in capital costs from the baseline 9%Ni steel 160,000 m³ full containment tank design. The majority of these cost savings are due to the shifting of on-site labor offsite and reducing the quantity of 9%Ni steel required.

Another benefit of C³T over traditional 9%Ni steel tanks is the ability to build an LNG storage tank much larger than 160,000 m³. In order to increase the size of the baseline 9%Ni steel tanks, the thickness of the primary tank wall steel plating must also increase to handle the larger load. The size of the baseline 9%Ni steel tank is therefore limited by the maximum practical thickness currently available in 9%Ni steel. In the C³T concept, the concrete structure and its prestressing material are the primary providers of wall strength, and so the tank size of C³T can increase without a corresponding increase in steel plating thickness as C³T does not use its steel vapor barrier for structural purposes, as shown in Figure 7.

The risk profile for C³T concept tanks when compared to a 9%Ni steel full containment tank is somewhat different, primarily because recent deployment experience with C³T type tanks is not available. The C³T design efforts to date, including third party review, have concluded that there are no technical risks that cannot be mitigated by design. There are several technical risk items that are the current subject of confirmation testing, which will either confirm the current design or require straightforward design modifications.

**Detailed Explanation of C³T’s Benefits/Advantages**

Listed below are possible benefits as result of the deployment of one C³T storage tank.

a. **Reduced On-Site Labor**
   Because much of the wall construction can be moved offsite to an existing precast fabrication facility, the on-site labor associated with tank wall construction is significantly reduced. Analysis by BergerABAM indicates that this is an on-site labor reduction of on the order of 70,000 to 90,000 hours for a 160,000m³ tank. This reduces all labor related site support requirements, reduces the potential for safety incidents, and helps to reduce overall project peak on-site labor requirements.

b. **On-site Heavy Construction Labor Skill Requirements**
   There is a significant reduction in crane lift numbers and frequency (form lifts, reinforcement lifts, cast-in-place concrete pumping related lifts) by shifting to fewer but heavier lifts (the precast concrete primary and secondary wall panels).

c. **Offsite Labor**
   Depending on the location of the LNG facility site, there may be an intermediate level of local benefits to in-country labor located in existing industrial areas while still providing reduced on-site labor related impact. There are also options for additional cost savings by taking offsite labor to a country with overall lower precast concrete construction and delivery costs.

d. **On-site Cast-in-Place Concrete Construction is Reduced**
   The C³T concept reduces on-site cast-in-place concrete work by approximately 6,000 m³ as result of the use of precast concrete wall panels.

e. **Relative Construction Cost**
   The relative construction cost, as compared to a baseline 9%Ni steel tank, is primarily influenced by the current cost of premium 9%Ni steel and the relative cost of on-site versus
off-site labor as it compares to the cost of transporting the fabricated precast concrete wall panels from the fabrication plant location to the construction site.

f. **Cost Escalation Effects Reduced**
The C³T concept is likely less susceptible to higher than average construction cost escalation due to increased offsite prefabrication and a reduction in the requirement for premium construction materials and skilled workmanship typical of 9%Ni steel tanks.

g. **Relative Construction Schedule**
The C³T construction schedule is estimated to provide a reduction of 7 to 9 months. The level of impact of this schedule reduction is dependent on the type of plant being built, and whether the tank construction is on the critical path for the overall plant. For regasification plants or liquefaction expansions, the impact will be larger than for green-field liquefaction plants.

If the LNG plant site is susceptible to significant weather events, the likelihood of having the C³T construction schedule substantially disrupted by site weather events is reduced because the wall construction for a C³T-type tank takes place over a much shorter time window than is typical for a 9%Ni steel full containment tank.

h. **Enhanced Construction Safety**
Because the precast wall panels for the primary and secondary containment are fabricated in a manufacturing environment (as opposed to an on-site environment) in a horizontal position, there is a substantial reduction in the number of manhours of work at elevated levels above the ground. This significantly reduces the potential for fall accidents.

i. **The C³T Concept Provides Robustness in Its Structural Elements**
In Figure 6 below, a section of the secondary containment wall is shown. The secondary wall of the C³T is similar in robustness to the cast-in-place concrete secondary containment wall in a conventional full containment LNG storage tank.

![Figure 6. Section of C³T Secondary Containment Wall](image-url)
However while the secondary containment walls are similar, the $C^3T$ primary containment wall is much different than the 9%Ni steel containment in that it is 14 inches (356 mm) thick at the base compared to 1.5 inch to 1.75 inch for a 9% Ni steel containment wall. The entire $C^3T$ wall assembly is prestressed both vertically and circumferentially by thousands of individual prestressing strands, each individually bonded to the concrete. This means that the performance of the tank is only slightly affected should one of these thousands of strand element fail. Additionally, the much thicker wall is not susceptible to elephant’s foot buckling or other buckling that is a concern for steel tanks subject to either internal or external overloads. Thus the $C^3T$ structure is not susceptible to many of the accidental and overload failure mechanisms typical of a steel tank and the $C^3T$ structure provides unusual structural toughness and redundancy in its load resistance behavior. See Figure 7, below, for a visual comparison.

![Figure 7: Comparison of 9Ni Steel and $C^3T$ Primary Containment Wall Structures](image)

**Concrete Wall Quality**

Typical cast-in-place secondary containment walls are either placed by lift or slip formed such that concrete must be successfully placed and consolidated in the narrow wall form which also includes reinforcement and post tensioning ducts. Conversely, the $C^3T$ wall panels are cast flat at or near ground level in a precast fabrication facility, and the panels do not have circumferential post tensioning ducts within the wall section. These features make reliable placement and consolidation of the concrete much easier to achieve. In the event of a serious fabrication problem of any sort, it is possible to reject an entire panel and fabricate a replacement prior to sending the panels to the job site. This is in contrast to the practical requirement of cast-in-place wall construction to correct any discovered construction quality problems with in-situ repairs.

**Quality Control Flexibility**

The ability to fully inspect precast wall panels prior to shipping them to the site provides significantly increased flexibility in the way any quality control problem is corrected. This can range from repairs made in a factory environment to complete replacement of wall panels in advance of shipment to the site. Thus the quality of significant portions of the tank construction is assured when the elements reach the job site.
n. **On-Site Labor Skill Requirements**
   The avoidance of the requirements for heavy plate welding and reduction in on-site 9%Ni steel welding reduces the average skill level needed for successful C³T tank construction. This allows labor requirements to be met more easily and reduces the reliance for attaining necessary quality on the performance of highly skilled laborers.

o. **Effects of 9%Ni Steel Production/Delivery Limitations**
   Most 9%Ni steel comes from a single source in Belgium that, depending upon demand at any point in time, can have long lead times for the delivery of this necessary material. The selling price of this steel depends both upon demand and on the cost of its constituents. In the recent past the price of Nickel, a primary ingredient of 9%Ni steel, has fluctuated significantly resulting in price uncertainty in the cost of 9%Ni steel at any point in time. Because C³T uses less 9%Ni steel, the concept is less affected by both availability constraints and price fluctuations associated with this material.

p. **Use of Local Construction Material**
   More local governments now support or even require the use of local construction material. The precast concrete panels can be fabricated of mostly locally sourced construction material. In particular in regions where the locally sourced content is measured in percentage of weight of total construction material used, the precast concrete walls can give a significant local contribution.

**Detailed Explanation of C³T’s Risks**
The C³T concept has been the subject of several formal risk assessments. These assessments have been used in the development of the current design and in the definition of the qualification testing program for the technology. Many of the following identified risks result from the fact that an initial (Serial Number 1) tank has not yet been built and put into service and should be resolved by laboratory testing (in process) or construction demonstration.

a. Handling of the long precast concrete wall panels, both in shipping and in erection could contribute to both cost and schedule risk. The intent of the planned C³T constructability demonstration is to mitigate this risk by confirming practical wall panel handling and erection methods.

b. For sites with high construction period winds, temporary wall panel erection support design represents a potential cost and schedule risk. Follow on efforts should focus on definition of cost effective temporary shoring methods especially for sites subject to high winds during the construction period.

c. For sites with seismic activity and/or seismic design specifications, provisions for seismic design of the C³T concept may add to tank cost and/or schedule. Solution is to address site specific seismic criteria in follow-on deployment work.

d. Use of carbon steel as a liner material for the C³T primary containment represents a cost risk if the confirmation test program, in progress, does not confirm this past practice as acceptable. The alternative solution would be to substitute thin (5mm) 9%Ni steel plate at increased cost compared to the cost of carbon steel.

e. Use of typical tank floor lap welding detail represents a cost risk if confirmation testing, in progress, does not confirm the acceptability of past practices. Solution would be to modify the tank floor plate lap weld detail at increased cost, if needed.
f. Procurement of smaller quantities of 9%Ni steel may prove to require more schedule time than planned, as the steel supplier may prefer to fill orders for larger quantities and thicker plate first. Solution would be to pre-order the necessary steel with the option to cancel in advance of the Notice to Proceed for a particular project.

g. In sensitive deployment locations, the import of structural insulation blocks containing wood and used for support of the C3T primary containment wall may require longer than currently scheduled due to import related delays. Solution is to start early action to determine timeline for this and if necessary test available non-wood insulation material if import of insulation blocks containing wood proves to require more time than planned.

Further Applications of C3T

C3T Hybrid – 9%Ni Steel Primary and C3T Secondary Containments
This concept employs a C3T type secondary containment with a conventional 9%Ni steel primary containment rather than a C3T type primary containment. The main differences in this concept when compared with conventional full containment tank technology are (1) the manner in which the secondary containment is post tensioned in two directions, and (2) the liner is on the exterior of the secondary wall, versus the interior where it can become in direct contact with an LNG spill. The secondary tank wall to foundation joint is also designed to behave in a more favorable manner in the event of an LNG spill into the annular space when compared to the fixed joint used in conventional cast-in-place concrete construction.

Other industries
The C3T containment tank is designed per the new American Concrete Institute (ACI) 376 code and can be used for any other refrigerated liquid storage where the temperature is higher than -270°F. Such potential other cryogenic applications include the following:

- Smaller LNG or LPG storage tanks for power users
- Peak shavers for utilities
- Storage tanks for liquefied acetylene, ethane, propane, etc. with boiling point at atmospheric pressure higher than -270 degree Fahrenheit. Other liquefied gases with boiling point below -270 degree Fahrenheit (i.e. nitrogen, hydrogen, oxygen) can also be considered, however, consideration to the fact that ACI 376 is only applicable to liquefied gasses down to a temperature of -270 degree Fahrenheit and the carbon steel plate testing performed as part of C3T only goes down to -320 degrees Fahrenheit must be considered.

Concrete liquid storage tanks are already used to store liquefied petroleum gas, nitrogen, oxygen, and ethylene. Tanks made of precast concrete wall elements can also be used for non-cryogenic liquid storage and are already largely used for water tanks. The high durability of concrete tanks and the associated low maintenance requirement makes them attractive for many markets. Where gas tightness is not a requirement, such as for water tanks, concrete tanks are often used without liner.

ADDITIONAL DEPLOYMENT CONSIDERATIONS
Greenfield LNG liquefaction projects are very costly and have long approval and construction cycles. In part as a result, the monetary benefits of any single technology alone may not justify the introduction of unknowns, such as those associated with new technology, particularly to a critical system like storage tanks. In the case of C3T, some re-focusing of the evaluation to include its significant non-monetary advantages may prove useful. Below are a few examples of these considerations.
a. **C3T's flexibility.** A drawback of conventional 9%-nickel tanks is the careful project planning required to accommodate their long “stick-built” construction step and “one-size-fits-all” approach. C3T has built-in flexibility. Due to its faster, simpler build requirements, C3T allows the tank construction step to become more flexible to fit the project’s construction constraints rather than the reverse where the project needs to accommodate the tank build. This is an important distinction that the C3T program needs to exploit.

Specific instances where C3T’s flexibility could demonstrate this over conventional tanks are as follows:

- C3T’s prefabricated wall panels allow moving significant amounts of work away from the construction site. This ability to move work offsite is important for sites that have high labor costs, logistical challenges, or strict quarantine restrictions. The ability to move work offsite is also important for construction sites located in areas prone to tropical weather systems and its associated schedule delays.
- C3T’s prefabricated wall panels allow moving work to the ground that usually occurs above grade with conventional tanks. This feature is advantageous at construction sites with strong winds or wind design requirements. Moving work to ground in high wind design environments can also reduce scaffolding complications.
- C3T’s prefabricated wall panels are somewhat analogous to modular construction. Modular construction is often chosen for LNG project sites with high labor costs, constricted lay-down space, and weather interference. Yet with conventional tanks, modular construction and its inherent advantages is not an option.

b. **C3T generates less waste.** Costs and logistics challenges associated with waste removal can become significant, especially at very remote sites or at sites with considerable environmental management restrictions. By building prefabricated panels offsite, C3T has inherently less waste to remove from the construction site. As an example, the large volume of foam glass insulation waste generated onsite with a conventional tank could be avoided by incorporating insulation during the offsite panel casting step for a C3T tank. Reduced waste will likely be well received by all project stakeholders.

c. **Recognize that the LNG project’s customers are stakeholders as well.** LNG liquefaction projects are different from conventional oil and gas projects in that they include longer term customer/supplier relationships. Often, large-volume customers are involved with the contracting process before Final Investment Decision, and may take equity positions in the project itself. Such customers may have a vote in project decisions and may bring additional concerns and issues, including social and environmental matters, to the discussion. informing customers early-on about options such as C3T may be helpful to deployment as well.

**IMPLEMENTATION AND NEXT STEPS**

In order to make it easier to implement a technology that will potentially replace the more expensive 9%Ni steel primary tank with less expensive concrete primary tank, a new code (ACI 376) has been developed and published. The 2013 version of National Fire Protection Association standard NFPA 59A will for first time refer to American Concrete Institute standard ACI 376 which allows for future regulatory approval.

In 2013 WMT&R will complete the testing program required for DNV to issue a fitness for service statement for the C3T system. The next step would then be to conduct a constructability test which demonstrates that the wall elements can be fabricated, erected, and joined within the required tolerances and within the expected time and effort. Such a constructability demonstration has been planned and would be launched as
part of a first prototype tank construction and would advance the technology development level to TDS6 as discussed earlier in this paper.

As mentioned earlier, it is not economically feasible to build a fully functional non-project demonstration unit and so after the constructability demonstration, C³T would be ready to deploy the technology to a major capital project for consideration during early FEED design. This deployment would include a site-specific C³T design and deployment support from the technology team.

CONCLUSION

The progression of the C³T thus far has been primarily one of technology confirmation and conventional business case development aimed at providing a viable lower cost alternative for a high cost component of LNG import and export facilities.

And while the C³T concept appears to offer significant benefits to the LNG industry at what is perceived by those that have been involved in the development as relatively low risk, successfully meeting technical and business case requirements alone may not be sufficient. Benefits to the project beyond cost and schedule savings must also be addressed, and one aspect of C³T that has not been previously emphasized is the flexibility to fit the tank design to the individual needs of the project. This will likely be an important selling point moving forward.

If the concerns and interests of the broader group of LNG supply chain and user stakeholders are better understood in the context of LNG storage as it relates to the long term interests of the stakeholder group, a more persuasive case could be made for the beneficial use of the C³T technology.

As the stakeholders involved in the development of a large scale LNG facility are many and their interests and concerns are varied, stakeholder engagement and management will become key. Understanding stakeholder concerns and successfully introducing new concepts, products and processes to the LNG industry that appropriately address stakeholder interests is critical for the long term success of the industry. Thus the opportunity to engage and understand stakeholder interests and the development of the skills needed to appropriately respond to concerns with tools other than extreme conservatism in technical advancement, are important to the further advancement of the C³T concept and to the adoption of other industry advancements.

CONCRETE TERM GLOSSARY

Casting – the construction operation whereby fresh plastic concrete is placed into the forms which will contain the fresh concrete during its initial curing (hardening) process. Casting may make use of large buckets handled by cranes or by pumping the concrete from the delivery vehicle into its location in the concrete form.

Cast-in-place (or Cast-in-situ) Concrete – refers to concrete that is cast into its final position. That is, once the concrete is cast into the form, it is not moved.

Casting position - In precast concrete this refers to the position in which the precast element is initially cast or manufactured. Generally precast elements are positioned for the most efficient and effective manufacturing, which may be a position or orientation that is different from that of the element in its erected position in the completed structure.

Erected position – refers to the final position of the precast concrete element in the completed structure. This position or orientation may be different from the casting position in which the element was manufactured (precast).
**Forms** – enclosures which are designed to produce a concrete element of the desired shape and which will contain and support the loads resulting from the fresh plastic concrete.

**Integration of precast panels** – refers to the connection of one precast panel to another in such a manner that the integrated panels behave in a manner that meets the performance requirements (load resistance requirements) of the final structure.

**Lifting table (or pulley system)**- a device or method that is used to transition a large precast element from the casting, storage or transport position to the erection position. Devices such as this are used to avoid having this transition be a controlling design condition for the precast concrete element.

**Lifts** – in concrete structures that are too large or otherwise cannot all be cast in a single concrete placement the concrete placement is made in multiple lifts. In a cast-in-place concrete tank lifts refers to the vertical height of the concrete placement made during a single casting event.

**Monolithic behavior**- behavior of connected multiple precast elements such that the load resistance behavior is similar to a structure composed on one piece (with no joints or connections).

**Off-site panel fabrication**- precast concrete panel fabrication that is performed at a location other than the construction site for the final structure.

**Precast element erection** - the process of lifting a precast concrete element from its position on a transport trailer or device to its position in the final structure.

**Precast concrete** – concrete elements that are fabricated by the precasting method by placing concrete into a form at a location or orientation that is different from that which the element will be in in the final structure. Precasting may occur on the construction site nearby the final structure location or may occur hundreds or thousands of miles from the location of the final structure.

**Precast prestressed concrete** – concrete elements that are both precast and prestressed.

**Prestressed concrete** – a concrete element fabrication method and design approach whereby the concrete element is placed into a state of compression such that tensile forces in the concrete that result from operational loading are minimized or avoided in the final structure. This approach provides the advantage of concrete’s substantial compressive strength while compensating for concrete’s relative lower tensile strength.

**Biaxially prestressed concrete** – concrete that is prestressed in two directions. In the context of a tank the compressive stress is in the in plane circumferential direction and the vertical direction of the tank wall.

**Post tensioning** – a method of applying compressive forces to a concrete element after the concrete has cured (hardened) to a controlled level.

**Pre-tensioning** - a method of prestressing concrete in which high strength steel strands within a precast concrete form are loaded in tension prior to casting the fresh concrete. The fresh concrete is then cast around the strands and allowed to cure (harden) to a controlled initial strength. Upon reaching the controlled initial strength the tension is released at either end of the precast concrete element, thereby transferring the stress in the strand via mechanical and chemical bond, creating compression in the precast concrete element.
Prestressing wire – continuous high strength cold drawn wire that is used in post tensioning by the wire wrapping method in which wire under load is wrapped around the exterior surface of the concrete tank wall.

Prestressing strand – continuous multi wire stranded cold drawn high strength wire (usually 7 wires make up a strand) that is used in post tensioning by the strand wrapping method in which steel strand under a controlled level of load is wrapped around the exterior surface of the concrete tank wall.

Shoring towers - structures that are used to support the individual precast concrete wall panels that make up the tank wall. The shoring towers support the panels and resist wind and seismic loading in the erected position until the panels can be integrated one to another such that they are self-supporting.

Reinforcement – elements with significant tensile strength that are embedded in concrete elements to resist tensile loads applied to or resulting from (as in the case of shrinkage) the concrete section.

Shotcrete – cementious material (generally a sand and cement mixture) that is applied by spraying the material in a controlled manner onto a surface. In the case of a tank the shotcrete is sprayed onto the exterior surface of the tank to embed the individual wrap prestressing strands or wires. The shotcrete serves both to anchor the strand and to protect the strand from corrosion.

Strand anchors – positive anchorage devices that are used to positively anchor the strand at the beginning of each reel (typically 22,000 ft long) of strand used in wrap post tensioning.

Strand wrapping (Wrap prestressing) – a concrete post tensioning method used for cylindrical structures where by continuous high strength steel strand is wrapped around the structure, thereby creating in plane compression in the concrete.

Wire wrapping (Wrap prestressing) – a concrete post tensioning method used for cylindrical structures where by continuous high strength steel wire is wrapped around the structure, thereby creating in plane compression in the concrete.

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