FEEDBACK ON THE CONSTRUCTION AND FIRST OPERATIONS OF THE FIRST US DEDICATED LNG BUNKER

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GTT North America, SEA LNG, TOTE Maritime

During LNG 18, a paper was presented to introduce the main features of the first ever dedicated LNG bunker barge for the marine clean fuel market in North America. At that time, the engineering of the 2200 m3 barge was just starting. When LNG2019 occurs in Shanghai, the barge construction will have been completed and she will have accumulated almost a year of operations.

The paper for LNG2019 will include the lessons learnt from each stage of the Project: design, procurement, construction and commissioning, including the regulatory process. It will also describe the challenges to develop such critical equipment while LNG as fuel infrastructure and the regulatory framework were under parallel development as well as the extraordinary level of cooperation among all the parties.

The crew training program developed to meet the USCG requirements for operations, including a unique purpose-built LNG bunker barge simulator, will also be featured. As far as operations are concerned, the paper will describe the necessary steps to perform the trials, review the performance of the cargo operations, including transfers, and compare them with simulations.

Finally, we will conclude with the introduction of a new concept for the next generation of LNG bunker barges for the US fuel market.
INTRODUCTION

Since September 2018, TOTE has been operating the Clean Jacksonville, the first LNG bunker barge constructed in North America, in its home port of Jacksonville, FL. Clean Jacksonville provides a barge-to-ship LNG bunkering service to the two TOTE Maritime 3,100 TEU LNG fueled containerships Isla Bella and Perla Del Caribe that are trading between Jacksonville, Florida and San Juan, Puerto Rico.

The LNG is loaded onto the barge at the purpose-built JAX LNG terminal, one mile away from the TOTE container terminal. After transit, LNG is transferred from the barge onto the Marlin Class container ship via the barge REACH4™ bunker mast developed by GTT. This innovative transfer solution allows a safe and reliable LNG transfer with a high level of operational flexibility.

The barge was delivered on August 20, 2018 by CONRAD Industries Inc. at their Orange shipyard in Texas. It features a single 2,200m³ GTT membrane tank. Designed to operate in inland waters, bays, harbors and US coastal waters, the barge does not have propulsion machinery. It is towed conventionally by hawser wire or is pushed from the stern and/or maneuvered from the hip. This Jones Act barge of dimensions 70.7m length by 14.9 m beam and 4.9 m depth has a lightweight of about 1,350 LT and achieves a speed of 8-10 knots.

The Regulatory authority for design approval, construction and life cycle surveys of U.S. flag vessels is the USCG. Owners appointed ABS as Classification Society as well. ABS was also authorized to carry out limited approval of the design on behalf of the USCG in accordance with the Code of Federal Regulation (CFR) requirements under the provisions of Navigation and Vessel Inspection Circular (NVIC) 10-82 and NVIC 10-92 CH-2. However, final authority for the approval of the LNG storage, LNG cargo systems and LNG safety systems was retained by USCG.

The barge constitutes a critical element for a safer, cleaner, cost effective and reliable fuel supply and demonstrates TOTE Maritime’s commitment to environmental stewardship and innovation.

LNG BARGE DESIGN OVERVIEW

A general view of the barge arrangement is shown in (Figure 1) below.

![Figure 1. 2200 m³ LNG barge general view](image)

The vessel is a double hull liquefied gas tank barge with a raised trunk deck. The barge is shaped and reinforced in the bow structure to withstand potential wave slamming during transit.
The vessel’s principal characteristics are shown (in Table 1) below.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall</td>
<td>70.7 m (232 ft)</td>
</tr>
<tr>
<td>Length of flat side</td>
<td>63.1 m (207 ft)</td>
</tr>
<tr>
<td>Breadth moulded</td>
<td>14.8 m (48.7 ft)</td>
</tr>
<tr>
<td>Depth at main deck</td>
<td>4.78 m (15.7 ft)</td>
</tr>
<tr>
<td>Depth at trunk deck</td>
<td>7.21 m (23.7 ft)</td>
</tr>
<tr>
<td>Lightship draft</td>
<td>1.62 m (5.31 ft)</td>
</tr>
<tr>
<td>Fully laden draft</td>
<td>2.60 m (8.53 ft)</td>
</tr>
<tr>
<td>Displacement (deadweight + lightweight tonnage)</td>
<td>2400.9 metric ton (2363 lt)</td>
</tr>
<tr>
<td>Design speed</td>
<td>8 to 10 knots</td>
</tr>
<tr>
<td>Life Cycle</td>
<td>25 years minimum</td>
</tr>
</tbody>
</table>

Table 1. Barge principal characteristics

The LNG barge is designed to be “unmanned” during transit and be attended during bunkering operations or while idling at anchor or at dockside. For the LNG barge to be unmanned, reliable means of monitoring and control of the cargo and associated safety systems has been provided. For this purpose, a remote monitoring and control system has been installed on the tow boat consisting of a fully redundant telemetry system based on proven Radio Frequency (RF) technology. The telemetry system is linked to the barge’s automated Control and Alarm Monitoring System (CAMS) located in the cargo control room. The person in charge (LNG PIC) on the tug boat is able to continuously monitor cargo status and monitor and control essential linked systems (e.g., start/stop, open/close), for example, linked equipment (e.g. liquefier units, spray pump), selected remotely controlled valves (except cargo discharge valves), fire prevention and suppression systems (e.g. water spray system), etc., while the barge is under tow.

A screen view of the CAMS operating system is shown in (Figure 2) below.
Commerciaally, the barge will be able to engage in loading/offloading the entire cargo or multiple parcels, in vessel-to-vessel transfers or transfers to/from dockside storage facilities. The barge is capable to unload the full cargo within 4 hours with one main cargo pump in operation (excluding connection/disconnection time, cooling down, ramp up/ramp down and topping off operations). For the purpose of offloading LNG to higher freeboard vessels, the barge is outfitted with GTT’s REACH4™ (Refueling Equipment Arm Methane [CH4]) bunker arm. In addition, a conventional deck manifold connection (one each liquid and vapor lines) is provided on the port side forward, primarily for loading operations.

The barge’s LNG Cargo Containment System (CCS) consists of a single tank of GTT’s Mark III Flex membrane type design with a maximum cargo capacity of 2,200 m³ LNG at 100% (2,197 m³) and maximum design vapor pressure of 0.7 barg (10.1 psig). The maximum tank loading limit is 98% of volume. Overfill emergency shut down (ESD) protection is set at 98.5% volume and is activated by the tank’s radar beam gauging system (secondary gauging system).

Two induction motor type centrifugal submerged cargo pumps with variable frequency drive (VFD) and one induction motor direct drive (fixed speed) submerged stripping and spray pump are mounted inside the tank on the GTT designed pump tower structure. Each cargo pump has a nominal flow rate of 500 m³/hr at 185 mlc differential head and the stripping pump has a nominal flow rate of 8 m³/hr at 121 mlc. A sump well is integrated in the tank design in way of stripping pump’s suction to enable extreme liquid stripping from the tank during preparations for maintenance (or for heel out). Each cargo pump will operate on an alternate basis to extend the pumps’ maintenance cycle and, together with the stripping/spray pump, provide necessary redundancy for the cargo offloading system.

The barge is able to perform cool down operations with the use of one cargo pump or stripping/spray pump.

A cargo machinery room is provided forward on the trunk deck and is divided in four separate compartments:

- a cargo handling room for housing six (6) Stirling cryocoolers and one LNG vaporizer,
- an electric motor room for housing the drive motors of the cryocoolers,
- an electric equipment room for housing the glycol water heater, water chilling units for the cryocoolers and the electrical control cabinets for the cargo handling equipment, and
- a fixed CO2 system room for fire suppression of the cargo machinery spaces.

A Cargo Control Room (CCR) is located aft on the barge in a gas safe zone housing the central control and monitoring system (CAMS) for the cargo tank and cargo handling equipment and systems.

Power generation and supply to consumers is provided by three straight diesel generators of about 500 kW each, two serving as main power generators and one as a stand-by unit for emergency power.

**DESIGN COMPLIANCE**

The design, construction, inspection, testing and commissioning complies with the USCG requirements in 46 CFR Subchapter D for tank barges and the LNG carrier requirements in 46 CFR Part 154, appropriately adapted for an unmanned non-self-propelled liquefied natural gas barge.

In addition, the LNG Barge is designed based on the following Rules and Regulations:

- ABS Steel Barge Rules
- ABS Steel Vessel Rules (Part 5C/8 as applicable)
- IGC Code (as applicable)
• International Convention of Load Lines 1966 including Protocol 1988 and amendments
• IEEE 45 Recommended Practice for Electrical Installations on Shipboard
• SIGTTO Guidelines for LNG Transfers
• Various other requirements and guidelines

REGULATORY ADAPTATION CHALLENGES
The barge has been designed based on USCG CG-ENG Policy Letter No. 2-15 “DESIGN STANDARDS FOR U.S. BARGES INTENDING TO CARRY LIQUEFIED NATURAL GAS IN BULK”. The extent of adaptation of the gas carrier requirements in 46 CFR Part 154 to non-self-propelled barges is reflected in Enclosure 1 of the aforementioned Policy Letter.

To obtain final Coast Guard approval, the Project team had to fulfill the following requirements:
• USCG consent and approval of the “Basis of Design” concept
• A comprehensive Hazard Identification study (HAZID) has been performed at the early stage of the design development to address any potential failures, assess consequences from these failures and introduce mitigation measures in the design and/or determine operational restrictions, if applicable;
• A site-specific risk assessment, a Barge Situational Assessment (BSA), to ensure the LNG barge is suitable for the planned bunkering operation, including evaluation of the risk of collision and allision of the barge during transits to, and at, the bunkering locations;
• An assessment of vessel compatibility for shore or vessel to vessel operations and crew training with respect to LNG transfers (in accordance with USCG CG-OES Policy Letter 02-15).
• Remote alarm monitoring and control of the cargo system on the tow boat while under tow; unmanned status being subject to satisfactory performance of the remote monitoring and control system onboard the tug by the USCG Officer in Charge in the barge’s operating area;
• Special considerations for Cargo Handling Room Hazardous Classification (Zone “0”) and certification of electrical installations and equipment in hazardous locations.

As the rules were to be developed in parallel to the Project, the strong support from USCG and open communication were critical to achieve smooth progress and final approval.

LNG TANK MAIN PARTICULARS
GTT Mark III flex system was selected for the Cargo Containment System (CCS). The tank’s internal dimensions at the inner hull plating are:
• L = 44.075 m [144.61 ft]
• B = 11.365 m [37.29 ft]
• H = 5.925 m [19.44 ft]
An illustration of the Mark III Flex system main components is shown (in Figure 3) below:

As the barge is designed for coastwise service, sloshing has been considered in the design and the vessel is able to operate without any fill level restrictions in its intended operating areas.

A combined dome (4.3 m x 4.3 m) has been designed that allows the incorporation of all necessary instrumentation, liquid and gas penetrations, as well as boil-off gas relief valves.

Another particular feature is the arrangement of the stripping pump which is fitted into an innovative sump well. This first application allows reduction of the minimum heel required to operate the stripping pump without tripping. The main cargo pump shuts down around 70 m$^3$ and the stripping pump is able to pump out to around 2 m$^3$. As a result, this maximizes the volume that can be bunkered for each bunkering event and hence optimizes the number of bunkering cycles.

Figure 4 shows the sump well with the stripping pump after completion.
LNG TANK MAIN PARTICULARS

The key design parameters of the cargo tank are indicated (in Table 2) below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored product</td>
<td>LNG</td>
</tr>
<tr>
<td>Hazard Zone</td>
<td>Zone 2 (Deck)</td>
</tr>
<tr>
<td></td>
<td>Zone 0 (Insulation spaces)</td>
</tr>
<tr>
<td></td>
<td>Zone 0 (Vent Mast)</td>
</tr>
<tr>
<td></td>
<td>Zone 1 (cofferdams and void spaces in way of tank)</td>
</tr>
<tr>
<td></td>
<td>Zone 0 (cargo handling room)</td>
</tr>
<tr>
<td>Maximum filling ratio of total capacity</td>
<td>98 % vol.</td>
</tr>
<tr>
<td>Nominal boil-off rate</td>
<td>0.38 (1) % vol / day</td>
</tr>
<tr>
<td>Operating density</td>
<td>443.5 kg/m³</td>
</tr>
<tr>
<td>Design density</td>
<td>500.0 kg/m³</td>
</tr>
<tr>
<td>Normal operating vapor pressure</td>
<td>1060 mbar abs</td>
</tr>
<tr>
<td>Design Tank pressure</td>
<td>max: +700 (2) mbarg</td>
</tr>
<tr>
<td></td>
<td>min: -10 mbarg</td>
</tr>
<tr>
<td>Normal LNG operating temperature</td>
<td>-161.3 °C</td>
</tr>
<tr>
<td>Design temperature</td>
<td>max: +60 (3) °C</td>
</tr>
<tr>
<td></td>
<td>min: -163 °C</td>
</tr>
<tr>
<td>Barge capacity @ 100% (excluding domes)</td>
<td></td>
</tr>
<tr>
<td>TOTAL CAPACITY</td>
<td>2197 m³</td>
</tr>
</tbody>
</table>

Footnotes:
1) Boil-off rate is based on pure CH4 and IMO conditions.
2) Based on set pressure of Cargo Tanks PSVs.

Table 2. Cargo tank design parameters

CARGO HANDLING AND CARGO SYSTEM OVERVIEW

The cargo handling system is designed for the vessel’s cargo capacity, temperatures and pressures in relation to LNG transported or transferred and the cargo tank’s vapor pressure management during the LNG transfers. The cargo handling equipment is described (in Table 3).

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Redundancy</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG Cargo Pump(s)</td>
<td>2</td>
<td>LNG Discharge</td>
</tr>
<tr>
<td>LNG Stripping/Spraying Pump</td>
<td>1</td>
<td>Complete discharge and tank stripping, cooling down operations &amp; occasional pressure management of tank</td>
</tr>
<tr>
<td>Re-liquefaction Plant</td>
<td>6</td>
<td>Cargo tank boil-off management and handling excess return gas during transfers</td>
</tr>
<tr>
<td>Equipment Description</td>
<td>Quantity</td>
<td>Function</td>
</tr>
<tr>
<td>------------------------------------------------------------</td>
<td>----------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Chilling Sea Water Units for Re-liquefaction Plant</td>
<td>2</td>
<td>Cooling of re-liquefaction plant</td>
</tr>
<tr>
<td>Vaporizer</td>
<td>1</td>
<td>Tank pressure control during discharge; Vapor generation if needed; Gas-up after docking &amp; Tank inerting with liquid nitrogen from shore if necessary</td>
</tr>
<tr>
<td>Glycol Water Heater</td>
<td>1</td>
<td>Heating media for vaporizer unit</td>
</tr>
<tr>
<td>Gas Heater</td>
<td>None &quot;0&quot;</td>
<td>Tank warming-up operations from shore facilities;</td>
</tr>
<tr>
<td>Gas Compressor (vapor return to shore during loading)</td>
<td>None &quot;0&quot;</td>
<td>Vapor return to shore during loading by free flow based on dedicated loading facilities</td>
</tr>
<tr>
<td>Nitrogen Generator</td>
<td>2</td>
<td>Pressure control of insulated spaces, inerting cargo piping/equipment, N₂ purging lines, and tank inerting</td>
</tr>
<tr>
<td>Nitrogen Buffer Tank</td>
<td>1</td>
<td>Store nitrogen produced by generator for use by consumers</td>
</tr>
<tr>
<td>Tank Level Gauging</td>
<td>2</td>
<td>Tank cargo level monitoring and overfill protection during loading</td>
</tr>
<tr>
<td>Custody Transfer (Fiscal Metering System)</td>
<td>1</td>
<td>Fiscal metering of LNG during transfers</td>
</tr>
</tbody>
</table>

**Table 3. Summary list of equipment**

**BOIL-OFF GAS MANAGEMENT:**

There are no gas consumers onboard the barge. In order to deliver the LNG as cold as possible at the highest calorific content and ease the transfer operations, a boil-off gas management system is necessary. In addition, as the tank maximum setting pressure is 700 mbarg, it is important to be able to control the pressure.

To do so, the barge is equipped with six Stirling StirLNG-4 cryocooler units. Four cryocoolers are able to maintain the tank pressure without time limit, so two additional cryocoolers are provided for redundancy in case of maintenance. All six cryocoolers can run during bunkering operation to help the client vessel manage his fuel gas tank pressure (i.e. increase the transfer rate) or can be used to cooldown LNG during idle periods.
The cryocooler units are electric driven with VFD motors in the adjacent room. An illustration is shown (in Figure 5) below:

![Figure 5. Cryocooler and VFD driven motors](image)

The cryocooler units work off the Stirling cycle, creating a cooling effect across the cylinder head using helium and a displacer piston. The helium transmits the heat for the boil-off gas that free flows across cylinder heads, condenses the gas to a liquid, then is cooled by the glycol/water mix.

The barge is equipped with three generators: two main and one standby. The standby generator is coupled with three cryocooler units for emergency cases. Figure 6 below shows the pressure variation in the tank versus time depending on the number of cryocooler units running. It shows that in an emergency case with three cryocoolers running it would take 27 days to reach the maximum tank pressure compared to simply one mile transit for the barge between the LNG terminal and the bunkering location.

![Figure 6. Pressure in tank versus Time](image)

**LNG TRANSFER SYSTEM(S)**

The bunkering transfer system (loading/offloading) consists of a conventional deck manifold with one liquid and one vapor connection of DN 150 (6” NPS) size located at the port side of the barge (forward). The deck manifold is used primarily for loading operations. For offloading (bunkering) transfers to LNG fueled ships, the barge is equipped with the REACH4™ bunker arm. The bunker arm (as illustrated in Figure 7) is equipped with one liquid
line (DN 200), one vapor line (DN 100) and one Nitrogen line (DN 25) for inerting and purging before and after transfers. It has also two safety features: one ESD Alarm box and one Controlled Descent BreakAway Coupling. The operating envelope allows a boom maximum outreach about 21m and a slewing range from $0^\circ$ to $340^\circ$.

CONSTRUCTION

**LNG Tank:**

One of the key elements of this new barge was the cargo containment system for the LNG tank. GTT signed a License Agreement with CONRAD Industries on January 7, 2015 for the design and construction of LNG vessels using GTT membrane technologies. CONRAD cut the steel for the barge in July 2015 with containment system engineering commencing in April 2015. The design, procurement and construction of the tank were all smooth with a very satisfactory result at the end. The design of the tank was very quick and containment system components were fabricated in less than 3 weeks.

During the design phase of the containment system, GTT worked with CONRAD to prepare their team for the installation phase of the containment system:

- all material components for the containment system dedicated to the barge were shipped from South Korea and arrived at the shipyard well in advance in November 2015. Cargo containment insulation panels, stainless steel membrane sheets and all related fittings were procured from Hankuk Carbon in South Korea, who is one of the major qualified fabricators of GTT’s tank system components and major suppliers to the shipyards in Korea and elsewhere that build vessels with GTT membrane tank systems onboard.
- all tools and equipment were specified by GTT and delivered to the yard also well in advance to allow the teams sufficient time for training prior to installation
- welding and bonding schools have also been set up.
The quality and tolerances of the hull were very good and made the marking and the installation of the containment system components simple.

All the flat bar welding, marking, flatness measurement and stud welding (except the bottom) were performed before the barge launching in February 2016. Because of the reduced size of the tank compared to large-scale LNG carriers, all the material components were loaded through the combined dome opening. The staging was also adapted from large-scale LNG carriers and used for half of the tank to allow easy circulation. In April 2016, the installation of all panels began and went very smoothly. Figure 9 below shows the different phases for the panels' installation.

![Crane on dome, mastic application, panels' loading, Forklift to move panels](image1)

**Figure 9. Different phases of panel installation**

Of course, as it was the very first time for the shipyard, the pace was slow at the beginning with a quick ramp-up once the teams gained confidence operating the equipment and handling and installing the components.

The bonding of the secondary barrier started at the end of May 2016. Due to the limited surface area to be glued, it was decided to perform the bonding manually and at ambient temperature. Three teams of three bonders each were trained for this phase. To avoid the cost of a dispenser, cartridges were used for the glue application. Figure 10 shows the bonders during training and a tank corner after the glue application.

![Training, Tank](image2)

**Figure 10. Secondary barrier bonding**

The primary barrier welding started in early September 2016. Twelve manual welders and two machine operators were trained for this purpose. One welding machine was used every day for the flat wall areas while the manual
welders progress the corners at the same time. Thanks to precise marking of the panels, the alignment of the membrane corrugations was very satisfactory. Figure 11 shows the tank during primary membrane welding and after completion.

The pump tower, combined dome plug and dome cover were fabricated by Conrad and assembled in the workshop. Before assembly, the actual tank height has been measured. This advanced assembly allowed a better welding quality and less risk of damaging the containment system that was already installed. Figure 12 below shows the different sequences of pump tower installation.

At each stage of the tank construction, tests were conducted. Secondary barrier tests were carried out through the vacuum box test method by CONRAD shipyard personnel. The secondary membrane sound test and secondary barrier tightness test (SBTT) were performed and results were well below the GTT specified criteria. During the primary membrane welding, an NDT (Non-Destructive Test) company performed random checks before the helium test. This is the first time that a helium test for the primary membrane was conducted for a Mark III containment system. Typically ammonia testing is performed. To do so, a mixture of helium and air was injected through nitrogen piping in the bottom of the tank. Leaks are detected through the welds when there is a welding defect. Testing lasted four days while usually the ammonia test cycle lasts about 3 weeks. This was a great success for a first application.

Once the tank was completed and tested, it was inspected by all parties including Classification Society ABS, USCG, CONRAD, Owner representatives and GTT before the tank was sealed.

The tank was completed in January 2017, almost 20 months before the delivery of the barge.
Due to unexpected delays in the regulatory process and detailed engineering, the equipment installation and piping experienced many challenges and delays. For instance, the P&ID modifications every month made difficult the completion of piping isometric drawings with huge impacts to the schedule. CONRAD decided to take all necessary actions to test all equipment and piping prior to commissioning to make sure that all function and safety aspects were fully satisfactory.
TRAINING PROGRAM FOR LNG BUNKER BARGE PERSONNEL

The GTT Training team has developed a training program for LNG bunker barge personnel. The primary objectives of this training program were to ensure:

- all personnel that will operate the barge are certified in accordance with USCG requirements;
- all personnel who will be operating or engaged in operating the barge (both marine and shore personnel) will be fully competent in all the procedures required in the handling of LNG and the specific requirements of the barge, no matter their previous backgrounds;
- all personnel are competent to undertake all the operations that may be conducted with the barge, both now and in the future, with full regard to the safety of personnel and the surrounding environment.

A two phase program was developed and approved by USCG.

Phase 1 – Certification of personnel to USCG requirements:

- Tanker-man Assistant LG (Liquid Gas) & Tankship PIC LG
  - USCG-approved 8 day Tankship PIC LG course
  - USCG-approved 5 day Liquid Cargo Operations Simulator course
  - Basic and Advanced Firefighting Course

Phase 2 – LNG Barge Specific Training:

- 5-Day LNG Barge Cargo Operations Course
  - Conducted using a specially designed LNG Barge / LNG Bunkering simulator model on the GTT Training “G-Sim” Liquid Gas handling simulator.
  - Operatives undertook the standard operations with which the barge may be involved.
- 4-Day LNG Barge Advanced Operations Course
  - Focus on handling of abnormal operations and problem identification.
- Barge Familiarization
  - Conducted with shipyard, GTT and manufacturer personnel.
  - Barge Equipment Training & Familiarization onboard the barge.
This training program has been critical for the operator’s crew of the barge from barge operator FOSS. Once completed, they were ready to undertake safely all the barge’s operations. Figure 14 below shows some screen shots of the purpose-built barge operation simulator.

![Figure 14. Screen shots of the purpose-built simulator](image)

**BARGE COMMISSIONNING**

*Onboard testing*

After mechanical and electrical installation testing and inspection was completed, the onboard testing began. This is a critical phase that lasted almost 10 weeks, during which all the following tests were completed at the shipyard:

- Cargo handling equipment
- Electrical systems
- Automation systems
- Mechanical Systems
- Ship Services Systems

*Cold tests*

Once all onboard testing has been completed, it is time to start cold tests. This is the first time that cold temperatures were introduced to the barge. The cold test is a specific process of introducing cold nitrogen to the system to perform the initial phase of testing. The main purposes of the cold test are to:

- Perform the initial testing of piping and mechanical system at cryogenic conditions using an inert gas.
- Remove all oxygen from the barge systems, piping, equipment, inter-barrier space (IBS) and insulation space (IS) and cargo tanks.
- Allow the IBS/IS spaces to be placed into auto-regulated operation and test the functionality of this system.
- Utilize LN2 to cool down the piping systems to ensure that all piping is leak free, can withstand the cryogenic temperatures and validate the expansions of the piping and cargo system equipment as per design.
- Validate that the design of the cargo handling equipment can withstand operating at cryogenic temperatures.
- Validate that all valves, valve operators, instrumentation, etc. is functional and can operate at cryogenic temperatures.
- Provide a “trial” run of operational and safety protocols for the gas trials.
Detailed procedures have been developed to provide the step-by-step instructions with functional diagrams for each procedure along with detailed check sheets to be documented by the trial team during the test. Figures 15 show a truck supplying LN2 into the barge systems and a side view of the barge during cold tests.

**Gas Trials**

Once the cold test is completed with full satisfaction, it is time to perform the gas trials. The gas trial is the introduction and testing of all cargo handling systems on board the vessel with LNG at full cryogenic temperatures. The main purposes of the gas trials are to:

- Perform the initial and controlled cooling down of the cargo tank on board the vessel.
- Allow all cargo handling equipment to be operationally tested at cryogenic conditions (cargo pumps, stripping/spray pump, cryocoolers, vaporizer, etc.).
- Validate the operation of all automated equipment and operations.

The gas trial is the final testing step of the building process before the barge is certificated for commercial trade.

Detailed procedures have been developed to provide the step-by-step instructions with functional diagrams for each procedure along with detailed check sheets to be documented by the trial team during the test.

To perform the gas trials, LNG in large quantity is required. There are not a lot of facilities in US that can accommodate the requirements for such gas trials. To achieve this goal, the barge has been moved from the CONRAD Orange shipyard facility to Port Fourchon, Louisiana at Harvey Gulf’s facility. This small onshore bunkering facility is used to bunker the five LNG fueled Offshore Supply Vessels (OSV) owned and operated by Harvey Gulf. The barge gas trials were performed without discontinuing the commercial operations of the OSVs. In general, the tests went smoothly and all the equipment was tested and validated to the satisfaction of the owner. Here below are some main facts of the gas trial operations with duration as indication:

- **Gassing up**: within 12 hours duration
- **Cooling down**: 13.5 hours
- **Loading**: due to lack of product at Harvey Gulf facility and the commercial OSV loading operations, the barge had to leave the dock several times, such that loading was achieved in five cycles. This was good to
train the crew and test the equipment. Loading occurred directly from trucks and via the onshore pressurized tanks, which is a first. At the conclusion, 635 m$^3$ of LNG were loaded, which was enough to start the pumps and commence the tests of the equipment.

- The cryocoolers ran efficiently during all operations with some adjustments needed on the chillers.
- Pressure rise: in black-out mode, it was observed around 16 mbarg/h to 27 mbarg/h pressure rise which are to be compared with simulations at the beginning of the project in the range: 23 to 28 mbarg/h. This is a very good reference point even though the simulation model was not taking into account the influence of the liquid level.
- Sump performance: only 1.7 m$^3$ of cargo was left in the tank after unloading with the stripping pump, which is remarkable.
- Warming up: almost 54 hours
- Inerting: 12 hours including piping
- Aerating: 23 hours

Once completed, the barge tank has been inspected and everything was found satisfactory allowing the barge to be officially delivered by CONRAD to TOTE on August 20, 2018. Figure 16 shows the barge leaving CONRAD shipyard facility before gas trials and the barge at the dock during gas trials.

![Barge leaving CONRAD shipyard](image1)
![Barge during gas trials in Port Fourchon](image2)

**Figure 16. Barge before and during gas trials**

**BARGE OPERATIONS**

Once delivered, the barge was moved to her home port of Jacksonville, Florida. Prior to first operations, dry runs with the LNG Loading terminal as well as with LFS (LNG-Fueled Ship) vessel were completed. These operations took place in early September 2018 and were essential to ensure that all procedures were well in place prior to the first commercial operation. Particularly, the dry run with the LFS is a unique occasion to fine-tune the adjustment of the mooring lines as well as all communication procedures before the first LNG transfer using the REACH4™ bunker mast.
First commercial operation

On September 26, 2018, the barge was loaded with 1,500 m3 of LNG at the JAX LNG terminal. It is to be noted that the barge was able to load LNG from the terminal at the terminal design rate without any vapor return compressors and with limited barge tank pressure increase to 200 mbarg. That was implemented in the design to avoid the need of such equipment on the barge.

On September 27, the barge is positioned alongside the Perla Del Caribe. Prior to connection, the two type C fuel tanks of Perla Del Caribe had a pressure of 5.5 barg while the membrane tank onboard the barge was close to atmospheric pressure. The connection is achieved within 30 minutes. After connection, line-up of the barge and LFS valves was performed but two control valves remain closed before starting the transfer. Liquid supply and vapor return are entirely controlled by these two control valves onboard the barge. The main objective is to simplify the bunkering operations for the LFS Perla Del Caribe.

Thanks to the variable speed pump, the barge operator started the transfer through the liquid line by building up the liquid pressure higher than the LFS back pressure before opening the discharge valve in order to avoid back flow to the barge tank. To prevent any mistake, the operator can check that the flow is going in the right direction thanks to the flowmeter. In addition, the barge is also protected against overfilling thanks to the high-level alarms and safety actions can stop the transfer at any time.

The barge recovered the vapor from the LFS Perla Del Caribe to help the management of the tank pressure, i.e. to increase the transfer rate. This is achieved thanks to the barge control valve’s ability to automatically and safely recover vapor from high pressure fuel tanks from Perla Del Caribe to the barge tank. In addition, thanks to the use of six cryo-coolers, the barge was able to recover more vapor return and maximize the flow rate.

Thanks to pump variable speed and automatic control valves, bunkering flowrate and vapor return are automatically controlled.

In total, 1,000m3 were transferred within 4 hours with a maximum flowrate at 280m3/h. It is to be noted that the bunker mast was designed based on maximum flowrate of 500m3/h with a maximum back pressure at 4.5 barg. In this case, the maximum flowrate was calculated in order to maintain the LFS tanks pressure at 5.5 barg.

After the first transfer was completed, a pressure rise test with no gas consumer was completed to confirm the trends during the gas trials. The barge tank has been isolated, and the pressure increase over 16 hours was about 355 mbarg which corresponds to a pressure rise rate of 22 mbarg/h confirming the trends observed during gas trials.

Without gas consumers, the pressure has been then collapsed thanks to spraying from 355 marg to 211 mbarg. This method allows to significantly increase the hold time (time to reach the maximum tank pressure set of 700 mbarg). If such trends are confirmed from future tests, this means that such methods can help increase the hold time by a factor of 2.4, meaning that with no gas consumers it will take 2.4 days instead of 1 day to go from 50 mbrag to 700 mbarg.
Figure 19 show some pictures of the barge alongside TOTE LNG-Fueled Ship

![Barge connected to LFS](image)

**FINAL REMARKS**

To date, several bunkering operations have taken place, allowing TOTE to gather more and more operations experience. While the LNG systems detailed design and integration proved a challenge, the strong collaboration between all stakeholders including regulators was a success, as well as the construction of the membrane tank by CONRAD completed 20 months before the barge delivery.

This concludes an unprecedented project and international collaboration to provide clean, safe and reliable LNG fuel to TOTE and beyond.

We thank all the stakeholders of the Project for their strong collaboration.