Ship to shore transfer – a new approach

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Abstract

LNG is the fastest growing hydrocarbon fuel in the foreseeable future. Capacity for liquefaction and shipping is coming available but a shortfall in import capacity threatens. In China this is a result of the congestion of port infrastructure due to rapid economic growth. Hence offshore LNG import terminals may be an attractive alternative.

This article, based on a paper presented at June's LNG Tech Asia Pacific conference in Shanghai, describes the design of a Single Point Mooring (SPM) system in combination with a subsea cryogenic pipeline for 'ship to shore' transfer of LNG. It discusses the design considerations for the key components and systems involved, and control and safeguarding systems.

The design work done shows that an LNG SPM is fully feasible. Although new in arrangement, all of the components are proven and have been used in terminals and offshore developments. An LNG SPM in combination with a subsea cryogenic pipeline allows an LNG import terminal with superior marine operations and greatly enhanced layout because of a large separation between the LNG carrier and other (existing) terminals and/or port facilities.

Introduction

China, the world's most populous country, is the second largest economy and the second largest consumer of primary energy after the United States. China's total primary energy demand will grow from 1242 million tonnes of oil equivalent in 2002 to 2539 by 2030, a 2.6% compound growth per annum. Coal is still the dominant fuel in China, but the share of oil, natural gas and nuclear power in the energy mix will grow. Oil consumption is expected to rise from 247 million tonnes in 2002 to 636 million tonnes in 2030, 25% of total consumption. Gas consumption is expected to rise from 36 billion m^3 to 158, or 6% of total consumption over the same period. The projected growth in gas demand will outpace the domestic gas production; 36 billion m^3 2002 and estimated at 115 billion m^3 in 2030, according to the World Energy Outlook - 2004 [1]. Note that these numbers are conservative: Chinese officials have announced that gas consumption will be 6% of total energy consumption already by 2020 and that 40% of gas imports would be satisfied by LNG imports. As a result, China will need to increase its gas import capacity. Australia will start sending LNG to the Guandong terminal by 2006. Later Indonesia will supply the Fujian terminal.

As further sources of LNG supply, Iran, Yemen and Sakhalin have been mentioned. So far, the China National Offshore Oil Corporation CNOOC has been the dominant force with two LNG import terminals under construction and a further nine announced. But also the China National Petroleum Corporation (CNPC) and the China Petrochemical Corporation (Sinopec group) have announced terminals, see *Table 1.* It is unlikely that all projects will proceed and a fierce competition is expected between the rival companies.

About the author

Max Krekel, senior naval architect, hull and marine systems, has been with Bluewater since 1986 in various positions. He was responsible for the conversion engineering of the FPSOs *Uisge Gorm* and *Glas Dowr*, and has been closely involved with a number of joint industry projects on FPSO design and operation. Since mid-2001, he has been based in Houston to support Bluewater's business development activities there. He holds a BSc in naval architecture from HTS Haarlem, The Netherlands.

Comparing the investment for an LNG project to that for a 'traditional' oil field development, the most striking difference is the capital required: an LNG project is nearly an order of magnitude more expensive. At the Zeus conference on non traditional LNG receiving terminals [2], a breakdown was given of the LNG supply chain costs which indicated that the receiving terminals only represent ~10% of the total investment. Even a substantial cost reduction in the import terminal will have a marginal effect on the overall project economics and thus the project developers have been extremely conservative in the selection of their terminal technology concepts as not to put the total project at risk.

LNG terminal location and layout

During the transit from the open sea to its terminal berth and return to sea, an LNG carrier will be exposed to the same profile of operational risks as any other ship of similar size in the same operational theatre. However, the consequences of severe structural damage to the LNG carrier may be far more serious. Hence every phase of the port transit must be analyzed to eliminate any credible probability of the carrier sustaining serious hull damage. This requires an assessment of the actual infrastructure, eg anchorages, approach channels as well as the associated port services such as pilotage, tugs and Vessel Traffic Services (VTS). The most important single determinant of risk attached to LNG operations in port areas is the selection of the site, in specific the location of the LNG carrier berths. This determines the entire subsequent risk profile for the marine operations: the approach channel, the berthing and un-berthing maneuvers, proximity to other port traffic and external ignition sources.

It is common practice to maintain a 'moving' exclusion zone around a transiting LNG carrier in which no other traffic is

Co	City, Province	Status	Year of startup	Initial capacity (MM tpa)	Final capacity (MM tpa)
CNOOC	Guangdong	a	2006	3.7	
CNOOC	Putian Fujian	a	2007	2.6	5.0
CNOOC	Shanghai	b	2008	3.0	6.0
CNOOC	Hainan	c	2009	2.0	3.0
CNOOC	Qinhuangdao Hebei	c	2010	2.0	3.0
CNOOC	Shantou Guangdong	c		2.8	
CNOOC	Guangxi	c			
CNOOC	Binhai Jiangsu	c		2.8	
CNOOC	Yingkou Liaoning	c		2.8	
CNOOC	Tianjin	c			
CNOOC	Zhejian	c			
CNPC	Tangshan Hebei	b	2009	3.0	6.0
CNPC	Rudong Jiangsu	b	2009	3.5	6.0
CNPC	Dalian Liaoning	b	2008	4.0	6.0
CNPC	Guangxi	c			
Sinopec	Qingdao Shandong	b	2008	3.0	5.0
Sinopec	Rudong Jiangsu	c			

Status: a = under construction, b = appr. by SDRC, c = announced

Table 1: Status of China's LNG import terminal projects.

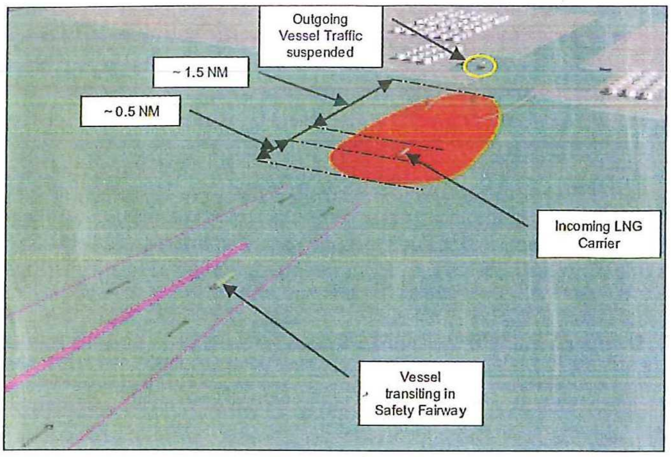


Figure 1. Moving safety zone around an LNG carrier.

permitted to enter in order to prevent an encounter that could have the potential to penetrate the hull, see *Figure 1.* The exclusion zone typically extends 1-2 nautical miles (nm) ahead and astern of the vessel, while traffic is not allowed to cross closer than 1.5nm ahead and 0.5nm astern. In ports with narrow access channels traffic coming from the LNG carrier's opposite direction will be stopped completely or halted in a passing place [3]. Thus the impact of LNG traffic on other port operations is significant and will affect the economics thereof.

Ports have dynamic environments; the pattern of their operations changes over time and with that the profile of their operational risk. Hence a terminal that was initially well sited may later be confronted by developments long after its operations are established. This particularly holds true in China where a tremendous economic growth necessitates the use of the existing port facilities to the maximum extent possible. Later developed port infrastructure and industrial complexes may prevent expansion of an LNG terminal. Also, the existing approach channels to the main ports in China may be too shallow to accommodate the upcoming 200,000-250,000m^3 class LNG carriers.

While the LNG shipping industry has a proven history of safe operations, the growing dependence of industrialized nations on imported LNG will have consequences for the security aspects of such operations. A recent study by Sandia [4] identified that the consequences from intentional breaches (eg terrorist attacks) can be more severe than those arising from accidental breaches. Worst case scenarios were identified that could have a high damage potential to critical infrastructure elements such as bridges, tunnels, industrial- & commercial centers, LNG unloading terminals harbors or populated areas in a 500-1600m range. Proactive risk management approaches that would reduce both the potential for and hazards of such events were identified as improved ship and terminal safety and security systems, improved LNG carrier escorts, vessel movement control zones, surveillance and searches, redundant or offshore mooring and offloading systems and improved emergency response coordination.

Offshore transfer of LNG

In the oil and petrochemical industry, similar constraints have led to the adoption of SPM terminals both for existing and new terminals; see *Figure 2.* These have proven to be very cost effective as there is no need to develop an extensive port infrastructure, eg channel dredging, breakwaters and jetties. Also the operation is more efficient and safe as navigation of congested waterways is circumvented, whilst the berthing of tankers at the SPM can take place with minimum tug assistance with vessels of virtually any size. Since the same reasons hold for LNG terminals, Bluewater recognized a need for a safe, efficient and reliable offshore LNG transfer system. As there is a wide variance in water depth and environmental conditions between the potential sites a whole suite of concepts has been developed to serve each application's specifics.

All concepts share a common philosophy:

- **High system availability.** The investments made in the LNG production and transport chain are large thus so are the costs associated with downtime of LNG production and/or demurrage of the carriers. High system availability is achieved by using weathervaning mooring systems, a robust flow path and a minimum number of cryogenic mechanical components. All concepts are based upon proven components.
- **Suitability for 'open' and 'dedicated' terminals.** The current market trend indicates that a spot market for LNG is developing. To allow flexible and efficient operation of the terminal facilities, it is essential that vessels of opportunity can be handled. Thus transfer of LNG in all systems takes place at the midship manifold and only a minimum of adaptation of the LNG carrier is required. At the same time, we recognized that the majority of projects are still developed on the basis of an integrated supply chain for the life of the field. Such terminals will handle a dedicated fleet of LNG carriers and modifications of the vessels to accommodate for instance a bow loading system will be a negligible investment in the greater scheme.

Fluid handling system

The key to safe transfer operations lies in the make-up and (emergency) brake-up of the flow path for LNG between the carrier's manifold and the mooring system's product system. The offloading equipment has been configured as a 'manipulator' from which the free end of either steel articulated loading arms or flexible catenary hoses are suspended. The advantage of this configuration is that it allows combining the free ends into a single assembly, handled by direct mechanical means. Individual hose or loading arm connections, although technically feasible, would lead to clash potential during high-offset emergency disconnects and also require more manpower in establishing first-line connections.

The principle of the manipulator is based on supporting the free end of the flowlines (flexible or rigid) from a tension leg, which maintains a slight vertical tension on the vessel interface while fully accommodating the relative wave frequency motions of the LNG carrier. The tension is generated by a counterweight which is moved in the fore-aft direction as a function of the

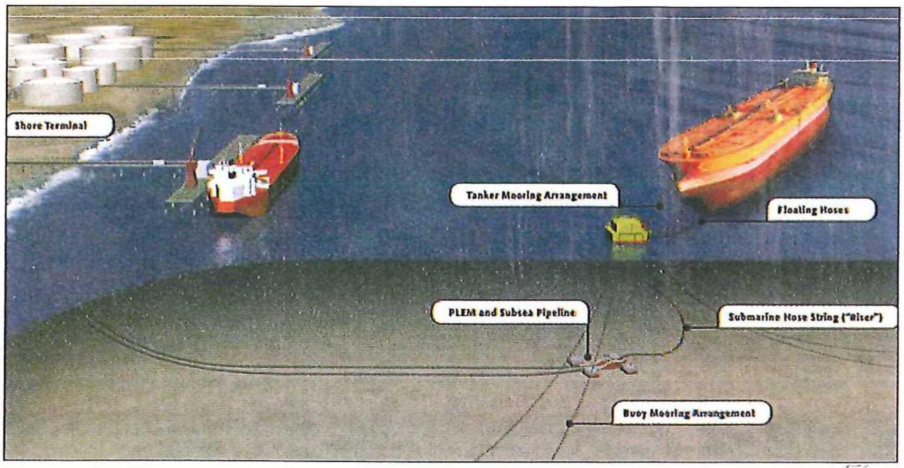
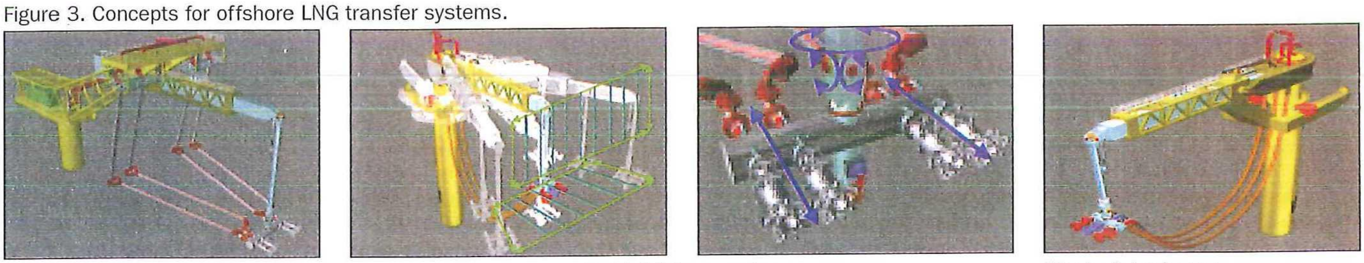
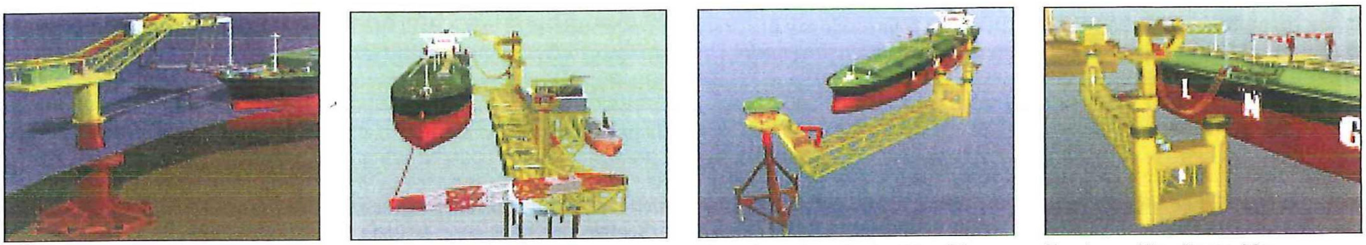


Figure 2. SPM-based terminal for oil.

Figure 3. Concepts for offshore LNG transfer systems.



Manipulator hard piping. Quick (dis)-connector. Manipulator hoses.



Bow offloading <40m. Shallow water terminal <40m. Nearshore terminal >40m-80m. Tandem offloading >40m.

stroking out of the horizontal boom. A redundant load pin measures actual tension in the tension leg and adjusts automatically the counterweight position.

When the tension leg experiences an angle of tilt, due to relative drift motions between mooring system and the LNG carrier, such angle is automatically detected and the manipulator's horizontal boom length and azimuth angle are automatically adjusted to bring back the angular value below a pre-set value, say <10°. The loads typically experienced by the manipulator assembly are in the same order of magnitude as normal offshore cranes and hence fully practicable. Since high frequency motions have no effect on the positioning demands, power demands are low.

Beyond the pre-set limits, the tension leg will automatically initiate disconnect whereby the entire connector part is lifted up and away from the carrier.

The connector in the lower part of the tension leg consists of a structural part and a multi-path flow part. All connectors are made up of standard commercially available components.

The structural connector is connected first, the flowpath connectors at that time still having a clearance at their mating faces of about 300-500mm. Once the structural connector is secured, the flowpath connectors are stroked out to make up the connection. The structural connector is winched-down against the slight over pull of the tension leg. This allows that the 'first line' connection is made in-phase and avoids impact loads in case of large LNG carrier roll events. All elements of the tension leg and its connectors are designed to fail-safe.

The concept of the 'manipulator' allows significant automation of functions which enhances safety and limits manpower demand.

The manipulator can be deployed from a mooring tower in a bow loading configuration, see *Figure 4*, or it can be configured to service the LNG carrier's existing manifold, see *Figure 5*, the so called 'Big Sweep' system.

There is a debate in the industry on the use of cryogenic hoses. Experience in offshore transfer of oil learns that hoses are preferred as they are more compliant than loading arms, have no mechanical components and therefore require no maintenance. There are a number of large diameter cryogenic hose designs 'technically ready' complete with class approval. However, most operators disregard them as they are not field proven and prefer hard piped loading arms, even though these have not been used in an offshore environment before. They consider the 'dynamic' cryogenic line swivels for such systems only a marginal technology increase from existing designs.

Note that the manipulator principle works both with hoses and loading arms.

Offshore LNG terminals

So far, the LNG industry has been more conservative, although some innovative concepts have been proposed, for instance by Ehrhardt [5]. In the US, where large scale LNG imports are expected a range of offshore LNG terminals have been announced, primarily to circumvent local community opposition to onshore LNG terminals. In their aim to mitigate technology risk, these new offshore terminal designs are based on traditional onshore technology; hence the selection of Gravity Base Structures (GBS), dolphin type mooring arrangements and transfer of LNG via loading arms. This technology approach overlooks the lessons learned in the oil and petrochemical industry where it is an established fact that SPM systems allow safe and efficient transfer of hydrocarbons in unsheltered waters.

It is our concern that the development teams, in their aim to prevent any technology risk, are in fact creating operational and security risks. The use of weathervaning moorings and transfer systems for the LNG carriers at a large distance from the LNG storage and/or re-gasification plant should be given serious consideration for the following reasons:

- Improved terminal siting. LNG carrier berths can be located away form confined waterways, thereby increasing safety and security while at the same time preventing costly civil works. Furthermore, impairment of future and existing shipping traffic will be minimized. With current subsea cryogenic pipeline designs, LNG can be efficiently transferred over

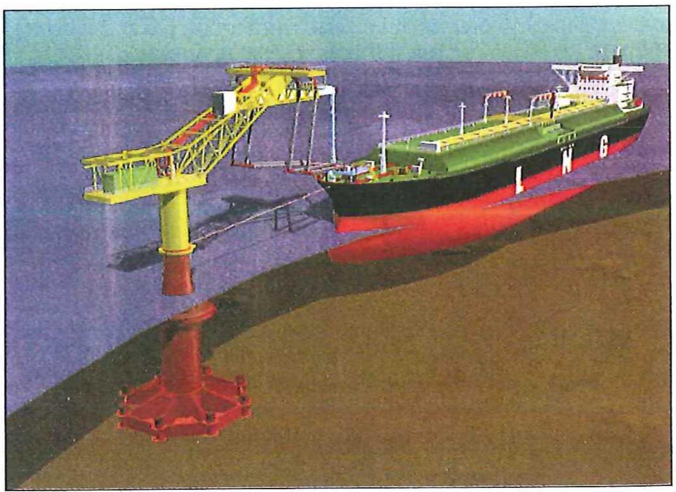


Figure 4. Tower mooring SPM and bow LNG transfer system.

distances of up to 20 miles.

- Separation of inventories, which will mitigate escalation of an incident on either the LNG carrier, the LNG and/or gas storage and the vaporization plant.
- Superior marine operations, as the LNG carrier will always approach the terminal 'up weather'. Should the approach for any reason need to be aborted, the LNG carrier will drift away from the SPM (fail to safe). A weathervaning system will also allow the possibility of roll mitigation and subsequent sloshing loads in partially filled prismatic tanks, by aligning the LNG carrier into the waves with the aid of a tug. Moreover, the LNG carrier's voyage time will be reduced as no lengthy transit needs to be made through confined approach channels to an inshore berth.
- Increased terminal availability, as mooring-, transfer- and disconnect operations can take place in more onerous conditions. For a non weathervaning berth, marine operations will be governed by tug operations. This will limit moor-up conditions, but more important, also (emergency) disconnect conditions as tugs may be required to pull the LNG carrier free from its berth. The latter implies that the weather window required will be the full duration of the discharge operation, ie up to unmooring: one can not start the operation if weather conditions do not allow abandonment of the operation at any moment in time.
- Expandability, as more SPM systems can be added with little extra costs to suite the terminals capacity.

Subsea cryogenic pipelines

Subsea cryogenic pipeline systems are an emerging technology that is essential for the new generation of offshore LNG loading and receiving terminals. It is a continuation of the pipe-in-pipe (PIP) technologies that were developed for subsea tie-backs of wells, that ensured the flow of the hot well effluent to remote production platforms. There are two major design issues: pipe contraction due to the low temperature of the LNG, and thermodynamic performance to ensure that LNG can be transferred without an excessive amount of boil-off.

So far, the methods to accommodate the line pipe contraction was to either revert to alloys that have an ultra-low thermal expansion, eg Invar, or to use of bellows, one in each segment (about 50ft long) of the pipeline, which is a self-contained pipe-in-pipe segment with vacuum insulation. While technically feasible, both methods suffer major disadvantages in cost, reliability, durability, or maintenance requirement. Another method is to restrain the contraction of the product pipe by anchoring it structurally in the carrier pipe.

To date, high value insulation was achieved by either maintaining a full vacuum in the annular space between the product and carrier pipe or by the application of micro-porous type insulation materials in combination with a partial vacuum. Recently, the extremely efficient nano-porous insulation materials have become available in commercial quantities. Use of these materials will enhance the thermodynamic performance of these PIP systems further, even without a (partial) vacuum.

The operation of the system normally relies on circulating a small amount of LNG through the pipeline via a return line in between LNG carrier discharges in order to keep the system in a cryogenic state. Maximum pipeline length currently claimed feasible is ~10 miles. Longer lines will be possible but require intermediate pressure boosting because of the limited head of the LNG carriers' pumps. Another advantage of elevating the LNG pressure is that the vapor boil-off is minimized. Consideration should be given to monitoring the pressures and temperatures within the cryogenic carrier pipe and in the annular space to check the efficiency of the thermal insulation and to detect internal leaks.

Key to the selection of a subsea cryogenic pipeline configuration is the consideration given to how the pipeline section can be fabricated and installed for the particular application as each line must be designed for a site specific application. The pipe-in-pipe configuration chosen is similar to the bundled pipeline configurations that have been installed through-out the world over the last 20-years, so the construction techniques used are familiar to the marine construction industry. These techniques were pioneered in the Gulf of Mexico and North Sea. A more complete treatise on subsea cryogenic lines is given by Prescott [6].

DOE/NETL study of 'Bishop Process'

Bluewater participated in a cooperative research study sponsored by the US' Department of Energy's National Energy Technology Laboratory (DOE/NETL) and conducted by Conversion Gas Imports (CGI) LP on their so-called Bishop Process [7]. The objective of this research was to design, construct, field test and evaluate the performance of key components of a salt cavern based LNG receiving facility and to describe their application in LNG receiving facilities in the Gulf coast. The study allowed the participating companies to further develop the key components for the new generation of offshore LNG terminals, among others weathervaning LNG offloading systems and subsea cryogenic pipelines.

In short, the Bishop Process comprises direct vaporization of the LNG and storage of the produced gas into man made salt caverns. Vaporization, or rather re-gasification, is done in dense phase using seawater as warmant in a proprietary designed heat exchanger, the Bishop Process Exchanger (BPE). The process has significant advantages over more traditional processes: it eliminates the need for cryogenic storage, resulting in a major capex saving. The main hydrocarbon storage is underground and may be dislocated from the mooring terminal and last but not least, a very rapid response to send-out demand can be achieved: from zero to maximum capacity in the order of minutes. Note that the Bishop Process requires the presence of salt formations and is therefore restricted to certain geographical regions.

'Vermilion 179' LNG import terminal

Bluewater, under contract to CGI, developed the conceptual design for an offshore LNG mooring and transfer system to a definition that allowed exploratory health, safety, security and environmental (HSSE) studies and an indicative cost estimate. The terminal consists of a mooring and transfer system located at 1nm away from a process facility.

The LNG carrier discharges its cargo via a weathervaning Single Point Mooring (SPM) system and a subsea cryogenic pipeline system to the remote re-gasification platform where it is vaporized and stored into the salt caverns and from thereon sent to the grid.

The pipeline connection between the SPM and the re-gasification platform comprises dual pipelines to allow recirculation of LNG between discharges. This keeps the subsea cryogenic pipelines at a temperature that minimizes vapor boil off and keeps them in a ready state between tanker un-loadings. An alternate to the dual pipeline configuration has been developed by Ehrhardt [5] and incorporates a smaller recirculation line nested within the larger cryogenic carrier pipe. The planned pipeline is approximately 1nm in length, which is well within the existing construction capabilities of the industry.

Note that it has not been the intent of the study to arrive at an optimized configuration, but rather at a working first implementation, based on the designers' experience. Summarizing the main particulars for Vermilion 179 site:

- located 47 miles south of the Louisiana coast,
- water depth of 100ft,
- top of salt at 1000ft below seabed, and
- within close proximity of three major gas gathering systems, ie Texas Eastern, Blue Water and Sea Robin allowing a peak send-out capacity ~2.5bcfd.

Mooring and discharge from the LNG carrier will be via an SPM system. This will be of the 'Big Sweep' type which consists

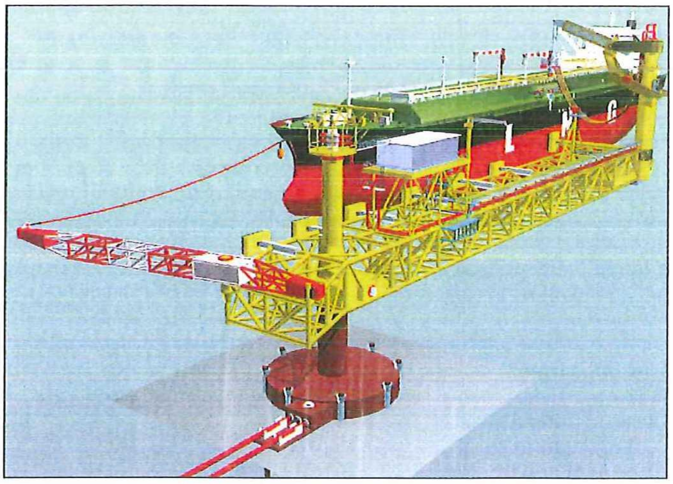


Figure 5. 'Big Sweep' SPM and LNG transfer system.

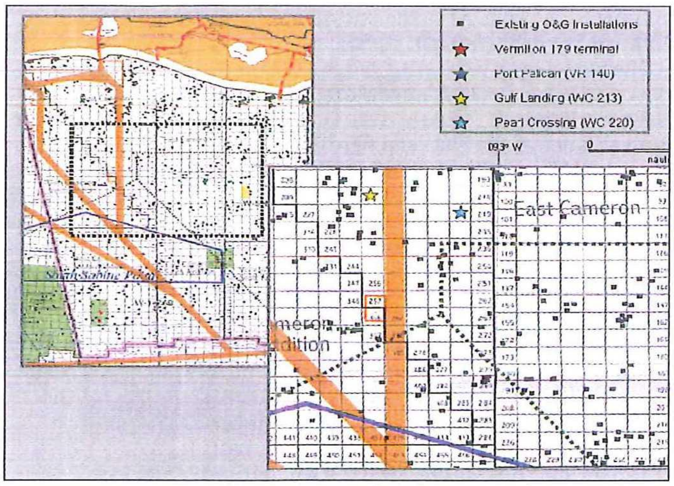


Figure 6. Location of 'Vermilion 179' LNG receiving terminal.

of three basic elements, (see *Figure 5*):

- a monopod structure with a swivel deck, piled to the seabed, from where the subsea cryogenic pipelines are anchored off,
- a partially submerged semi buoyant Rigid Truss Arm suspended from the monopod, a mooring outrigger fitted at its forward end from which a hawser assembly is deployed, its aft end terminating with a buoyant column, and
- an LNG transfer system, starting at the LNG carriers manifold and ending at the seafloor at of the monopod structure.

LNG carriers tie up to the mooring outrigger fitted on the forward end of the truss arm by means of a bow hawser. The overall length of the rigid arm is such that the buoyant column is positioned nominally near the midship cargo manifold of the LNG carrier. By adjusting the length of the mooring hawser, the carrier's cargo manifold can be lined up to the offloading station for vessel sizes ranging from 125,000m^3 to 200,000m^3 storage. For a more complete description of the 'Vermilion 179' terminal refer to OTC 16717 [8].

Marine operations

In order to maintain a maximum send-out of 2.5bcfd, up to five LNG carriers per week need to be discharged; this incurs 24 hour operation. Although the terminal is located offshore, navigation to the site will not be unrestricted because of the large number of oil and gas installations in the area, see *Figure 6*. Considering that three more LNG terminals have been announced in the same region, a high number of LNG related marine operations is expected which, in combination with the existing oil and gas operations, will need some sort of overall coordination and planning, for instance in the form of a vessel traffic management system. Ship arrivals at the terminal can be normally planned within hours; however an anchorage area close by is planned to cater for any shipping disruptions, eg after a hurricane. An aside observation is that even though all currently planned LNG import terminals are 'project based', terminals that are able to handle 'cargos of opportunity' will have a significant operational advantage, eg by accommodating an incoming vessel destined for a nearby terminal that is temporarily out of operation.

LNG carriers are foreseen to navigate via the existing Safety Fairways to Sabine Pass to a latitude of 28°50'N from where they would take an easterly course, into the prevailing weather, towards the Vermilion 179 terminal, some 35nm distant. Along this leg one or two escort tugs will connect, depending on the handling characteristics of the LNG carrier. At the terminal site the tug(s) will deploy to 'fully tethered' mode to control the maneuvering in close quarters and the carrier will continue dead slow to the SPM. A messenger line will be transferred from the carrier and connected to the pick-up rope which in turn is connected to the mooring hawser assembly, see *Figure 7*. The LNG carrier will winch itself in and secure the hawser chafe chain in its bow stopper, in line with standard oil tanker procedures. The forward tug, if present, will now disconnect. The aft tug will remain tethered at the stern throughout the duration of the discharge operation. This is primarily as back-up in case the propulsion of the LNG carrier fails, but also to 'tension up' the system and make it more stable in very light environments, or to provide heading control for roll mitigation. Once the operation is complete, the LNG carrier will disconnect and the stern tug will pull it away. When sufficiently clear the LNG carrier will continue its voyage under its own power in a westerly direction back towards the safety fairway.

Model basin tests

An important part of the cooperative research study was to perform a model basin tests. The main objective was to prove the feasibility of the system. The water depth of about 30m and hurricane conditions result in onerous survival conditions during which the loads on the structure can become significant. Also the clearance of the arm with the seabed may become critical and had to be investigated.

During operational conditions, the relative motions between the LNG carrier and the structural arm are of importance. The distance between the two bodies and the dynamics shall remain within certain limitations to safely transfer the LNG. Operational tests allow to assess the operability and to determine the main required characteristics for the DP system.

Finally, test results are used to calibrate numerical software tools, to be able to further analyse and optimize the configuration.

Prior to the model tests, an initial analysis has been executed to determine the main load levels to be expected in the structure. By doing this, the size and amount of braces can pass a first

Figure 7. Mooring up of LNG carrier to 'Big Sweep'.

optimization cycle. Also, the buoyancy element was designed to obtain a favorable natural period of the arm.

The model tests were executed in the Offshore Engineering Basin (OEB) of Oceanic Consulting Corporation in St John's, Newfoundland, at a scale of 1:40. Oceanic Consulting Corporation is an alliance of the National Research Council of Canada, Memorial University of Newfoundland and the private sector. The average LNG carrier size to berth at the loading facility will be an approximate 135,000m^3. The terminal has been designed to accommodate both membrane as well as spherical tank carriers. Vessels with spherical tanks are heavier and have larger windage than membrane tankers, thus a typical spherical LNG carrier has been used for this model test series. The LNG carrier was moored via a 60m bow hawser to the outrigger. The rigid truss arm was equipped a thruster. A relatively simple control system has been modeled to actively control the distance between the end of the arm and the LNG carrier's midship manifold.

The following signals have been measured:

- Tanker motions: surge, sway, heave, roll, pitch and yaw
- Buoyancy column positions: X, Y and Z and pitch & yaw
- Tower loads: Fx, Fy, Fz, Mx, My
- Hawser tension
- Thrust of DP system
- Bending moment truss: mid span of truss
- Relative wave motions: at tower, bending moment transmitter and the column.

Besides the main signals measured, the following have been derived from the measurements:

- Accelerations in 6° of freedom for the buoyancy column centerline at the top of the column (40m above 'keel' level)
- Tanker motions at starboard midship manifold (145m aft bow)
- Combined horizontal signal for tower loads
- Horizontal distance between starboard manifold and buoyancy column at centerline
- Clearance between bottom of buoyancy box and sea-bed.

Two types of environmental conditions were calibrated and tested. These conditions reflect the maximum operational conditions desired and the 100-year hurricane survival conditions.

Static and calibration tests were done in order to obtain specific characteristics of the structures like natural frequencies, damping as well as drag loads at different angles in current.

Irregular wave tests were performed, in which the Big Sweep structure was exposed to a combination of wind, current and random generated waves for two different environmental conditions:

- Hurricane conditions that govern the structural design and integrity of the Big Sweep,
- Operational conditions that determine the requirements for the DP system and the tanker mooring hawser. Different combinations of wind, current and wave directions were tested.

Moreover, regular wave tests were executed to investigate the response of the Big Sweep structure in waves with different heights and periods. Results of these types of tests are very valuable for calibration of analytical tools.

Model basin test results

The following observations outline key results from the survival condition tests:

- The maximum tower loads were experienced during the crossed survival condition. The order of magnitude was 20,000kN horizontal load.
- The maximum range of pitch angle experienced by the arm for collinear survival conditions was 4.8° while for the crossed conditions it was 6.0°.
- Minimum seafloor clearance of about 12m occurred.

The key observations made from the operational tests were the following:

- Loads at the tower reached a maximum of 5800kN with an upper mean limit of 1750kN. Generally, the tower loads decreased as the environment moved from a collinear direction to the crossed direction. This may be due to the sheltering effect the tanker has on the arm in the crossed conditions.
- The maximum hawser load did not exceed 1780kN.
- The tanker experienced some fishtailing depending on the environment. This was more apparent in the collinear environments than in the oblique and crossed cases.
- The DP system as modeled proved adequate for controlling the arm and maintaining separation from the tanker. During hawser break tests, the DP system also proved adequate in moving the arm clear of the tanker.

The model tests clearly showed the feasibility of the Big Sweep concept, both in terms of survivability during Hurricane conditions and operability during the vast majority of time in the Gulf of Mexico.

The following quotes come from the report prepared by Oceanic Consulting:

> "Throughout the tests, general observations showed that the arm and tanker would prove adequate for this type of mooring arrangement"; and
>
> "Overall, nothing observed during the tests indicates that such a setup will not be able to operate in the conditions tested."

Apart from the visual observations, captured by video recording and photos, an enormous amount of data was acquired by measurements. This data has been and will continue to be used extensively as input for structural analysis, establishment of functional requirements for sub-systems as well as for calibration of numerical tools to further analyze and develop the Big Sweep mooring system.

Conclusion

Offshore LNG receiving terminals can be an economic, safe and secure alternative to land based ones, provided that the experience gained in ~40 years of offshore oil terminal operation and design is respected. Mitigation of technology risk, by qualifying only proven onshore equipment and configurations, will have an adverse effect and in fact incur operability and safety risks.

Terminals offshore, located far from populated areas and congested ports will heighten community acceptance and reduce security concerns.

The conceptual design studies, the analytical analysis and the model basin tests confirm feasibility of 'Big Sweep' concept. The conceptual design studies, the analytical analysis and the preliminary flowline LNG tests confirm the feasibility of the subsea cryogenic pipeline concept. **OE**

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