Offshore LNG receiving terminals, new architectures

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1. Introduction

With the rise in natural gas consumption, many countries are constructing their LNG receiving capabilities, and will continue to do so in the coming years. Yet, in some industrialized or populated areas, it sometimes proves difficult to overcome environmental concerns of local residents to install a new-built, land-based terminal due to the NIMBY (Not In My Back-Yard) syndrome. Offshore LNG receiving terminals provide a way to overcome these troubles, and thus both floating (FSRUs) and gravity base (GBSs) solutions have been developed.

Gravity Base Structure LNG receiving terminals (LNG GBS) were the first to be developed and later, to be considered mature. Indeed, GBS rest on the seabed and hence some of the issues linked to floating LNG terminals (e.g. LNG transfer at sea) appear to be far less critical. One somehow re-creates an artificial (concrete) island to host an LNG terminal.

Through the various projects on which GBS’ have been developed up to engineering or bidding stages, a particular design seems to emerge as an “industry consensus”, whereby all terminals’ functions are gathered on one single concrete structure described below. This looks effective; however, gravity base offshore terminals economics usually do not compare favorably to onshore terminals’. Hence, this design has been challenged in an attempt to bring down the CAPEX of the facility on a typical case (see table 1). Options have been considered for each sub-system of the terminal, and then assessed technically and economically:

- Storage tanks architectures: rectangular or cylindrical tanks
- Containment systems families: membrane or self-supporting (9% Ni steel tank, SPB)
- Process and utilities: on tanks, on an-other structure (concrete caisson, steel jacket)
- Offloading operability: need of a long breakwater structure?

The new architectures developed are presented in a first part of this article, together with the advantage they bring.

Floating Storage and Regasification Units (FSRUs) have also been developed, and have gained in the past few years a new interest from customers. A number of projects have reached advanced engineering phases (e.g. the Livorno project offshore Italy) and enabled to make progress on the design of such facilities.

Yet, these projects have generally been considered into significantly smaller storage and regasification capacities compared to onshore or GBS receiving terminals projects under development today. Building on the experience gathered during the extensive works that have been performed on smaller capacities FSRUs, a design of floating LNG receiving terminal has been developed for a significantly increased throughput and storage capacity, and is presented in a second part of this article.

The various capacities of the studied terminals are indicated below.

<table>
<thead>
<tr>
<th>Location</th>
<th>Studied GBS case</th>
<th>Studied FSRU case</th>
<th>Livorno case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity (m³)</td>
<td>250,000</td>
<td>320,000</td>
<td>137,000</td>
</tr>
<tr>
<td>Design throughput (bcf/d)</td>
<td>1.0</td>
<td>1.3</td>
<td>0.46</td>
</tr>
</tbody>
</table>

**Table 1: GBS and FSRU terminal capacities**
2. Gravity Base Structures new architectures

2.1. Introduction and design basis

A gravity-based offshore LNG receiving terminal fulfills some specific functions, among which:

- **Berthing/loading:** the LNG carrier must be able to unload its cargo in open sea. The GBS must have berthing equipment adapted to the different size of ships that will unload their cargo. A sheltering can be provided by the GBS so as to increase the operability of the terminal and be able to unload in most weather conditions.

- **LNG Storage:** LNG carriers unloading operations take place every 3-4 days, while the regasification is a continuous process. A buffer is necessary as the LNG carriers unload their cargo faster than it is vaporized. The terminal must have a sufficient LNG storage capacity to be able to send gas continuously between two unloading operations.

- **LNG regasification:** the primary function of a terminal is to vaporize the LNG shipped by the LNG carriers, in order to feed the local gas network,

- **Constructability:** the GBS is built onshore and installed offshore. This generates some constraints on the design of the structure, such as e.g. general dimensions of the structures or draft during towing.

Compared to its equivalent onshore counterpart, the GBS terminal has proven to pay a cost penalty, which is a usual phenomenon when putting facilities at sea. Narrowing the Capex gap with the onshore solution is hence a challenge for these terminals. Building upon the experience of the existing GBS designs, a development program has been performed in order to evaluate alternative GBS architectures. The optimization work has been based on a typical Gulf of Mexico delivery, with the following main functional assumptions:

<table>
<thead>
<tr>
<th>Studied GBS case</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Gulf of Mexico</td>
</tr>
<tr>
<td>Net storage capacity (m³)</td>
<td>250,000</td>
</tr>
<tr>
<td>Design throughput (bcf/d)</td>
<td>1 (equiv. 7.7 MTPA)</td>
</tr>
<tr>
<td>Water depth at site (m)</td>
<td>20</td>
</tr>
<tr>
<td>100-yr wave data (m)</td>
<td>Hs=7.0m Tp=11.2s</td>
</tr>
</tbody>
</table>

Table 2: Main GBS functional assumptions

2.2. Reference architecture

Through the various projects on which GBS’ have been developed up to engineering or bidding stages, a particular design seems to emerge as an “industry consensus”. It features one (or two) large rectangular concrete box (es), inside which the LNG storage tanks are fitted. Conventional regasification facilities, utilities and living quarter are installed on top of the concrete box. The concrete structure is usually designed such that it provides a long protective wall, alongside which carriers can come and berth in order to offload LNG in the sheltered area obtained.

The reference architecture (“shoe box”) consists of two rectangular caissons of nearly 200m long and around 70m wide housing each one LNG tank of 160m x 40m x 28.5m. These caissons are made of typically high performance, normal density reinforced and post-tensioned concrete with 60 MPa cube strength. Such structure brings a number of advantages in terms of durability, and its strength and resistance to external hazards (impacts; fires) are unmatched. Concrete structures also have a large track record of long-term use at sea (e.g. the NKossa concrete FPU, reference 1). All this makes them particularly well suited to host LNG storage tanks and segregate them from the topside facilities onboard the GBS, with a high safety standard.

The total concrete volume for the GBS is around 115,000m³. The structure is typically built in a graving dock before being put afloat.

The caisson is topped with a single-leveled topsides deck of 7,700 tons, spread over the whole surface of the concrete structure, and will be integrated on the concrete structure in the graving dock before its tow out to the final terminal installation site.

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2.3. Optimization process and identification of solutions

The first step of the study consisted in identifying ways of optimization to be explored. The following main elements were selected:

- **LNG storage tanks.** Their geometry can be challenged (parallelepiped as in shoe box design, or cylindrical tanks as built onshore) as well as the containment type (membrane or self-supporting tanks, e.g. 9%Ni Full Containment or SPB)
- **Overall layout** of the terminal and relative positioning of storage / process / offloading facilities. The relevancy of building multiple independent elements with each its specific function, rather than one single massive structure gathering all the functions of the terminal, has been evaluated. For instance, process and utilities can be located on the tanks or on an independent structure (e.g. steel jacket).
- **Process and utilities.** Although a conventional regasification process has been chosen, flat or compact, module-type architecture can be chosen for the topsides.
- **Offloading operability:** the need of a long continuous breakwater has been evaluated.

Various ways to combine these design features exist, and entail radical changes to the overall arrangement of the terminal. The effective potential of several configurations was assessed through technical feasibility studies such as:

- Structural analysis of the concepts,
- Analysis of compacted topsides arrangement (layout, structural design, and safety)
- Assessment of requirements to provide a large sheltering zone to enable LNG carriers unloading.

Finally preliminary cost and schedule analyses were performed to assess the relative gains brought, all of these based on installation of the terminal in the Gulf of Mexico and construction of all structures in the US, typically Texas.

2.4. Proposed configurations

All solutions identified as most promising by the preliminary analyses were based on cylindrical concrete tanks lying on concrete caissons. Actually, cylindrical tanks stand today as the solution of choice for onshore applications and hence optimized – they are known to be most effective to store liquids. Thus, the driving idea was to adapt these tanks to an offshore application, with as few modifications as possible. The following then needed consideration:

- In onshore tanks, the concrete outer tank is only fixed at its base, so that it can directly contain LNG in case of failure of the inner tank, without cracking under thermal strain. Thus, the adaptation of onshore tanks to an offshore application requires letting the walls of cylindrical tanks free to contract.
- Foundations of onshore tanks cannot be directly transposed offshore. The GBS must have an “artificial” foundation so as to gain sufficient deadweight to rest on the seabed. The tank is built on a stiffened concrete caisson, typically around 8m high. This caisson is able to withstand the irregularities of the soil and the weight of the LNG.
and the structure. The caisson itself is ballasted with seawater for on-site stability purpose. Depending on site specificities, the caisson may be fixed on the seabed thanks to concrete skirts that penetrate in the soil.

- Tanks need to be protected from wave & boat impacts, as well as from permanent seawater contact. The chosen solution was to create a secondary stiffened concrete barrier around the tank and above the concrete caisson that can withstand wave pressure and boat impact without being directly connected to the tank itself. This barrier provides a "dry" space around the tanks where solid dry ballast is then installed to further ensure on site stability of the structure.
- Topsides cannot be installed above the cylindrical tanks, as their dome-shaped roof cannot withstand such load. As a consequence, topsides have to be installed on another supporting structure. This implies that they be compacted, so as to limit the size and cost of that structure.

Regarding regasification process and utilities, a conventional process flow scheme has been chosen, in line with previous works performed on onshore & offshore terminals. In particular, the vaporizers used are Open-Rack Vaporizers (ORVs).

From the equipment list derived, the effort has been focused on how to reduce the footprint of such processing facilities, while keeping uncompromised safety, operability and maintainability levels. This was made possible from expertise gained on previous projects (LNG carrier’s conversions) for which compact regasification plants had been engineered.

Based on these considerations, several configurations have been studied and compared to the reference “shoe box” GBS. Two of these are further described below.

### 2.5. Solution #1 overview

**Overall layout and structural arrangement**

LNG is stored in two LNG storage tanks that lay on the same rectangular, 170 x 100 x 8 m concrete base caisson. Similarly to the reference case, this concrete structure is made of reinforced post-tensioned concrete with 60 MPa cube strength. This structure serves as a foundation for the LNG tanks, and also acts as a double slab to provide structural strength to their base.

Above the peripheral walls of the structure, an external concrete barrier is built so as to protect the storage tanks. Concrete stiffeners provide to this barrier sufficient rigidity to withstand wave and boat impacts. Its height is sufficient to prevent water overtopping.

The berthing and unloading facilities are also located on the same caisson. The topsides and the living quarters are supported by independent jackets, distant by 50m from the main concrete caisson to which they are connected by steel bridges. The flare is on another jacket, away from the main topsides deck.

![Figure 2: Outline process flow scheme](image-url)
LNG storage tanks
Two cylindrical concrete tanks, with a diameter of 67.5m and height of 50m provide storage capacity. Inside the outer concrete envelope, a system is installed to provide insulation and containment of LNG. This system can either be an inner 9%Ni steel envelope completed with insulation, or a membrane-type system. Both type of tanks, Full Containment and membrane, have good track record and provide the high safety level required by such offshore facility.

Process and utilities facilities
The topsides layout has been designed so as to obtain a compact arrangement (on two levels), taking into account structural and safety issues. A two-leveled deck has been designed, with overall dimensions of 63x47m, and weight of 7,000 tons. Distinct areas have been segregated:
1. All the equipments dealing with gas are gathered on one side of the deck,
2. They are separated by a blast & fire wall from the other utilities equipment (in particular the power generation),
3. In addition, emergency equipment and living quarters are installed away from the process platform, on a separate jacket.
LNG unloading
Transfer of LNG from LNG carriers to the terminal is achieved by means of conventional loading arms enabling the complete transfer operation from the LNG carrier to the terminal to be done in about 12 hours. LNG carriers come alongside the concrete caisson to berth. Mooring hooks are located on the concrete caisson itself and on additional dolphins.
The GBS provides only a partial sheltering over the length of the LNG carriers compared to a traditional “shoe box” GBS which is far longer. Such configuration is probably not suitable for all environments, but the Gulf of Mexico presents long periods of calm sea where offloading operations can take place, and rare but much harsher conditions during which no offloading operation at all can be performed, regardless of the sheltering provided by the GBS to LNG carriers. Statistical analysis of the sea states in the Gulf of Mexico show that an acceptable operability level may be reached even with a limited sheltering effect due to the GBS.

Construction
The concrete caisson and the tanks are built in a graving dock. The dimensions of the concrete caisson are selected so as to cope with a maximum allowed tow-out draft of 13m.
The topsides are fully built in a separate yard. These two packages are installed independently on the final site, before being interconnected. This configuration makes it possible to build independently topsides and tanks, thus limiting interfaces during construction. This comes with the need to install the topsides jackets and decks offshore, either by heavy lift or by float-over.

2.6. Solution #2 overview

This configuration goes one step further in spreading the various functions of the receiving terminal.

Each LNG storage tank lies on its own cylindrical concrete foundation caisson (100m diameter).

Four steel jackets of various size support:
1. The topsides,
2. The living quarters,
3. The flare,
4. The offloading facilities.

Steel bridges are required to connect all the structures / piping. Special care needs to be given to differential settlement between the various supports, which need to be taken into account for structural and cryogenic piping design.

The LNG carriers will berth and be moored on independent dolphins. In this configuration, the sheltering effect brought by the terminal to the LNG carrier, is much reduced. Hence a solution that is best suited for environments where calm day to day environment can be expected.
Such a solution is very flexible in terms of construction as the tanks, the topsides and the other platforms can be built independently from each other.

![Diagram](image)

**Figure 6: Solution #2 outline**

### 2.7. Comparison of concepts and conclusion

Cost estimates of the various concepts studied (two were presented above, some others were considered) have been performed. A number of items are similar whatever the terminal design, and most of cost differentials can be aggregated in a number of items:

- Civil works costs (mainly linked to concrete volume, but also to structural complexity),
- Construction site development costs, since graving docks need to be developed or adapted for all studied options,
- Containment system cost,
- Decks, jackets and bridges structural steel,
- Offshore installation and hook-up.

All the alternative solutions studied came up with the following main advantages:

- They led to lesser concrete quantities and hence civil works cost,
- They reduce the surface of containment system for an equivalent volume of LNG
- They enable to separate construction of various elements (tanks and concrete structures in a graving dock, jackets and bridges in other locations), which may result in increased schedule flexibility.

However, this comes with some penalties which may, depending on the zone where the LNG terminal is to be installed and local construction / installation capabilities, become significant:

- They led to increased structural steel quantities (jackets, bridges...),
- They require significantly increased offshore installation and hook-up so as to complete the connections between the various elements of the terminal - which in turn may adversely impact the schedule confidence. It also has a negative cost impact compared to installing a fully pre-commissioned unit offshore in one single block,
- They do not bring an equivalent level of sheltering of LNG carriers during unloading operations compared to the base case design, which makes these designs less adapted for harsher day-to-day environments. In areas with such metocean conditions, the terminal availability may be altered. Some ways may be implemented so as to...
restore adequate protection of LNG carriers (e.g. additional concrete caissons similar to those used for harbor breakwaters), they however counterbalance the civil works gain brought by these new architectures.

In conclusion, the various solutions studied seemed overall promising. Yet, the gains that have been identified change quickly depending on a number of “local” factors, which may come from technical (need of additional breakwater?) or execution matters (cost of offshore installation and hook-up). GBSs featuring cylindrical storage tanks may turn out to be more cost-effective than “shoe box” ones, but this requires particular validation for any project specificities.

3. Large capacity FSRU – an alternate to onshore receiving terminals

As for the GBS concept, the use of such floating unit avoids dredging and construction of port facilities and allows shuttle tanker operations to be kept away from congested waters.

Over the past few years, the requirements in terms of gas send-out capacity and availability of the LNG receiving facilities (currently onshore terminals) have considerably increased. Similarly to liquefaction plants, there exists a scale effect, with a lower marginal Capex per mt/day when the size of the terminal increases. Today, the new built terminals reach storage capacities of 320,000 m$^3$ with send-out capacity around 3 bscf/d. The second driving parameter of these facilities is their availability. Natural gas needs to be supplied to the grid on a continuous basis, and the terminals’ availability over one year is around 95% to 99%.

Up until now, the most advanced floating terminals concepts focused on small capacity units based on an adaptation of LNG carrier’s design, e.g. the EBRV of the Energy Bridge™ (Reference 6) or the Livorno FSRU. These smaller units in terms of storage and regasification capacity (140,000 m$^3$, throughput ~3.6 mtpy) do not aim at providing long-term and significant gas supply to a given area: they may stand as early gas delivery systems, or deliver a complement of gas to the grid. They may not be directly compared with onshore receiving terminals.

In order to propose a floating terminal which can stand as an alternate to an onshore terminal, a large capacity FSRU has been developed taking into account typical Gulf of Mexico conditions. It holds a storage capacity of 320,000 m$^3$ associated to a gas send-out of 1.3 bscfd (~10 mtpy). These characteristics are in line with requirements applying today for grassroots onshore LNG receiving terminals. In addition, work has been done to ensure that the unit meets industry requirements in terms of terminal’s safety and availability.

3.1. New-build FSRU. General features.

The large capacity FSRU was designed with a storage capacity of 320,000 m$^3$ LNG and an average regasification of 10 mtpy (1.3 bcf/d or 2650 m$^3$/h). The buffer LNG volume provides to the terminal, when operating at the design send-out capacity, autonomy for 5 days. LNG carrier’s rotations should then be, ideally, every 2 to 3 days so as to maintain an adequate level of buffer capacity (based on 140,000 m$^3$ tankers).

The floater is a double-hulled steel vessel, designed for a 20 years service life. LNG is transferred from LNG carriers to the FSRU at a 12,000 m$^3$/h flow rate, by means of conventional offloading arms.

LNG is stored in the hull, inside six dedicated tanks lined with a membrane containment system, achieving a boil-off rate of 0.15%/day. Membrane systems are widely used in LNG carriers, and the FSRU developed could use any of the membrane systems in use today (NO96, Mark III or more recently CS1) (Reference 7).

LNG is then pumped to the export pressure of 80 bars through in-tank submerged pumps and high pressure pumps, into the regasification equipment.

The gas is sent to shore via export risers, through the turret located at the bow of the FSRU. These risers are connected to a gas pipeline that sends the gas to the onshore network.

The FSRU is maintained stationary by a turret and mooring system, which enables it to freely weathervane.

Figure 7: LNG FSRU 3D view
3.2. Hull design

The FSRU hull has been designed to:

- Accommodate 320,000 m$^3$ of LNG in six dedicated tanks,
- Operate while permanently moored at a field location with a minimal water depth of 50 m under typical environmental conditions of Gulf of Mexico,
- House adequate water ballast volume and different tanks which can store operational fluids,
- Provide on its deck, a large area to support the process facilities, Living Quarters with helideck and all marine facilities.

The main characteristics of the FSRU are summarized in table 3.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loa – Length overall</td>
<td>m 345</td>
</tr>
<tr>
<td>B – Breadth</td>
<td>m 56</td>
</tr>
<tr>
<td>C – Depth</td>
<td>m 27</td>
</tr>
<tr>
<td>Δfl – displacement in full load condition</td>
<td>t 222 000</td>
</tr>
<tr>
<td>Draft in full load condition</td>
<td>m 13.5</td>
</tr>
<tr>
<td>Δbl – displacement in full ballast condition</td>
<td>t 102 000</td>
</tr>
<tr>
<td>Draft in ballast condition + full ballast tanks</td>
<td>m 11.3</td>
</tr>
</tbody>
</table>

**Table 3 : FSRU main features**

On port and starboard sides of the storage tanks, 6m wide lateral cofferdams enable to arrange water ballast compartments on the whole length of the hull. Under the LNG storage tanks, a 4m high double bottom hosts additional ballasting compartments. A central duct is kept dry for ballast piping maintenance. Hence the net maximum water ballast volume of 128 000 m$^3$. An additional tank of around 2500 m$^3$ is positioned at the stern side, under the accommodation, to compensate the trim of the FSRU. At the stern side, the various utilities fluids (incl. Fresh water, diesel oil, etc) are stored under the accommodation zone in dedicated compartments.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>m 44</td>
</tr>
<tr>
<td>Breadth</td>
<td>m 44</td>
</tr>
<tr>
<td>Height</td>
<td>m 32</td>
</tr>
<tr>
<td>Upper chamfer</td>
<td>m 10.5</td>
</tr>
<tr>
<td>Down chamfer</td>
<td>m 3.5</td>
</tr>
</tbody>
</table>

**Table 4 : Main tank dimensions**

![Figure 8 : FSRU hull plan, side and section views](image)
3.3. Regasification facilities and utilities

As depicted above, LNG regasification process and the associated utilities do not differ significantly from those used onshore.

Some equipment however deserved particular attention during FSRU design. This is the case of vaporizers. On the FSRU, the send-out capacity is achieved by means of (8+1) Intermediate Fluid Vaporizers (IFV), each with a 150t/h capacity. The annual send-out flow rate is reached with one vaporizer and one HP pump not running. The peak send-out flow rate is reached using all the equipment including the spare vaporizer and HP pumps.

Conventional vaporizers as those used onshore or on GBSs are not best options for floating facilities. Open Rack Vaporizers (ORV) offer challenges that cannot be overcome due to support motion, and Submerged Combustion Vaporizers offer (to a lesser extent) the same issues. IFV are better suited for the floating application. However, they are located longitudinally along the hull centerline so as to limit the impact of roll motion on these vaporizers.

To reach the peak send-out value, all the vaporizers (9) operate at the same time.

![Intermediate Fluid Vaporizer principle](image)

Similarly to vaporizers and HP pumps, all key critical equipment of the process (including in particular pumps, power generators) have a spare element in order to ensure an annual availability of the regasification plant above 99%.

<table>
<thead>
<tr>
<th>EQUIPMENT</th>
<th>Number of installed equipment x Capacity per equipment</th>
<th>Total available capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG unloading arms</td>
<td>3 x 33%</td>
<td>100%</td>
</tr>
<tr>
<td>NG return arm</td>
<td>1 x 100%</td>
<td>100%</td>
</tr>
<tr>
<td>In-tank pumps</td>
<td>8 x 17%</td>
<td>133%</td>
</tr>
<tr>
<td>BOG compressor</td>
<td>3 x 33%</td>
<td>100%</td>
</tr>
<tr>
<td>Recondenser</td>
<td>1 x 100%</td>
<td>100%</td>
</tr>
<tr>
<td>HP pumps</td>
<td>9 x 12.5%</td>
<td>112.5%</td>
</tr>
<tr>
<td>Vaporizers</td>
<td>9 x 12.5%</td>
<td>112.5%</td>
</tr>
<tr>
<td>Seawater vaporizer pumps</td>
<td>9 x 12.5%</td>
<td>112.5%</td>
</tr>
<tr>
<td>Gas turbines</td>
<td>4 x 33%</td>
<td>133%</td>
</tr>
</tbody>
</table>

Table 5: FSRU main features

All the topsides facilities located above the LNG tanks are elevated 5m above the deck to let air circulate in the process area (and evacuate possible accidental natural gas releases). They are supported by series of beams lying on the hull girders. Mainly safety has driven the process lay out. Following considerations were taken into account:

- Living quarters are located at the stern far from gas export lines located in the turret. This safe area accommodates the emergency diesel generator. On the contrary, all potential gas release sources (process + fuel gas system), and especially high pressure gas (from outlets of vaporizers to the turret), must be far from LQ and safe zones.
- Power generation and utilities are located between the process and the living quarters. The electric sub-station is placed between the power generators (using gas turbines) and the living quarters and a blast protection is provided. Sufficient distance is also provided between the air inlets of the power generators and the helideck, to avoid generating depressions that might endanger helicopters landing.
- The vent is located next to the turret (hazardous area). It is oriented laterally to move away gas releases from the process and to avoid excessive radiations, if the gas is burnt above export lines and vaporizers.
3.4. Berthing and unloading facilities

During the LNG carrier unloading operation, the oncoming LNG carrier and the FSRU are in side-by-side configuration. LNG transfer is performed by four rigid loading arms enabling a 12,000 m³/h LNG transfer rate. Compared to onshore arms, these are equipped with a targeting system developed for offshore LNG transfer, facilitating the connection operation between the two floaters. Such targeting system requires only a limited adaptation of the LNG carrier's manifold area, which design has been worked out in previous studies.

All marine operations, from LNG carrier approach to departure, as well as maintaining adequate side-by-side configuration, require that the FSRU be turret-mounted so as to weathervane freely. Additionally, thrusters mounted at the stern of the FSRU, help maintaining the wave heading of the FSRU during the various maneuvers as close to zero as possible, so as to limit especially roll motions.

The location and design of unloading arms have been examined for this particular application. Indeed, while for an onshore terminal the vertical position of unloading arms is fixed, the FSRU could experience significant draft variation between its full and ballast conditions. So as to be able to receive a range of LNG carriers, the ballast system of the FSRU had then to be adapted in order to limit the freeboard of the ship within certain range. So far such design does not enable to host very small LNG carriers (50,000 m³ typ.), which may for other reasons not be best suited to feed the large size FSRU. The design has rather been worked out to receive all LNG carriers with conventional size (in a typical 125 – 150,000 m³ range), and opens the door to receive later new large size 200,000 m³ carriers.

3.5. Sea keeping analysis

Hydrodynamic calculations have been performed to provide preliminary values of the hydrodynamic behavior of the FSRU. This hydrodynamic behavior is described through vessel RAO (Response Amplitude Operator) curves, which depend on FSRU's geometrical characteristics. The curves were obtained with a computation code DIODORE V3R3 developed by Principia (Reference 8), which can take into account the influence of liquid motion occurring inside the tanks on vessel hydrodynamic behavior.

Among the various works performed, some was dedicated in assessing for that application, the impact of cargo on overall sea keeping behavior of the unit, as a cross influence was expected for the large size FSRU. Two filling configurations have been studied, and some outline results given below:

- 97% of LNG in each tank (0 tons of ballast)
- 30% of LNG in each tank (47000 tons of ballast)

The calculations have shown that the strongest influence of the liquid motions occurred with the lowest filling level (30%) in surge, sway and roll motions. For the 97% filling rate, only the roll motions are significantly impacted. The RAO curves showing the most significant influences of liquid motion are given in figure 11.
Figure 11: Surge, sway and roll motion impacted by liquid motions

Note that the values obtained for roll motion are strongly dependant of the damping coefficient which is arbitrary chosen for this study (10% of the critical damping).

Roll: For the roll motion, two different phenomena could be observed. The first one is given on the 30% loading case diagram where the amplification at the 10s resonant period is strongly decreased. This is due to the phase difference between liquid motion inside the tanks and barge motion. The second phenomenon is the increase of the peak period which is shown on the 97% loading case diagram. The resonant period is finally equal to 19s instead of 16s without coupling effect.

Sway: For the 30% filling rate (90° heading), the liquid motions induced a peak at wave period around 7s (the amplification is multiplied by 2). Nevertheless around 10 s wave period, the amplification is strongly decreased (divided by 3). This result could be explained as the roll motion by the phase difference between liquid motion inside the tanks and barge motion. Indeed, the sway and roll motions excite the same mode of liquid cargo in tank.

Surge motion: For the 30% filling rate (45° heading), the liquid motions induced a peak at a wave period around 10s. The RAO reaches more than 1.5 m/m at this point. Note that no surge damping has been taken into account.

Thus, the coupling between liquid motions inside tanks and vessel motions induces peaks for certain motions. These could be critical if the wave spectrum is in the range of the structure resonant period. But it is also denoted that depending on filling level, liquid motions could have a benefic influence on the RAO (increase of the peak period for example). This correlation between filling level and barge motion could be taken into account to develop an adapted cargo operational philosophy.

3.6. Some operational considerations

The FSRU is designed so as to reach an availability level equivalent or as close as the level of an onshore terminal, i.e. about 99%. Several aspects have been taken into account in that respect.

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The availability of the regasification plant itself is the first driving criterion. Provided that it is fed by LNG, the regasification unit has been designed with sufficient redundancies and spares so as to be able to operate more than 99% of the time. Special attention has been paid to key equipment (e.g. vaporizers, recondenser) which may be affected by floater motions.

Availability of the terminal to perform the LNG carrier unloading operation adversely impacts terminal availability. The side by side configuration chosen for unloading, with conventional rigid arms, has inherent limitations in terms of operability. This is in particular due to the moorings between the FSRU and the LNG carrier, which cannot be sized in side by side configuration, past certain environment range. Unloading therefore decreases overall terminal availability. However, the latter point may be counterbalanced by sufficient LNG buffer storage coupled with an adequate handling philosophy of the cargo. Some hints have been identified.

Topsides operation (e.g. vaporizers) requires that the FSRU be operated with a nil trim angle. Initial vessel trim (e.g. due to topsides eccentricity) is balanced with the water ballast located in stern. When LNG carriers unload their product to the FSRU, a preferred method consists in filling all FSRU storage tanks at the same time. This method enables to balance the trim and to reduce the still water bending moment induced by the cargo loads.

As indicated previously, the coupling of FSRU and liquid motions may induce issues depending on the wave spectrum on the site. A very effective methodology to prevent such situations consists in designing FSRU cargo handling system so as to enable the transfer of LNG between tanks, in order to avoid the critical filling level when the incoming wave spectrum can be detrimental. Reasonable automation of such transfer procedure, coupled with forecast of sea conditions, is doable so as to get rid of critical configurations.

4. Conclusion

Offshore LNG receiving terminals are now close to reality. Several solutions are made available through constant development effort. The final selection of a given configuration: floating? Gravity based? Shoe box architecture or alternatives with cylindrical storage tanks? depends of course on some key elements of the design basis, namely the location of the terminal, the required design throughput, the storage capacity and the overall availability of the terminal. The facilities presented above have been tuned for one extremity of the spectrum of receiving terminals: significant natural gas emission capacities and important availability. The design work performed has shown that the main driving parameters mentioned above do not suffice to point out the best adapted facility for owner’s final needs. For instance, selecting a type of gravity base terminal requires information beyond mere engineering analyses (industry background in the zone of the terminal, such as offshore installation operations or civil works costs). Hence a need to mix needs of customer, engineering and design capabilities, and way to build the facilities, so as to progress towards the most efficient solution for any application case.

Last but not least, the strides that have been made in the development of these LNG receiving terminals provide new technologies in key areas of offshore LNG, open new horizons and somehow pave the way for the next step: offshore LNG production and export facilities (LNG FPSO).

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