OTC 16077

Offshore LNG Terminals: Sunk or Floated?

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Abstract

The first offshore LNG import terminal project that received approval from the US Coast Guard shortly after the Deepwater Port Act was amended is of the Gravity Base Structure (GBS) type. However, floating solutions are following closely in its footsteps with a first application recently approved for a Gulf of Mexico location, and with new Floating Storage and Regasification Units (FSRU) applications expected to be filed during this year for the west and east coast of the U.S.

Because the GBS and FSRU concepts are quite different, they are generally proposed by different industry sectors. Apart from a few exceptions, a civil contractor is generally not in the business of floating steel vessels and vice versa. Each of these industries likely has its own perceptions of so-called drawbacks of the concept proposed by the competition, while turning a blind eye to its own concept limitations.

This paper analyzes in which circumstances the FSRU, and in which the GBS would be the preferred solution, depending on project-specific conditions. This is done by means of a technical comparison, as well as a sensitivity analysis on the respective main cost-affecting parameters for both concepts.

The paper highlights how the FSRU and the GBS concepts differentiate themselves on issues such as environmental conditions, berthing, bathymetry, constructability, operability, technology selection for storage, and regasification, etc.

The results of this study showed that the two concepts showed siginificant differences in sensitivity to project-specific conditions.

Background

There is a need for increased LNG transport to support the fast growing demand of LNG, especially in the USA. Until now only onshore import terminals have been built for receiving LNG, storage of LNG, regasification to natural gas (NG) and send-out of NG. Preferably these terminals are located close to densely populated areas, where the majority of consumers of this type of energy are found.

However, public opinion in several countries is getting more and more opposed against onshore LNG terminals, considering perceived safety risks and/or visual pollution of surroundings. Furthermore governmental issues like permits, environmental impact studies, etc. may significantly slow down the progress of new onshore LNG terminal projects.

Therefore the alternative of offshore LNG import terminals has been proposed. Such facilities should fulfill some important constraints:

- They should be located practically out-of-sight from the coastline, in order to prevent public concern regarding safety and visual pollution of horizon (NIMBY)
- They should have a high operability with regard to:
    - Berthing & offloading operations of LNG Carriers, which is dependent on environmental conditions
    - Processing of stored LNG to NG, which might be impacted by environmental conditions like seawater temperature or wave-induced vessel motions
    - Redundancy of systems (enabling maintenance and repair without decreased performance)

There are basically two fundamental concepts for offshore LNG terminals:

Floating:	*Floating Storage and Regasification Unit (FSRU)*
On seabed:	*Gravity Base Structure (GBS)*

The FSRU is typically a turret-moored weathervaning barge with a steel hull that contains the LNG storage tanks. Regasification modules are installed on the deck and gas is sent out via a riser and a subsea pipeline to the customer.

The GBS is typically a pre-stressed concrete caisson with sufficient ballast compartments to lower it down to a stable position on the seabed. The caisson contains the LNG storage tanks and has regasification equipment installed on top, while acting as a breakwater for the shuttle carrier during offloading.

A comparison study has been carried out to quantify the aspects regarding the relative competitiveness of both concepts. This paper addresses under which conditions one concept can have advantages over the other one. Thereto the following aspects have been taken into account:

- Technical issues
- Initial investment costs
- Lifecycle costs
- Construction schedule “first-gas-to-customer”
- The sensitivity to location parameters.

Study approach

For each concept a design has been developed, based on the assumption that the conditions for each concept are optimal, hence to arrive at the most competitive design for each concept. The design assumptions for each concept are given in the respective concept descriptions below.

Both concepts have been designed for the same gas storage volume and send-out capacity. For this comparison study a benign environment was selected, with occasional heavy storms. The environmental conditions are reflected in the design basis, and are based on data available in the public domain.

For the GBS first a design model was developed, to establish the dimensions and construction costs as function of main parameters (being the overall length L acting as breakwater, and the water depth WD at the site location). In this way the sensitivity of the GBS to these parameters could be assessed quantitatively.

For the FSRU the basis was given through the results of SBM’s internal FSRU development program. Also for this concept a translation to a design model was made, which allowed a cost comparison on equal terms, using the same cost basis and assumptions.

Having specified the designs, both concepts were then compared with respect to:

- Technical differences which may result in (un)favorable conditions for either concept
- Construction schedule
- Relative cost sensitivity to site-specific parameters, such as water depth, distance to shore, wave height, soil conditions, weather directionality, and location of construction site or shipyard.

An absolute cost comparison is not given in this paper, although the comparison study included the calculation of capital investment costs (CAPEX), operational costs (OPEX), and overall life cycle costs (LCC). The reason that these costs are not directly quantitatively compared is that the comparison was based on optimal design conditions for each case, which results for both concepts in the lowest possible cost. However, since the concepts differ fundamentally (floating vs. gravity-based, weathervaning vs. fixed orientation, entirely different construction and installation methods), an optimal condition for one concept nearly automatically results in unfavorable conditions for the other concept.

As a general comment it can be stated that the FSRU has a lower cost for the optimized conditions relative to the GBS, both on CAPEX as on LCC.

It was therefore decided to concentrate on the technical differences, construction time, and on sensitivity to location-specific conditions. This type of comparison will generally point into a direction of the most attractive concept for the chosen conditions.

In more detail, the following aspects were taken into account for the life cycle cost estimate:

- Building site development (GBS)
  - Graving dock (GBS)
- Construction phase
  - Fabrication of hull and containment system
  - Tank installation method in hull (FSRU)
  - Topsides installation
  - Schedule and deferred production
  - Pipeline to shore
- Transport and installation phase
  - Tow to site
  - Channel dredging (GBS)
  - Sinking and stabilizing (GBS)
  - Anchoring and hook-up (FSRU)
- Operational phase
  - Berthing and mooring (tugs etc.)
  - Maintenance and inspection
  - Fuel
  - Personnel
- Decommissioning phase (not included in costs)

Finally, the flexibility and risks of both concepts were qualitatively compared.

Design basis

This paragraph lists the main design parameters that are used for both concepts. They are the same where possible, but differences occur mainly in the chosen water depth and corresponding wave heights.

Capacity. The chosen capacity of both concepts is as follows:

Storage capacity	250,000 m^3
Specific mass LNG	0.45 ton/m^3
Regasification	6.3 MTPA
Gas send-out rate	720 ton/h (normal) 900 ton/h (peak)
Supply by LNGC	138,000 m^3
Offloading rate	10,000 m^3/h

Environment. The 100-year storm conditions are as follows:

	GBS	FSRU
Storm condition H_s	6.9 m	9.6 m
Wave period T_p	13 s	13 s
Current: surge & tide	1.1 m/s	1.1 m/s
Wind speed 1-hour avg.	41 m/s	41 m/s

These data are used to check the design of the GBS (stable foundation on soil during storm condition), and the

FSRU (strength & excursions of the mooring system).

For every-day operations, additional environmental data are used as follows:

- The probability that the following environmental conditions are not exceeded is 95%: Hs = 2 m, with associated period Tp = 7.4 s, and associated wind speed (1 hr average) = 11.3 m/s.
- The probability that the following environmental conditions are not exceeded is 99 %: Hs = 2.8 m, with associated period = 8.4 s, and associated wind speed (1 hr average) = 13.9 m/s.

These two non-exceedance probabilities provide input for the determination of downtime. The (relative) motions of the LNGC in the abovementioned conditions, may exceed certain limits for the offloading arms and/or the LNG carrier mooring system.

The significant wave height of 2 - 3 m is generally regarded as an upper limit for tugs providing assistance in berthing of the LNGC next to the terminal (either GBS or FSRU).

Bathymetry and water depth. The GBS can be located in shallow water, which is advantageous for its construction costs. The smallest feasible water depth has been calculated as follows:

- LNGC draft laden	11.5 m
- LNGC static trim angle	0.6 m (0.25°)
- Minimum keel clearance	1.0 m
- Allowance for siltation	1.0 m
- LNGC max. heave motion	0.5 m
- LNGC max. pitch motion at bow	1.4 m (0.6°)
	-------- +
- Minimum required water depth	16.0 m LAT

This value is considered as an absolute minimum, as it does not take into account the pitching of the LNG carrier during its approach to the berth, which may be larger than that in the moored condition.

For the FSRU a design water depth of 40 m is taken. This is based on the results of SBM's internal FSRU development study, in which the mooring system was optimized for minimum water depth, and in which the influence of water depth on the mooring system was investigated.

General assumptions.

- Lifetime 25 years operation
- Distance to shore: 10 nm (18.5 km)

GBS assumptions.

- Suitable nearby location for graving dock available, with favorable soil conditions (low water-ingress rate), in USA.
- Sea bottom: sand, nearly flat (< 1 % slope).
- Sea bottom slope near graving dock: 0. 5°.

FSRU assumptions.

- Fabrication and topsides integration in East-Asia.
- Sufficient water depth at assumed distance from shore.

GBS description

The GBS is a rectangular structure for ease of construction (this applies both to the concrete work as well as to the membrane containment system inside). Furthermore, a rectangular structure can provide a large length, acting as a breakwater for the moored LNGC's. The large length is combined with a restricted width, to reduce the span of the transverse beams supporting the main deck and topsides weight.

A sketch of the chosen layout and internal cross-section is shown in fig. 1. It has a concrete double bottom and concrete double walls all around, providing inherent safety of the structure against boat impact, as well as space for ballasting of the GBS, in respect of sufficient foundation on the sea bottom.

Two large tanks provide storage for LNG. Although some designs show only one storage tank, the chosen concept is based on two tanks, to ensure a certain degree of redundancy in case one tank has to be repaired (however remote the chance of repair is, the consequences of shutting down the whole terminal in respect to the LNG supply chain cannot be tolerated).

A cofferdam separates the two storage tanks, with the same width as the transverse double skin.

All double skin spaces, as well as double bottom are strengthened with ribs, dividing them into compartments.

Furthermore, skirts are provided underneath the base slab. A minimum skirt height of 2 m is always applied, in order to prevent rapid erosion of the soil underneath the bottom slab, by the action of waves, current and tide. A skirt height of more than the minimum 2 m might be necessary for stable foundation on the sea bottom (soil sliding criterion). Due to the skirts, the draft during tow will be increased. This can however be partially offset by pumping air underneath the base slab, which will be trapped between the skirts.

All installations (topsides systems, accommodation) are fitted on the main deck. Due to the large area L*B of this deck, and the high L/B aspect ratio there is no design problem for a proper arrangement of the topsides in view of functionality and safety. This aspect is therefore disregarded in the comparison study, as the FSRU also has sufficient main deck area available.

The accommodation is assumed for an operating crew of 30 people, with a maximum POB (persons on board) of 50.

The GBS should be positioned perpendicular to the daily waves and wind conditions, in order to provide an optimal breakwater function. This requirement implies that there should be a predominant daily wind & waves direction: e.g. from the south, with sectors to southwest and southeast of not more than 45°. Furthermore, the current should be predominantly parallel to the GBS length direction, in order to have the LNGC's facing the current during berthing.

It is assumed that the GBS is located in an area where the abovementioned constraints are fulfilled. This scenario is shown in Figure 1:

- It is positioned in east – west direction, south of the shoreline. The predominant wind & wave direction is from the south.
- The current direction is always from the west.
- The hurricane wind and waves can come from any direction between 90° and 270° (measured from north = 0°).

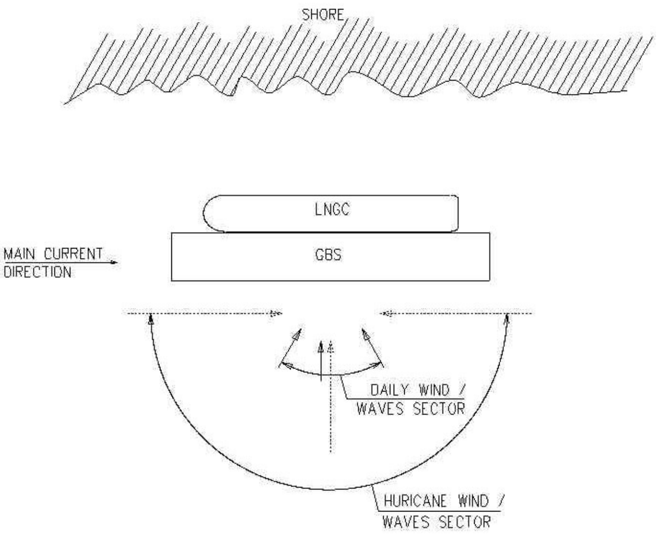

Figure 1 - Orientation GBS relative to environment

The GBS is assumed to be founded on a sea bottom of medium/dense sand, with the following soil characteristics:

-	Internal angle of friction	$\phi = 30^o$
-	Submerged unit weight	9.6 kN/m3 (= apparent weight in water)

This type of soil provides the best foundation, requiring only moderate skirts below the base slab.

The sea bottom at the GBS site is assumed to be approximately flat (< 1% inclination), therefore requiring little preparation before the GBS can be installed at the site.

GBS design model. For the purpose of the comparison study, a simplified design model was made. This model calculates the construction costs (structure + containment system) on the basis of a limited number of parameters: for a set of main dimensions (length, width, depth, skirt height, water depth) and some secondary dimensions (e.g. width of longitudinal double skin) the program calculates the amount of concrete and membrane area. By multiplication with specific cost data, the construction costs are then determined.

The program also checks a number of constraints, which have to be fulfilled for a feasible design:

- Storage capacity
- Freeboard (distance of main deck to water level)
- Clearance between skirt tip and seafloor during installation
- Stability GM
- Height of air cushion
- Soil sliding criterion
- Soil bearing criterion
- Skirt penetration factor

Only in case all constraints are fulfilled, a feasible set of main dimensions is calculated.

The design model is simplified, as it does not carry out strength calculations. The design model is sufficiently accurate to predict construction costs of a concrete GBS fitted with a membrane containment system.

The design model is used in this comparison study to gain more insight in the sensitivity of the GBS design as a function of length L, and water depth (WD). This provides quantitative data to assess the relative costs of the FSRU versus the GBS.

According to this model, the GBS with the lowest cost has the following dimensions:

-	Length L	350.0 m
-	Width B	52.4 m
-	Depth D	39.0 m
-	Skirt height	4.1 m
-	Water depth WD	16.0 m
-	Width of longitudinal wall compartments	6.0 m

The optimum length equals the minimum allowable length required to provide a sufficient breakwater length for the LNG carrier. Figures 2a/b show the different ballast conditions during tow and after installation.

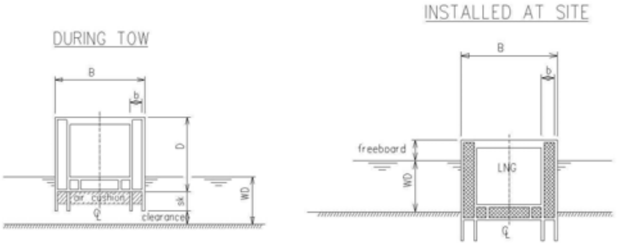

Figure 2a/b - GBS position during tow and after installation

It is assumed that the accommodation is located on the GBS main deck without having to extend the main structure, assuming that the high integrity of the concrete allows this arrangement (the feasibility depends on whether the gas carrier code requirements apply for the GBS).

For the rectangular shape, pre-stressed concrete is used as the structural material. The concrete GBS has several characteristics:

- It has thick walls and bottoms, which is necessary to provide a stable founded structure
- All walls etc. have to be flat, and the formwork is therefore simple
- Concrete has excellent low-temperature strength characteristics, providing a fail-safe temporary barrier in case of LNG leakage
- Concrete provides sufficient temporary insulation in case of leakage
- Concrete itself has a large durability, but the

durability of the pre-tensioning cables under dynamic loading could prove to be the critical element in this respect. If properly constructed, the lifetime is well in excess of the GBS functional lifetime, but if cracks occur as a result of pre-stressing cable problems, it will be a major problem
- Concrete is fire resistant
- Concrete requires no maintenance (in case the fabrication & pouring is well done), but inspection of the structure and its foundation will be necessary

The use of concrete imposes however also some important requirements to the quality of the fabrication process. Furthermore additional materials shall be supplemented during the fabrication of the concrete, to give the concrete a special treatment (so called "high performance concrete").

Furthermore additional materials shall be supplemented during the fabrication of the concrete, to give the concrete a special treatment (so called "high performance concrete"): instead of the normal capillary void structure, the air is entrained in voids, which are closed (not connected to each other) and smaller than normally. This prevents water or moisture ingress through the thickness of the wall. This is of great importance, as the concrete wall cannot be inspected on leakage: on one side the double skin space is filled with ballast material (typically a sand/water mixture), while on the other side the membrane system is directly attached to the concrete wall.

Besides the GBS structure and the LNG containment system, additional facilities are required for the operation of the unit. These are categorized as processing, marine systems, and installation support systems. These systems are briefly described below.

GBS topsides and cargo system. The topsides processing facilities consist of the following:

- Regasification plant, including cargo and booster pumps
- Boil-off gas handling
- Fuel gas
- Glycol/water system
- Vent and relief system
- Drain systems
- Export gas metering

The regasification plant consists of the cargo pumps in both tanks. From these pumps the LNG is fed to the booster pumps, which are located on the topsides above the cargo area. The booster pumps increase the LNG pressure to that of the export pipeline. Then the LNG is vaporized in vertically mounted intermediate fluid (based on a glycol-water mixture) shell-and-tube type heat exchangers. The vaporized LNG is then routed via the metering system to the riser feeding to the export pipeline.

The boil-off gas is compressed and used as fuel. The excess boil-off is recondensed in a combined recondenser-surge vessel. The recondensed LNG is added to the send-out LNG stream.

Fuel gas is taken from the low-pressure boil-off gas, and is mainly used to fuel the main power generation plant.

The vaporizers use a mixture of glycol-water in a closed-loop circulation system. The intermediate fluid is cooled against seawater in plate-type heat exchangers.

A topsides HP and LP vent system is provided, to take care of any relieved vapors due to emergency conditions. No flare is installed.

Any cryogenic leaks, spills or drains from the topsides are collected in an open compounded area, from where it is pumped back into the system.

The export gas is metered before reaching the riser, downstream of any fuel or other gas offtakes.

Figure 3 provides a typical equipment and piping layout of the GBS topsides.

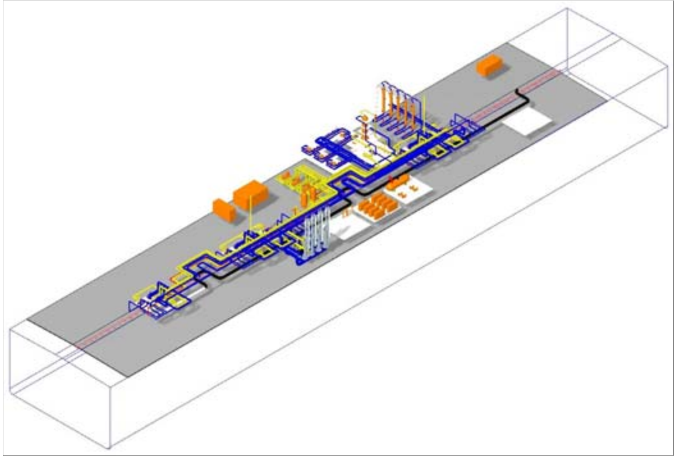

Figure 3 - Topsides arrangement of GBS

GBS marine systems. In addition, the GBS is provided with the following marine systems:

- Seawater and chlorination system
- Main power generation
- Emergency & essential power generation
- Glycol solution storage tank
- Air systems (instrument & plant air)
- Fire water and foam system (incl. foam tank)
- Tank inerting equipment
- N_2 generation system
- Fresh water system (drinking & service water)
- Cargo piping, gauging & control
- Sewage system
- Cranes
- Life saving facilities, lifeboats etc.
- Mooring, fenders etc.
- Berth
- Loading arms
- GBS management system

Not all marine systems will be described here, but a selection is made for those systems, which are unusual for offshore applications:

The seawater system is mainly used to provide a heat sink for the LNG vaporizers. The seawater system capacity is 14,000 m^3/hr, based on a temperature drop of 10 ^oC.

GBS installation support systems. In addition to those systems required to support the daily operations of the plant, the following extra functions are required for the GBS for the installation and decommissioning phases:

- Ballasting / de-ballasting of internal compartments (double bottom and double skin) with seawater.
- Filling of internal compartments with sand/water mixture
- Fluidising of sand/water mixture in internal compartments during decommissioning
- Emptying of internal compartments during decommissioning
- Inflating / deflating the spaces in-between the skirts with air
- Grouting of cavities between bottom slab and soil, after installation on seabed
- Fluidising of soil underneath bottom slab, for decreased suction during re-floating

GBS building site. Although it is technically feasible to build a GBS in a shipyard dry-dock, this option was disregarded because of the long ocean tow from a European, Brazilian or an East-Asian shipyard. Such long voyages affect the overall schedule and would require that the GBS be designed for a 1-year storm condition during the tow, which would add significantly to the cost. Shipyards have no experience in working with concrete. In addition, the dock time (15 months) would not be attractive for most of the shipyards.

For the purpose of the comparison study it was therefore assumed that a suitable location could be found in the vicinity of the offshore installation site for the GBS building dock (the graving dock). To enable the float-out of the GBS after construction, the dock floor must be deep enough for the floated draft of the GBS. Although various techniques can be applied to construct the graving dock, a method was selected whereby the entire GBS can be constructed in the dock, including the installation of the containment system. Although this method requires a deeper graving dock compared with a method where the GBS is only built in the dock until it can be floated and whereby the GBS-construction is completed offshore, it is still assumed to be cheaper. Offshore completion and containment system installation is logistically much more challenging and time-consuming.

It was assumed that the topsides modules installation would be installed in the graving dock, with pre-fabricated modules being rolled onto the deck with hydraulically operated carts via a temporary structure.

It was assumed that the soil conditions for the base-case GBS are most favorable, i.e. with a soil structure that limits the amount of water flow to the area underneath the dock floor, while at the same time having properties that allow easy dredging of the dock by e.g. a small cutter dredger. Based on those assumptions the cost of the graving dock could be minimized. It was assumed that the dock area could be drained using deepwell pumps around the dock floor, and by having a water-retaining bentonite shield around the dock. It was assumed that no waterglass-type shield was required underneath the dock area, to avoid excessive extra costs.

The graving dock has the following facilities:

- Construction people camp (approx. 1,500 men)
- Parking
- Offices
- GBS dock
- Cranes around GBS dock (typically ~ 6 to 8)
- Carpentry
- Concrete/cement factory
- Steel/wire storage area
- Process facilities storage area (covered)
- Membrane system storage area (covered)
- Mechanical workshops
- Electrical workshop
- Main power generation facility
- Disposal site
- Utilities site (potable water etc.)
- Servicing quay (200 m long), including cranes

Creating the graving dock will require the following steps:

1. Dredge the required profile of the graving dock, with dock floor to the required depth, and with side slopes.
2. Backfill the soil on the seaside, to create a protective dike up to sufficiently high level (above storm tide), and apply appropriate dike protection.
3. At the upper side of the slopes dig a narrow trench to a depth well below the dock floor, and fill this with bentonite. This is to maintain the hydrostatic pressure on the trench-walls, and to plaster these walls, in order to have a watertight screen all around the graving dock.
4. Install a well pumping system within the screen, and pump out all water, such that water level in soil is approx. 1 m below dock floor.
5. Drive in two rings of steel sheet piles which will later become the skirts of the GBS.

A total area of approx. 550 x 400m is required (area = 220,000 m^2): see Figure 4 below.

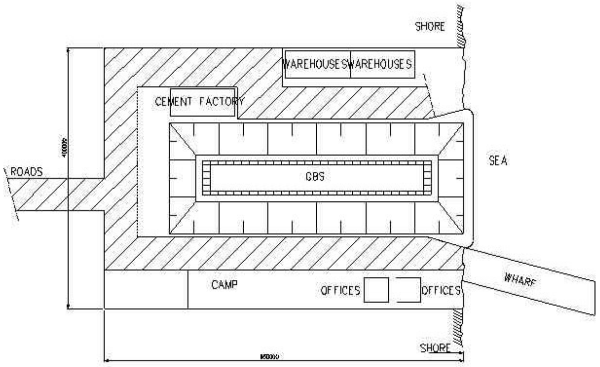

Figure 4 - Top view of graving dock

GBS installation procedure. After construction in the graving dock, the dock will be flooded. Then the space between the skirts will be filled with air (so-called air cushion) to have the GBS floating at smallest feasible draft.

After that, the GBS will be towed-out by tugs to deep water. There the air cushion will be deflated before the sea tow is started. A channel must be dredged to sufficiently deep water for this purpose.

On arrival at the installation site, the air cushion is again inflated to decrease the draft. The tugs will connect temporary anchor/chains to the GBS, to position it at exactly the right spot.

After exact positioning, the air cushion is deflated and the GBS will touch with its skirts onto the sea bottom.

Penetration of the skirts into the bottom is considered as a delicate operation, because of the extremely large dimensions of the GBS. The probability exists that in one corner the skirts may experience more resistance from the soil. This could create too large forces on that part of the skirts, with consequent damage.

Therefore, a method must be applied, by which complete control over the penetration is kept at all times. This is achieved by pneumatic excavation: The space in-between the two skirt rings is filled with compressed air, so people can enter this space. They will then remove the soil in-between the two skirt rings ("pneumatic excavation"), layer by layer. After removal of a certain layer thickness, the GBS will penetrate its skirts some millimetres deeper into the soil. Then the next layer of soil is removed, and so on. This method excludes the possibility that at some spot a higher penetration resistance can build up.

The disadvantage of this method is however that it is expensive (\$50/m^3 excavated soil), and that it is time consuming: approx. 1 month will be needed to penetrate 4 m into the soil.

During penetration of the skirts, the GBS will be water ballasted. After skirt penetration into the soil, the spaces underneath the bottom slab will not everywhere make even contact with the soil. Therefore all spaces will be injected with grout, to get a proper load distribution between the GBS base slab and soil.

The space in-between the two skirt-rings will be poured with concrete. This is necessary, as the skirts are made of steel, and are not designed to take the transverse loads during storm conditions.

Finally, to obtain a sufficient foundation weight to resist hurricane wave loads, the double bottom and double skin spaces will all be ballasted with a sand/water mixture.

FSRU description

The hull design is driven mainly by the containment system for the LNG. For the FSRU the consideration of partial filling of the cargo tanks in combination with vessel's motions is of paramount importance in the choice of the containment system.

At present, the membrane-type containment system requires further investigation to demonstrate its suitability for partial loading in harsh environments.

Spherical tanks can be used but their application either results in larger FSRU main dimensions, or it requires a new type large-diameter tank. Extra deck space is required outside the cargo area for the regasification plant.

The IHI-SPB type tanks have inherent anti-sloshing behavior. This is due to the fact that its internal structure of swash bulkheads, stiffeners and horizontal stringers effectively dampens the sloshing motion of the liquid inside.

Furthermore, the construction of the SPB tanks is standard shipbuilding practice (stiffened flat plate panels), which makes it possible to have these tanks constructed in accordance with standard shipbuilding practices.

In view of the above considerations, the IHI-SPB (Self-supporting Prismatic IMO type B) tanks have been chosen for the base-case FSRU.

It should be noted, however, that if the environmental conditions permit, of if commercial considerations favor another system, there should be no reason why they could not be applied as well.

The layout of the FSRU is shown in Figure 5. The cargo storage area is the main part of the FSRU. The LNG tanks are located within a double hull (double shell and double bottom). There are 5 storage tanks, separated by transverse bulkheads.

The cargo area is separated from the forward compartments and the aft peak by a cofferdam.

Aft of the storage area is the aft peak, which has a double function:

- Provide safety for the LNG tanks in case of collision
- Provide space for the thrusters, which are used in assisting the weathervaning capability, especially during side-by-side offloading of a LNGC

Furthermore the aft peak deck area can be used for the foundation of the optional SYMO ® soft yoke tandem mooring system.

Forward of the storage area three main compartments are located, separated by transverse bulkheads:

- A compartment for the internal turret system.
- A compartment housing the engine room and the accommodation block on top
- The forepeak, with the helicopter deck on top

The large main deck on top of the cargo area provides sufficient space for proper layout of the topsides. The process vent stack of the topsides systems is located well aft, so the wind blows the vented gas away from the FSRU and the side-by-side moored LNGC.

In accordance with the IGC code each LNG storage tank also has its own independent emergency vent post.

Due to the large required height, all vents are supported by prismatic shaped tower structures, made from cryogenic-resistant steel.

The accommodation is assumed for an operating crew of 32 people (two more than on GBS, to operate and maintain the active ballast system, which is always in use).

FSRU design. The design of the FSRU is based on well known naval architectural principles. It is sufficient to list here the design aspects involved:

- Weight calculation
- Tank volumes calculation
- Loading conditions

- Intact stability
- Damage stability
- Motion behavior
- Longitudinal strength
- Local strength (Rules minimum scantlings)
- Environmental loads for mooring system
- Mooring system design (intact and damaged case)

The main dimensions length L, width B, and depth D are dictated by the required storage capacity.

Figure 5 - Outline FSRU

The ratio's B/D and L/B (and implicitly L/D) are taken in accordance with naval architectural practice, to ensure good stability, weathervaning capacity, longitudinal strength, and sufficiently small environmental loads on the mooring system. This has resulted in the following main dimensions:

- L_{oa}	336.3 m
- L_{pp}	323.4 m
- B	59.4 m
- D	32.4 m
- T	11.0 m

The length L includes the cargo area, plus additional required ship's length for aft peak, turret, engine room, and forepeak.

The width B of approx. 60 m ensures that the FSRU can be built in existing Far-East shipyard dry-docks.

The freeboard (D – T) of approx. 21 m ensures a proper main deck level for side-by-side offloading operations, as well as good sea keeping behavior in storm conditions (no green water on main deck).

The draft T is kept constant during operations, by active water ballasting. This is preferred in view of the main deck level for offloading operations.

The hull structure of the FSRU, being a floating unit, is not governed by specific location parameters. This is due to the following facts:

- The large depth of the unit provides ample strength against overall bending moments.
- The overall bending moments are relatively small as the storage tanks are positioned over a large portion of the ship's length.
- In case one storage tank is empty, the corresponding hull section will be water ballasted (in double bottom and double shell), thus maintaining the same weight distribution.

The water depth in which the FSRU is moored is however a main parameter for the mooring system. A small water depth is generally favored, since this will often decrease the distance-to-shore.

The design of the mooring system is governed by the hurricane environmental survival conditions.

The optimized mooring system is feasible in water depths of 40 m.

FSRU hull and containment system. Contrary to the GBS, the FSRU will be built from normal shipbuilding steel (partly requiring higher grades: see below).

While the GBS needs the large weight of its concrete structure for proper foundation on the sea bottom, the FSRU weight is minimized by the use of steel, in order to get the smallest main dimensions possible and thus the smallest environmental loads on the mooring system.

The hull is made of higher tensile strength steel. The advantages are a lower steel weight, and better low temperature properties.

Care will be taken in the construction details, to avoid fatigue problems, which might otherwise occur due to the smaller scantlings. The double hull construction is however inherently advantageous regarding fatigue, as all construction parts are contained within the double hull, and are continuous along the length of the ship. All construction parts can be inspected periodically, as the water ballast tanks in double bottom and double shell are easily accessible, with horizontal stringers (spaced at proper intervals) that can be used as walking platforms. Any fatigue cracks in stiffeners and/or girders can be repaired in-situ, as the construction parts are not in contact with dangerous goods on the other side of the plating (either void or seawater).

The tanks are fitted with a partial secondary barrier (on the outside of the insulation layer), as required for this type of tank by the IMO IGC-code.

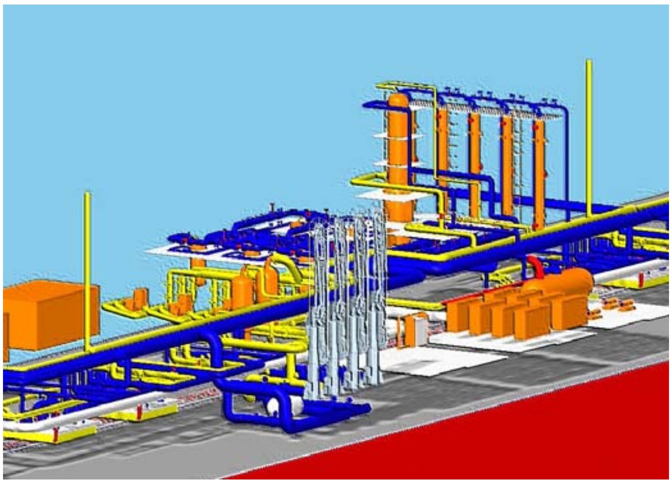

Figure 6 - Detail of FSRU topsides

FSRU topsides and cargo system. For the purpose of the comparison study it is assumed that the topsides of the FSRU and the GBS are similar. It is therefore also assumed that the vaporizers for both concepts are the same as well, although for the GBS also typical onshore type vaporizers, such as open-rack vaporizers (ORV) may be selected.

The main difference with the GBS is the amount of LNG cargo pumps, which is larger for the FSRU, but with smaller pumping capacities.

Reference is made to the topsides of the GBS concept for a description. A typical detail of the topsides layout is provided in Figure 6, where the loading arms, vaporizers and boil-off recondenser are visible.

FSRU marine systems. The marine systems of the FSRU are partly different from those of the GBS. The FSRU is provided with the following marine systems:

- Seawater and chlorination system
- Main power generation
- Emergency & essential power generation
- Air systems
- Fire water and foam system (incl. foam tank)
- Tank inerting equipment
- Ballast control system
- N_2 generation system
- Fresh water system (drinking and service water)
- Cargo piping, gauging & control
- Thrusters, 2 off
- Sewage system
- Cranes
- Fuel oil system and tank
- Glycol solution storage tank
- Life saving facilities, lifeboats etc.
- Mooring, fenders etc.
- Loading arms
- Vessel management system

For the FSRU it has been demonstrated in a separate study that the impact on the local marine environment or that of short-circuiting of low-temperature water is insignificant. This is demonstrated by an example shown in Figure 7.

It is assumed that the sea water requirement for the GBS and the FSRU are identical, i.e. that there are also for the GBS no issues with respect to local temperature impact on marine life or short-circuiting of discharged cold sea water into the intake.

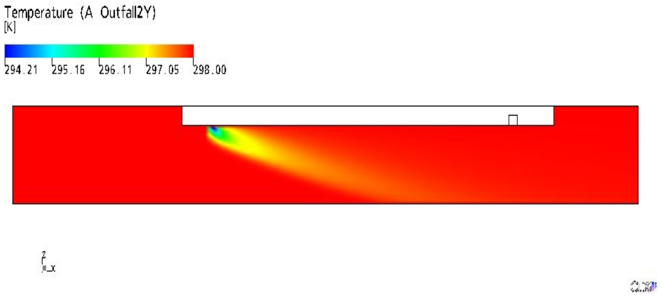

Figure 7 - Temperature profile of discharged 'cold' water

FSRU fabrication and integration. For the purpose of the study it was assumed that the FSRU hull would be built in a shipyard in East Asia.

The LNG containment system can either be built by the same shipyard or could be supplied as a free-issue item to the shipyard. The tanks are supplied as complete units, including applied external insulation. Once the hull is sufficiently complete, but without the deck on it, it is floated out of dry-dock to sufficiently deep still water and ballasted. The tanks are then installed in one piece using 2 large-capacity sheerleg-type floating cranes opposing each other with the tank hanging in between the cranes. The hull is then pulled underneath the tank, and the tank is subsequently lowered. Once the tanks are installed, the hull is dry-docked for a short time again, to install the main deck. Then the hull is taken out of the dock and moored alongside the quay for further outfitting and completion.

It has been assumed that the topsides are prefabricated modules, which would be built in any competitive module fabrication yard around the world. The topsides are then installed and integrated on the hull in the same shipyard that has built the hull. The topsides installation would take place using a sheerleg-type floating crane while the hull is alongside the quay.

FSRU installation and hook-up. The completed FSRU is towed from the shipyard to the intended installation site, which for the purpose of the study was assumed to be in the USA. The duration of the tow is approx. 2 months.

Upon arrival at site the turret is hooked up to the pre-installed mooring lines, and the risers are connected.

Technical comparison GBS-FSRU

For the technical comparison the various functions of the offshore import terminal are taken as starting point. Some functions are very specific for only one of the concepts. They will then be discussed in isolation.

Design phase. For the design phase the main differences between both concepts lie in the permitting and site selection. These are described below.

Permitting. The application for a permit involves describing the project and alternative solutions, mitigating measures for e.g. emissions, and spills, an environmental impact assessment (EIA), and demonstration of compliance with regulations and federal authorizations, such as: Deep Water Port Act (DWPA), National Environmental Policy Act (NEPA), Federal Water Pollution Control Act (Clean Water Act), etc.

Typical differences between both concepts will likely be in the following areas:

- Impact on seabed habitat,
- Berthing safety,
- Fire and explosion risk,
- Hurricane impact and procedures,
- Cryogenic spills, and
- Decommissioning.

Since the GBS has now been subject to the permitting process since 2 years, it is further developed, and it could therefore be perceived as easier and less risky than for the FSRU, for which the first permit application has only been submitted since late 2003. However, this is only a very temporary and minor advantage.

In case also a permit for a graving dock is required, it is likely that the permitting procedures will be more time-consuming and complex compared to offshore units. Considering the offshore GBS and FSRU only, the permitting process for both concepts will be very similar.

Generally the impact on the environment is smaller for the FSRU, because it is a floating installation that does not require a graving dock. Its footprint on the seabed is limited to the anchor points of the mooring system and the connection of the risers with the pipeline end manifold (PLEM). Channel dredging and soil improvement are not required for the FSRU. Pipeline trenching is similar for both concepts.

Nevertheless it is believed that both concepts are equally suitable to obtain a permit from the regulatory authorities.

Site selection. The GBS should ideally be located in water depths less than 20 m. A larger depth will add to the cost, and will make its construction and installation more challenging. For a larger water depth, the GBS itself needs to be higher, the graving dock needs to be deeper and the dredged channel into sufficiently deep water longer. For the GBS the soil condition is an important design parameter, as it governs the installation method, the cost and the duration significantly. The GBS location could therefore be restricted to locations with favorable soil conditions, which might result in longer pipeline lengths. This is not the case if existing pipeline infrastructure of sufficient capacity is available.

For the graving dock, the site selection is even more important. Since the dock needs to be excavated to a significant depth below the lowest tide, there is significant risk of large water ingress into the dock area due to the surrounding inherently higher ground water level. This will cause a large upward force on the dock floor. A special water-retaining layer could be required below the dock floor (at approx. 35 m depth) in case the water permeability is too excessive to offset by costly well pumping. On the other hand, a soil with good water retaining properties is generally more expensive to excavate or dredge.

In case a graving dock already exists, the costs will be lower, and permitting easier, but the dock will likely have to be tailored for the new GBS requirements.

Although it may seem attractive to build the graving dock outside the USA (for availability, permitting or labor cost reasons), this is not necessarily cheaper. The longer tow, which is very slow, may prohibit this option due to bad weather risk. Furthermore, the required high-quality concrete for the GBS requires that sufficient qualified expatriate staff is deployed to the building site, at a significant cost. Also the schedule will then likely be longer.

For the FSRU the site selection is less critical. The FSRU may be located anywhere where the water depth is sufficient to moor the unit safely. Its sensitivity to soil conditions is small because they will only affect the cost of piling for the mooring system. Although in some areas required water depth would involve a large distance to shore, this is certainly not the case in many other areas. In many cases the distance to shore is governed by the requirement to be out-of-sight, both for the GBS and the FSRU. The FSRU can also be located in areas with worse weather conditions, due to its weathervaning capability, with significantly reduces the wave impact forces on the unit, and allows berthing and offloading in higher sea states.

In this respect the conclusion is that the FSRU can be more flexibly deployed, compared to the GBS.

Construction phase. During the construction both concepts differ in many respects. The main differences are discussed below.

Construction site. For the GBS construction a graving dock must be developed, as described earlier in this paper. Alternatively, an existing graving dock may be found, but it is likely that extra costs are required to make it suitable for the construction of the GBS. Permitting for the graving dock may cause delays.

The FSRU will be built in a shipyard, according to standard shipbuilding practices. In the Far East and in Europe, several yards are capable of building such a facility.

It is therefore concluded that the construction risks and potential for cost escalation can be better controlled for the FSRU.

Fabrication. Provided that a suitable graving dock location is available, the GBS can be built in the vicinity of the installation location.

The fabrication requires skilled construction supervision staff, to ensure that the quality of the concrete meets the specification. However, local labor can be used quite extensively, which may be an advantage for political reasons. A concrete structure can essentially be built in any country.

Concrete can be prepared locally, but the materials for the concrete production may have to be shipped from a distant location, if no suitable sand is available nearby.

The FSRU will likely be fabricated in East Asia, for cost reasons. The construction of the hull is in accordance with standard shipbuilding practices. However, not all shipyards will necessarily be interested in building an FSRU. Many of the existing shipyards have a full order book until late in this decade, and not all are in the business of LNG. However, it is judged that at least several of them will be interested in building the FSRU.

For both concepts, the topsides are assumed to be installed by floating sheerleg-type cranes once GBS or FSRU hull are afloat.

Once the graving dock for the GBS is available, both concepts are considered equally straightforward to fabricate.

Topsides integration. For the purpose of the study it was assumed that topsides would be pre-fabricated in modules. It is therefore considered that there are no major differences between both concepts related to topsides installation and integration.

For the FSRU the piping design is slightly more critical due to hull bending. For the GBS the hull penetrations are more critical and allow very little flexibility once the construction is started.

Overall, both concepts are considered equal in this respect.

Transport. Unlike a ship-shape hull, a GBS is normally not designed for sea transport over long distances, e.g. for a 1-year storm condition. The GBS is a simple rectangular block with skirts underneath it. It has therefore very poor sailing properties. The GBS transport distances should be limited to approx. 1 week in view of weather forecasting. This requires that the graving dock is relatively nearby. The tow speed will likely not be higher than 2 knots and possibly lower. The graving dock distance should therefore not be further away that approx. 350 miles, unless sailing in relatively protected waters.

The FSRU is designed for a long-distance tow from East Asia to its installation site. This means that it can normally withstand a 1-year storm around the Cape of S-Africa. The tow speed is approximately 6 knots, i.e. the transport will take approximately 2 months.

The shorter transport duration is an advantage for the GBS, but this is reflected in the overall schedule. Technically the transport of the FSRU is much more flexible that that of the GBS.

Site preparation. For the GBS installation location, the seabed must be flat, and any silt and mud must be dredged away until a stable soil foundation is obtained. Depending on the mud layer thickness, the depth of the GBS will have to be increased with the earlier-mentioned cost penalties.

After installation of the GBS (lowering by means of pneumatic excavation, filling void areas with grout and filling areas between skirts with concrete) it will be necessary to backfill the area surrounding the GBS. It is likely that also stone dumping or installing stone mats around the GBS to avoid scouring, will be necessary. Any settling must be avoided to prevent damage to the pipeline.

For the FSRU installation location, site preparation is generally not necessary.

It is therefore concluded that this aspect is an advantage for the FSRU.

Installation. Installation of the GBS is a much more tedious and critical operation than for the FSRU. Particularly the lowering and leveling operations are critical. Care must be taken that the loads on the concrete structure are equalized, and that the local loads are not excessive as a result of unstable or unequal soil conditions. It is therefore judged that pneumatic excavation underneath the GBS is necessary during its installation to mitigate those risks. This installation will take approximately 5 weeks.

Installation of the FSRU involves the hook-up to the pre-installed mooring lines and piles, tensioning of the lines, and the hook-up of the pre-installed risers to the turret. A pipeline end manifold (PLEM) serving as an anchor point for the pipeline must be pre-installed as well. This is done using an offshore installation vessel. Due to the large pipeline diameter and the potentially long pipeline, the PLEM will be quite heavy. The installation will take approximately 1 week.

It is therefore concluded that the installation of the FSRU is easier and less risky.

Schedule. The shortest schedule for the GBS is approximately 6-7 months longer than that for the FSRU, due to the time required to develop the graving dock, assuming start dates when the EPC contracts are signed, and after the FEED-phase is (partly) completed. It is assumed that permitting and land acquisition for the GBS graving dock are also done prior to contract signing. The schedules include site preparation (for the graving dock only), hull fabrication, tank installation, topsides installation and integration, outfitting, gas trials, tow to site, installation, and commissioning.

In case a suitable graving dock is available in the vicinity the GBS schedule will be shorter, and could by similar to that of the FSRU, which is estimated at 36 months.

Bearing special circumstances it is therefore concluded that the FSRU has a clear schedule advantage over the GBS.

Cost escalation. Although the costs of both concepts were evaluated in the comparison study, it is not felt appropriate to directly compare both concepts, since they differ too much in nature to compare on a fair basis for a given location. Depending on the location parameters, one of the concepts would obviously have the cost advantage over the other one.

Qualitatively it can be stated however, that being the conditions optimal for both concepts (although this is not a realistic scenario for a single project location), the FSRU has a lower CAPEX and LCC. The OPEX of both concepts is comparable.

It is nevertheless more appropriate to analyze under which conditions each concept has the best performance, or when it is particularly unattractive. Therefore a cost sensitivity analysis has been carried out, of which the results are given in the next chapter.

From the sensitivity analysis it appeared that the GBS is quite sensitive to a number of location parameters, which can lead to a significant increase in cost, compared with the most optimal conditions.

It can therefore be concluded that the GBS has a significant upward cost escalation risk, which are influenced by site-specific parameters.

Operational phase. During the operational phase the differences lie mainly in the fact that the GBS is a fixed concrete installation, whereas the FSRU is a floating steel hull type installation.

Berthing and mooring. Any differences between both concepts depend on the selected location and its local environmental conditions. For example in the Gulf of Mexico, there will be very little difference between the operability of both terminals as far as related to berthing and mooring, due to the benign environment. In other areas, e.g. for the US West or East Coast in unprotected open sea, it is expected that the FSRU will have a higher operability than the GBS due to its weathervaning capability, which makes it easier for the carrier to approach and moor.

The FSRU will also need fewer tugs (one compared to four for the GBS) to assist the carrier during its approach and mooring. The FSRU is fitted with thrusters capable of adjusting its orientation to facilitate the berthing operation.

It is therefore expected that the LNG carrier can berth and moor in higher sea states to the FSRU than to the GBS.

LNG transfer. The offloading of LNG from the carrier to the import terminal in a side-by-side arrangement is probably easier for the FSRU than for the GBS. Although the FSRU itself is also moving, the relative motions between the carrier and the FSRU are not necessarily larger than those of a carrier moored to a GBS berth.

The offloading will be possible in higher sea states for the FSRU than for the GBS, due to higher mooring limits. For the GBS the limits are roughly 1.5 m for berthing, and 1.5 – 2.5 m for the moored condition offloading, depending on the wave period. For the FSRU the expected berthing and moored condition limits are approx. 2.5 m, but also depend on the wave period.

Further study will be required to assess the relative differences between both concepts regarding LNG offloading, depending on the local environment.

Storage. There are no significant (dis)advantages between both concepts as far as storage systems is concerned. Choice is available and is merely driven by cost considerations.

Vaporization. Vaporization on the GBS is straightforward. Onshore technologies can be applied, such as open rack vaporizers (ORV), condensing-type intermediate fluid vaporizers (C-IFV), water/glycol-type intermediate fluid vaporizers (WG-IFV), or submerged combustion vaporizers (SCV).

For the FSRU the choice is slightly limited to the use of GS-IFV, C-IFV or SCV. The ORV type is not (yet) suitable due to its sensitivity to motions.

However, the use of C-IFV is not recommended, as it requires the use of a refrigerant such as ammonia, propane, R134 etc. All of these refrigerants have certain drawbacks, ranging from being an ozone-depleting gas, being toxic, or being flammable/explosive. Direct vaporization with seawater in shell-and-tube vaporizers (STV) is not considered proven technology by all users.

It seems that either the ORV or WG-IFV are the best choices for the GBS, with back up from one or more SCV's if some independency from seawater supply is desired.

For the FSRU the best option would be the WG-IFV, with back up from one or more SCV's.

Both concepts are equally well placed in this respect.

Send-out. The gas send-out from the GBS is done via a fixed single riser to the seabed, where the connection with the pipeline is made. A PLEM is not required if suitable provisions for anchoring are made on the GBS at seabed level. Metering can be done using in-line flow meters (e.g. ultrasonic type), in combination with tank level measurement (radar-type) if desired. Depending on the distance to the grid and the requirement for future expansion, a 32-inch to 42-inch diameter will be required.

On the FSRU, the gas send-out runs via a swivel stack in the turret with 3 or 4 stacked toroidal HP gas swivels. Although this is more complex, the swivel technology is proven and has been applied on several FPSO's. From the turret 3 or 4 flexible risers run to the PLEM at the seabed, where they are manifolded to the pipeline. The gas is metered using in-line flow meters. Tank level gauging is not suitable due to the vessel's motions and trim/list.

In conclusion, the GBS gas send-out system is considered simpler and slightly more reliable than that of the FSRU.

Maintenance. In case a membrane-type containment system is selected for the GBS, external inspection of the tanks is not possible. However, the concrete walls are considered very rigid and any moisture can be prevented from penetrating to the insulation system. The probability of water ingress occurring during the lifetime of the GBS is therefore considered very remote. Any leaks or defects are likely to be discovered during the commissioning phase. However, should a leak or other defect occur, the consequences are quite severe. Because the GBS has only two tanks, one of them being out of service for a prolonged time will have consequences for the gas delivery. Repairing the defect is time-consuming, and scaffolding will have to be applied to the tank interior.

The SPB tanks that are applied in the FSRU can be inspected both internally and externally for cracks or other defects. In case of a defect or leak, the external insulation can be removed and the tank can be repaired in-situ. The FSRU does not have to go to dry-dock. The tanks have internal girders and ladders for easy access and internal inspection.

The external inspection can be done likewise if the inner hull is provided likewise. Since the FSRU has 5 tanks, one tank being out of service has only limited or no consequences at all for the gas send-out. Adjacent tanks can also remain in service.

The GBS structure does not need any maintenance that affects the production. Regular inspection of the GBS foundation is required by divers to check for any cracks in the concrete or scouring.

Since it is intended to maintain the FSRU on station without dry-docking for its entire lifetime (say 25 years), the FSRU hull needs to be inspected on a regular basis. The hull internal design must allow easy access to all spaces. Obviously a sufficient corrosion allowance must be applied to critical areas of the hull. The hull must also be inspected externally by divers, e.g. every 5 years, for any cracks or other defects. Any repairs should be carried out locally, which will require a complete shutdown of the send-out system.

Also the mooring system and risers need regular inspection to check their integrity. This is a normal operation that is applied for FPSO's as well. The mooring system is designed with sufficient redundancy to enable replacement of e.g. chains, swivels etc, should this be necessary. This is very uncommon though.

As for the topsides there is little difference between both concepts. Topsides maintenance is quite common on

FPSO's as well as on GBS structures around the world. If necessary, complete new equipment or even modules can be removed or added offshore.

For the GBS maintenance dredging around the structure may be needed, especially for the approach and departure channels of the LNG carriers. The GBS causing a disturbance in normal water currents could cause local sand replacements, resulting in scouring and sand accumulations nearby the structure. Regular sea bottom inspection (say yearly) may therefore be required.

Stability. In principle the GBS is a very stable platform. There are however some design risks that have to be adequately addressed: wave impact and run-up, and soil instability. The former is relatively easy to address in the design. The latter involves a larger risk, and therefore justifies extensive soil investigation. There have been examples of past GBS structures where excessive settling required a costly uplifting years after initial production. Should this occur with the GBS it would require a complete shutdown for a prolonged period.

The stability of the FSRU is of a different nature. The vessel is designed to operate in any loaded or ballasted condition in the 100-year design storm, even in case one of the tanks is damaged and water is entering the tanks. Stability should therefore not be a concern. With respect to the operation of the plant, the FSRU motions could potentially affect the performance of the vaporizers (SCV) or the recondenser. It is judged however that those issues can be solved in the engineering phase. Several large contacting columns are in operation now, and generally their performance improves with motions.

Operability. For the GBS it appeared that for the selected design data the expected downtime in terms of lost send-out capability is approx. 0.6%. The offloading downtime is approximately 1.2% (also slightly pessimistic). For the FSRU a similar or slightly lower value is expected. Since the differences for this location are insignificant, the results of the downtime analysis have not been further taken into account for the life cycle cost analysis. It is noted, however, that this situation is likely to be different in case a less benign location is selected. This will require further study.

Safety. The GBS' thick concrete walls provide excellent protection against collision impact. The concrete is capable to withstand cryogenic spills, dropped objects, or fire and explosion in the topsides plant. The stored LNG will not be inadvertently released in such events. However, since it is a fixed structure the local impact loads from a collision with a LNG carrier can be high, resulting in damage to the LNG carrier. It is therefore recommended to have a separate (relatively flexible) berth adjacent to the concrete structure, which can absorb most of the impact load in such an event. Of course this adds significantly to the cost.

The GBS performance is not sensitive to storm conditions. If desired, the unit can continue its operations during the storm with minimum manning. However, care must be taken during the design stage to avoid 'green' water on the deck due to wave run-up in beam seas.

Since the GBS is a fixed facility, there is a certain rollover risk, similar to onshore terminals. This can be mitigated through operating procedures and tank monitoring.

The FSRU has different characteristics than the GBS. Cryogenic spills must be mitigated by engineering, and by protective shielding from the hull steel. The topsides have therefore been provided with stainless steel plating underneath, and the main deck of the vessel is protected where necessary with foam or wood.

For the FSRU the risk of a large vessel (LNG carrier) collision is rather remote for a side-by-side berthing operation. The FSRU is equipped with thrusters, which will be used to keep the FSRU-stern away from the approaching vessel and allowing it to approach head-on to the waves and wind. Normally the vessel should approach in line with the orientation of the FSRU, and should come alongside the FSRU at a distance of approximately 5 beam widths, after which it will be pushed softly towards the FSRU. This procedure will avoid any collisions with the stern of the FSRU. The carrier will therefore undergo very little forces, unlike the carrier approaching the GBS, which could be subject to strong beam wind and wave forces. Also, because the FSRU is moored 'softly', it will give in to impact loads.

For the FSRU, rollover is considered very unlikely due to the motions and continuously changing trim.

It is therefore concluded that both the FSRU and the GBS provide a safe platform for offshore LNG imports. Although each concept has its own specific safety features, the overall safety of both concepts will be well within accepted industry standards.

Future phases. Differences in future phases are mainly related to capacity expansion and decommissioning. These aspects are discussed below.

Expandability and re-use. The GBS capacity can technically be expanded by adding a second structure adjacent to the first one, connected with a bridge. The additional cost would depend on the added storage capacity. The topsides can be relatively easily expanded by adding new modules on the first or on the second structure.

Issues to consider are the simultaneous operations of LNG offloading and installing the second structure while several other vessels operate at the same location (dredger, support vessel, crane, flotel, etc.), in view of the relatively long installation period (4 –5 weeks).

Re-use of the GBS in another location is considered to be impossible.

The send-out capacity of the FSRU can be relatively easily expanded, in the same way as for the GBS. Expansion of the storage capacity of the FSRU itself is not possible, unless a modular expandable concept is selected from the beginning (for which SBM has already developed a concept). In case more storage is needed, another possibility is to remove the existing FSRU, to redeploy it to another import location, and to replace the present FSRU with one of a larger capacity. Capacities of up to 400,000 m^3 are possible.

In case the FSRU is leased this option can be exercised with very little risk for the gas importer. In case of a turnkey supplied unit, it may be sold back to the supplier of the unit, who can then re-use it somewhere else.

The change-out of units will take approximately 2 weeks, during which period the gas send-out will be interrupted.

It is therefore concluded that both concepts are equally flexible with regard to future expansion.

Decommissioning. The GBS can be decommissioned by refloating it, provided that sufficient facilities are built into the unit during construction. After disconnecting from the pipeline the GBS can be towed to a decommissioning yard. The tank membrane material may be reused. The concrete structure must then be disposed of. This is one of the key difficulties with concrete structures. Therefore it is sometimes proposed to reuse it as a quay, or to sink it into the deep ocean. Both options are likely not very realistic or carry risk.

Generally the decommissioning costs are presently assumed to be in the order of 10-20% of the initial total project realization costs (based on North Sea estimates). It is uncertain how those costs will escalate in the far future.

Decommissioning of the FSRU is relatively easy. The risers and the mooring chains are disconnected, and the unit can be taken to a scrap yard. A part of the investments can be recovered at scrap value at the end of the life of the unit. The tanks may be re-used, as they have a very long design life. The chains and risers are removed while the piles can be left behind. Also the PLEM can be removed by cutting it loose from its anchor piles. The pipeline can be left behind, as it does not contain any polluting fluids or hazardous materials. It will corrode away over time.

Summary technical comparison. The above-discussed issues are summarized in Table 1 below.

Table 1 - Summary technical comparison

	GBS	FSRU
Design Phase		
Permitting	o	o
Site selection	--	+
Construction Phase		
Construction site	o	+
Fabrication	o	o
Transport	--	+
Topsides integration	o	o
Site preparation	--	o
Installation	--	+
Schedule	o	+
Cost escalation	--	o
Operational Phase		
Berthing and mooring	o	+
LNG transfer	o	o
Storage	+	+
Vaporization	+	+
Send-out	+	o
Maintenance	o	o
Stability	+	+
Operability	?	?
Safety	+	+
Future Phases		
Expandability and re-use	o	o
Decommissioning	--	+

o = Average
\+ = Good
-- = Poor

Cost sensitivity analysis

A cost sensitivity analysis has been carried out to determine how each concept would be affected by better or worse local conditions. For each sensitivity case the same baseline cost value was used, for which the sensitivity to changes in conditions was subsequently determined. The basis for the comparison was the total initial investment cost, up to initial start-up. The results are summarized below. The following aspects were addressed:

- Water depth
- Pipeline length
- Wave height
- Soil conditions
- Steel (FSRU) or concrete (GBS) cost
- Schedule

It should be realized that the above-mentioned cost parameters are analyzed separately, whereas in certain cases some of them may in fact be dependent. In those areas the combined effect of the relative cost sensitivities should be multiplied.

Where necessary the dimensions of the GBS are modified to fulfil the design criteria as set forth earlier in this paper.

Water depth. Figure 8 shows how the relative costs vary. It is observed that the costs of the GBS are much more sensitive to the water depth than those of the FSRU. From this result it is also clear that each concept has its own specific range of water depths. A practical upper limit for the GBS is probably around 30 m, whereas this is likely the lower limit for the turret-moored FSRU. In benign areas the FSRU may be fitted with a soft yoke type mooring system, which will allow shallower water depths, e.g. down to 20 m.

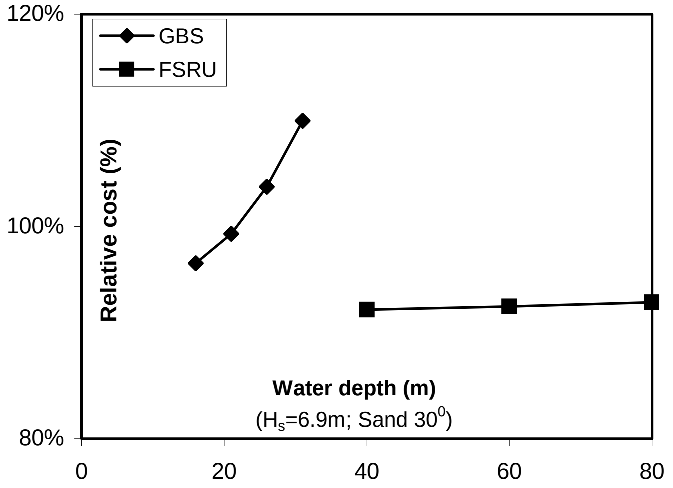

Figure 8 - Relative cost vs. water depth for GBS and FSRU

Pipeline length. For the FSRU as well as for the GBS the pipeline length may vary, depending on the distance to shore or to existing pipeline infrastructure. The effect of the pipeline cost on the total CAPEX is shown in Table 2 below, and can be quite significant if conditions are unfavorable.

Pipeline Length (nm)	Relative cost
10	100 %
20	106 %
40	121 %

Table 2 - Cost of Pipeline for GBS or FSRU

Wave height. Figure 9 shows how the total costs of both concepts vary with this parameter. It should be noted that in shallow water the wave height is depending on the water depth. Too large waves coming in from deeper water will break in shallow water and will thus reduce the maximum wave height in shallow water.

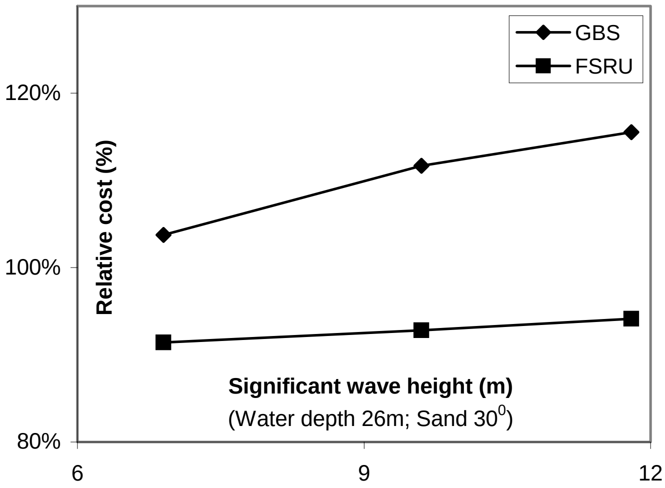

Figure 9 - Relative cost vs. significant wave height for GBS and FSRU

Soil conditions. The GBS was believed likely to be rather sensitive to soil conditions, which is why also a sensitivity check on this parameter was carried out. Figure 10 shows how both concepts relatively compare. It shows that the GBS is indeed very sensitive to soil conditions, whereas the FSRU is nearly insensitive.

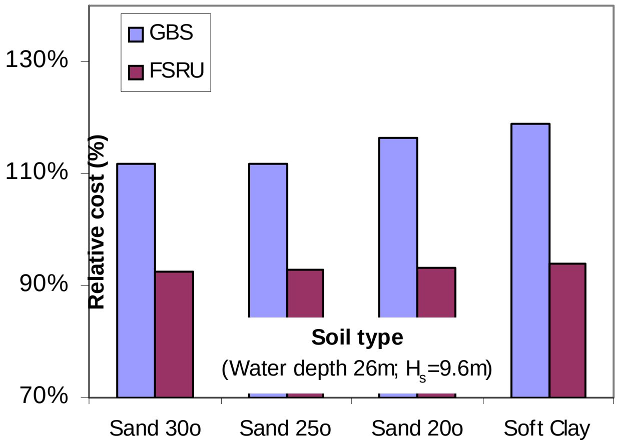

Figure 10 - Relative cost vs. soil type for GBS and FSRU

Steel (FSRU) or Concrete (GBS) Cost. The steel price for the FSRU-hull and the cost of applying the high-quality concrete (incl. pre-tensioning cables) for the GBS was also expected to have an impact.

Figure 11 shows how the total cost of each concept is affected by the cost of steel or concrete. The steel price level will depend on shipyard occupancy and country of fabrication. The concrete cost will for the most part depend on local labor costs and to a lesser extent on material costs.

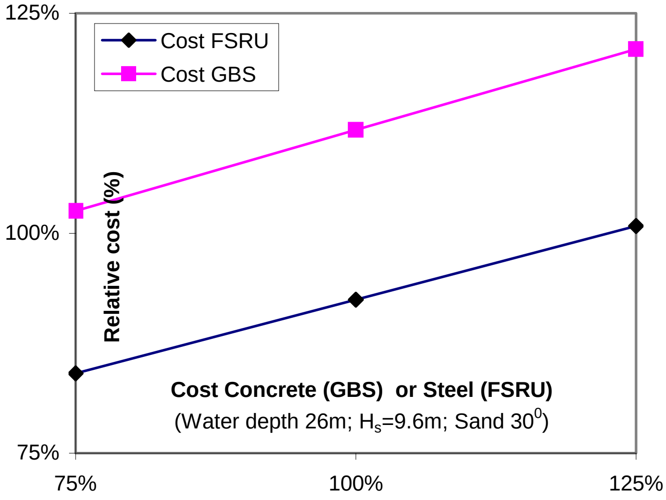

Figure 11 - Relative cost vs. steel (FSRU) or concrete (GBS) cost

Schedule. Any difference in schedule will result in delayed start-up and deferred revenues. It is estimated that the schedule of the GBS is 6 – 7 months longer than that of the FSRU. A sensitivity check was therefore made to observe how this would affect the overall relative economics of the GBS compared with the FSRU. The base case schedule for the FSRU is 36 months. The deferred revenues were estimated based on the average terminal throughput of 720 ton/h (6.3 MTPA). Figure 12 shows the results.

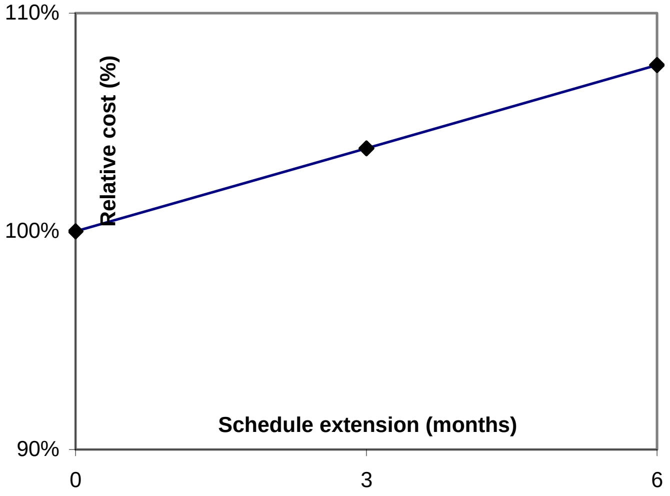

Figure 12 - Relative cost vs. schedule extension for GBS

Conclusions

The comparison between the GBS and the FSRU has revealed a number of interesting differences, some of which were generally qualitatively known, and frequently used as arguments in comparative discussions. In this study an effort was made to quantify several of the cost issues so that the combined results of the technical comparison and the relative cost comparison could be used to support a decision-making process, where a justifiable choice between the FSRU and the GBS is sought for offshore LNG import.

The key parameters that nearly exclusively affect the economics of the GBS concept are the water depth, the soil conditions, and the significant wave height.

The costs of the hull fabrication materials (steel for the FSRU and concrete for the GBS) have a significant effect on the cost of both concepts. It is therefore vital to have both the GBS and the FSRU built in locations where these costs are low. For the GBS this is not necessarily in low-(labour)cost countries. The GBS has the drawback that it likely has a longer building schedule, which also adds to its cost.

For both concepts the distance to nearby existing pipeline infrastructure is vital as well, to avoid excessive cost penalties for the pipeline.

Although the study also addressed the operating costs of both concepts, these were not reported in this paper, since they did not differ much. The maintenance costs for the FSRU were higher, but the GBS showed higher costs for tugs. The extra manning for the FSRU is only 2 persons, and other operating costs were quite similar. Fuel consumption is an important contribution to the yearly operating cost.

Although the future decommissioning costs for the GBS are likely quite high and potentially a drawback, this has not been included in the comparison, because of the large degree of uncertainty and the long duration before the expense will have to be made.

In conclusion, the GBS is more expensive than the FSRU, even in its most optimal environment. In benign environments, if the unit can be built in shallow water, and where soil conditions are not cost-prohibitive, the difference is relatively modest.

However, the upward cost risk for the GBS is much larger than that for the FSRU if the conditions are sub-optimal, which is shown in the figures 8, 9 and 10.

Since the FSRU costs are almost independent of the environment, it is easier to estimate the development costs for the FSRU, irrespective of the location. In addition, the FSRU is always less costly than the GBS, unless the pipeline costs are strongly in favour of the GBS.

Finally, the cost of the FSRU can be better controlled than that of the GBS, because the FSRU is built in shipyards, using experienced crews, which is not likely the case for a GBS.