A HIGH CAPACITY FLOATING LNG DESIGN

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ABSTRACT

The Prelude FLNG solution is capable of processing rich gas. Developments with rich gas using similar facilities may also benefit from the considerable amount of revenue possible from condensate and LPG. However, some fields have gas that is significantly leaner, and will not have the benefit of condensate and LPG revenue streams. To ensure robust and economic development of gas fields with lean gas compositions, Shell has developed FLNG Lean.

FLNG Lean is an FLNG concept with a nominal LNG production capacity of 6 million tonnes per annum and reduced functionality for other liquids. FLNG Lean is a natural development of the Shell FLNG design selected for Prelude. The substructure design with its utilities, the accommodation, the operating and the safety philosophies, the flare and blow-down system, the cooling water systems, the LNG containment systems, the LNG off loading system, and the turret and mooring system design are all the same, enabling repeatability gains. Lessons learnt and the latest technology developments have also been implemented. Some utilities are relocated to the substructure to create sufficient deck space for the liquefaction trains and process equipment. Modern aero-derivative gas turbines will drive the liquefaction compressors and power generators. All process heating requirements will be met by waste heat recovery units.

This paper will describe the FLNG Lean design and its application area. We will first describe the economic drivers, then highlight the approach followed, explain the main features of FLNG Lean, compare it with Prelude, and conclude with an outlook on the future of FLNG.

INTRODUCTION

The importance of the role of natural gas to meet the world’s energy needs now and into the future is clear, and we believe the case for LNG is equally compelling. International trade in natural gas is set to grow rapidly, and the share of LNG in total gas trade is expected to rise [1]. Like other forms of natural gas, LNG offers cleaner energy than oil or coal, important in a world increasingly concerned about environmental issues. In many situations (large distance from market, rugged terrain etc.), LNG is cost competitive with other forms of gas delivery and has a commendable track record in reliability and safety. This track record, spanning around 50 years, underpins the crucial role of LNG in ensuring security of supply in the future. Another advantage is the flexibility of LNG. Unlike pipeline gas, buyers are able to source LNG from multiple supply points providing additional supply security.

Shell has a long history in creating innovative technologies to safely and reliably deliver energy to the world’s markets, and is one of the pioneers of the LNG industry. In the early 1960s we participated in the first base load LNG plant, which started up in Arzew, Algeria, and we have continued that technical innovation and delivery to become the world’s largest international oil company (IOC) by equity LNG production with ownership in many liquefaction projects currently in operation or under construction. Shell is a leader in LNG shipping with a track record of delivering first class commercial, technical and ship management services over five decades. We were partner in the first-ever purpose-built LNG carrier in 1964 and today are one of the largest LNG vessel operators in the world with equity, management and/or staffing positions in more than a quarter of the industry’s LNG vessels in operation. We also have a proven track record in marrying
production technologies with offshore environments, successfully installing the world’s first floating production storage and off-loading (FPSO) vessel, the Castellon in Spain in 1977. In May 2011, Shell announced the final investment decision (FID) to build an FLNG facility to develop the Prelude gas field – 200 kilometers off Australia’s north-west coast.

With the FLNG technical hurdles resolved, and increasing opportunities where a FLNG solution may be applied, FLNG projects have now gained significant interest in the LNG industry. However, FLNG technology remains challenging, as our investment in design and research over the last decade shows. Our experience in offshore field development, floating production facilities, LNG production and LNG transportation prepared us to be a pioneer in the development of FLNG. Built on these experiences and lessons learnt from Prelude we are now introducing FLNG Lean, which is particularly attractive for larger gas fields with relatively low liquid content.

FLNG offers a route to greater flexibility and increased access to natural gas resources. It also enhances our ability to operate responsibly in environmental sensitive areas. The market circumstances, the environmental circumstances, and the technical maturity let us believe that FLNG has now grown to become a very serious gas monetisation option in a widening portfolio of opportunities.

**ECONOMIC DRIVERS FOR FLNG PROJECTS**

To illustrate how production capacity is a key driver for FLNG to be cost competitive, a comparison has been made between a *midsize* and a *large* FLNG facility. Reference is made to figure 1.

![Figure 1 – Economic comparison between a midsize and large FLNG facility](image)

In this context, with ‘midsize’ a capacity of 2-2.5 million tonnes per annum (mtpa) is meant while for with ‘large’, a capacity of approximately 6 mtpa is assumed. The two data points represent one midsize FLNG unit and on large FLNG unit respectively. Although the comparison has been made for gas that is relatively lean and a reservoir containing 4 trillion cubic Feet (tcf) of gas, implying different production periods, the conclusions can be shown to be valid over a range a gas compositions and reservoir sizes. The left y-axis compares absolute cost, expressed in Net Present Value (NPV), while the y-axis on the right compares normalized unit technical cost (UTC), which is the same cost –again expressed in NPV- per unit of LNG.
production. The costs have been normalized; the graph only provides an impression how cost components scale, and cannot be used for cost calculations or absolute cost comparisons. It should also be noted that cost numbers exclude upstream cost, which for a typical FLNG project can be significant. The graph shows that although total cost i.e. capital expenditures (CAPEX), operating expenditures (OPEX) and other (like owners cost and contingency) of midsize floater is 65% of a larger floater, UTC—as key indicator for economic feasibility—may be roughly 30% higher as compared to a large floater.

Although Shell’s Prelude FLNG facility is normally quoted as having an LNG capacity of 3.6 mtpa, it actually has three product streams: LNG, LPG and stabilized condensate. LPG is exported as a separate product as otherwise the resulting heating value of LNG would be too high for certain markets. The gas from the Prelude field is rich with a condensate to gas ratio (CGR) above 50 bbl/MMscf. As such, when all these separate product streams are taken into account, the overall hydrocarbon export rate becomes 3.6 (LNG) plus 0.4 (LPG) plus 1.3 (condensate) i.e. equal to 5.3 mtpa. A significant revenue stream for Prelude originates from condensate, which explains why FLNG economics—for a Prelude-like facility—would drastically change if a field is developed with a leaner feed composition. If one would compare fields with CGRs of 50 and 5 respectively, the associated revenues for condensate would almost be zero for the lean case compared to the rich case. This is illustrated in figure 2 below, where UTC for two identical FLNG facilities but with i.e. a rich and a lean feed respectively, have been compared. In the same chart, the target UTC area for a high capacity FLNG lean design has been indicated. The conclusion is that to make an FLNG Lean development economically feasible, the UTC of the floating LNG facility needs to be lowered significantly.

![Figure 2 – Midstream unit cost as function of the field size for designs similar to Prelude and the new high capacity FLNG design](image)

**APPRAOCH FOLLOWED TO DEVELOP FLNG LEAN**

In previous papers, we described Shell FLNG [ref 2-5]. The first application of Shell FLNG is for the Prelude field in Australia, and several other applications are being considered. In this paper, we refer to this design as the Prelude design. From several detailed analyses—in essence similar to the one described above—the economic solution space for a FLNG facility targeting lean fields was derived. Assuming operational expenditure similar to the Prelude project, the challenge could be framed as can we increase the facility’s
liquefaction capacity while maintaining the capital expenditure to levels that would be similar or even lower than Prelude. At the start of the project, no target LNG export capacity was set but the project team was encouraged to aim as high as practical.

The starting point for FLNG Lean design was to replicate the Prelude design where possible and as much as possible. The substructure, containment systems, mooring and LNG offloading facilities, cooling systems, living quarters and the turret and flare system are all similar to the Prelude design. Besides replicating physical parts of the Prelude facility, the same underlying design and safety philosophies were used. The FLNG Lean design is also using the Shell dual mixed refrigerant (DMR) process for liquefaction, a process which has been proven in Sakhalin [ref 6].

**Process safety** is the single most important guiding principle for developing the layout [ref 7]. It is primarily managed by adherence to the relevant process safety standards and evaluation of the layout through quantitative risk assessments (QRAs), performed at different design phases of the project. The overall aim is not only to reduce the risk for personnel operating the facility but also to be able to demonstrate that the design choices made demonstrably satisfy ‘As Low As Reasonably Practicable’ criteria (ALARP). In other words the cost to reduce the risk further would be grossly disproportionate to the benefit gained.

Product tanks and the (relatively) non-hazardous equipment like most utilities, the power generation and marine facilities are installed ‘below deck’. The process units are located on the ‘barge deck’. If space is limited on the deck, the equipment for Monoethyleneglycol (MEG) regeneration and local equipment rooms (LER) an also be placed inside the hull. The more safety sensitive areas such as the turret, the flare and the process units with a large liquid hydrocarbon inventory are separated from the accommodation block by placing the relatively low risk equipment and utilities in between.

On the barge deck and the main process deck escape ways are provided at the both starboard and port side, running over the full length of the FLNG facility. The central alley between the port and starboard side modules provides a third escape way on the process deck level.

Lean fields with a CGR smaller than 5 bbl/MMscf will require refrigerant import. Although difficult to source and transport to the facility, an ALARP assessment clearly showed that risks associated with handling and storage of ethane and propane import would be less than those associated with ethylene which is much easier to obtain.

Although the QRA showed slightly increased risk levels for locating a tandem offloading system at the stern of the facility, the presence of such a tandem offloading system reduces the risks generated by side by side offloading in harsh environments.

As per Prelude design, the main process modules are separated by so called ‘safety gaps’, which are open and uncongested areas of at least 20 metres that run over the full width of the barge. The safety gaps reduce the risk of an escalating event impacting the integrity of the Temporary Refuge within the living quarters. There are three mechanisms by which the safety gaps fulfill this function. (Firstly, the free circulation of air in the open area improves the dispersion of gas releases, reducing the size of any potential gas cloud. Secondly, physical separation of hazardous equipment reduces the risk of escalation. And thirdly, in case of a very large gas cloud covering multiple modules, the absence of equipment and piping in the open area prevents continued flame acceleration along the entire length of the process area, which could result in high overpressure levels.

As per Prelude design, most process units of the FLNG facility are located as modules on the vessels topside. The barge deck is used for routing of large bore piping. Modules containing the process equipment are placed on stools above the barge deck. The main process deck, some 6 to 8 metres above the barge deck, interconnects the process deck of all modules. The four main modules are split into smaller sub-
modules for lifting and constructability purposes. As mentioned earlier, a 20 metre open area, the so called safety gap, is maintained between the modules. A 10 metre wide central alley forms the main transportation route and runs over the full length of the process main deck between the port and starboard positioned sub-modules.

For reference, a picture of the Prelude design has been added below (figure 3).

![Figure 3 – Prelude FLNG facility from birds eye perspective](image)

Having agreed these replication principles, it was quickly realized that some exemptions had to be made as well. In order to create space on the deck, some utilities had to move into the hull and the topsides’ functionality needed to be reduced. Due to lean nature of the gas, there is no need to remove LPG to stay within the LNG heating value constraints. This reduction in functionality allows for a simplification of the gas conditioning line-up, leading to a reduction of FLNG topside space and weight. Refrigerant can be extracted from a slipstream by a small dedicated unit or the refrigerant components ethane and propane can be imported. In addition, for the smaller amounts of condensate considered, the natural gas liquids (NGL) extraction scheme can reduced. The space reserved for condensate storage could be reduced, freeing up space in the hull for the utilities. The lower total heat requirement, as well as the developments and confidence in aero derivative gas turbines, allows the use of these for both power generation and compressor drives. This not only provides weight and space advantages, but also reduces greenhouse gas emissions.

For process design purposes, a range of feed compositions was evaluated. The range was set by compositions from Shell’s opportunity portfolio with a CGR of 20 as upper range and a CGR of 5 as lower
range. From the same list of opportunities, it became clear that the acid gas removal unit had to be developed for CO₂ concentrations ranging from 1 to 10%. For cases with a high CO₂ content in the feed gas, CO₂ sequestration facilities are projected. Although most of the fields considered have relatively small amounts of nitrogen, it was decided upfront to verify what extra process equipment is required for N₂ concentrations up to 3 mol%. As product specifications, standard export values applicable were assumed for both LNG and condensate. It was further decided to target the design for moderate climates in terms of temperature but to ensure it could successfully be operated in very harsh metocean conditions. Flow assurance requirements were to include continuous MEG injection for deepwater applications to cater for both condensed and water produced from the upstream wells.

The project execution strategy was also embedded early on the frontend phase of the FLNG Lean design. A main feature of the execution strategy is that FLNG Lean will be built by the Technip Samsung Consortium (TSC), and this implies that the topsides modules have to be sized such, that they can be handled at the Geoje shipyard in Korea. And finally to ensure repeatability going from one FLNG Lean application to another, it was decided that standard building blocks will be used for the topsides process modules.

DESCRIPTION OF THE FLNG LEAN CONCEPT

The line-up for feed gas receiving and condensate stabilization facilities unit is similar to Prelude and is located on the topsides at the forward end of the FLNG facility near to the turret area. This unit receives the gas from the turret area where the subsea gas flow arrives. The feed gas arrival pressure is typically 75 bara early life, and 35 bara at end of field life. Depending on the specific opportunity, the gas arrival temperature can be below the gas hydrate formation temperature requiring MEG injection for hydrate inhibition.

Figure 4 – Process line-up for FLNG Lean

The feed gas from the turret is sent to vertical high pressure (HP) inlet separators which have minimum slug handling capacity. The gas is sent via the depletion compressors to the amine treating unit.
In view of the small amounts of condensate compared to Prelude, a configuration with one condensate stabilization train is selected for this case. The overhead gas from the stabilizer is compressed in a two stage off-gas compressor and re-injected in the main gas stream. The stabilized condensate is combined with plant condensate, cooled in the condensate cooler and sent to storage.

Different technologies have been screened, and a conventional amine unit process line-up based on Shell ADIP-X technology as per Prelude design was found to be most suitable. Standard designs have been engineered to cater for levels up to either mol 1% or 10 mol% CO\(_2\) in feed gas. Again closely following the Prelude design, gas will be dried using molecular sieves and mercury will be taken out using conventional mercury guard beds to levels that are typical in industry.

The objective of the C5+ removal unit is to meet the C5+ and benzene specifications for the gas to the liquefaction unit, which is to avoid freeze out of these components in the cold part of the liquefaction process. Compared to Prelude, a NGL extraction column is not required. For that reason a simplified NGL extraction scheme was developed that will work in a robust fashion for the expected range of compositions.

Several small and large capacity liquefaction technologies have been compared by taking into account specific cost, equipment count, specific power (low specific power is equivalent to lower CO\(_2\) emissions), maintenance, availability and operational flexibility. Based on this evaluation and as per Prelude, the Shell’s Dual Mixed Refrigerant process has been selected as the preferred technology.

LNG liquefaction can be done at 50-60 bara, which is the pipeline arrival pressure minus the pressure drop through the treating facilities or it can be done at 90 bara (dense phase liquefaction). Since the selected concept requires a booster compressor to enable 60 bar liquefaction, it is also possible to increase the pressure to 90 bara. Although application of 900# steel is more cost intensive than 600# steel used for the conventional liquefaction, this is compensated by the reduction of piping diameter and the higher LNG production.

Modern aero derivative gas turbines have been selected as the preferred direct driver for the liquefaction unit compressors. They are relatively simple, robust, with a small footprint, a high availability, low maintenance requirements, and have a favorable CO\(_2\) footprint. Depending on composition and environmental conditions a capacity of around 3 Mtpa can be achieved with one liquefaction string. Hence two of such modules each containing one liquefaction string will be required for a 6 mtpa high capacity FLNG design. To be able to accommodate elevated levels of nitrogen, the endflash vessel can be replaced by nitrogen stripper which is required to bring the LNG to a specification below 1 mol% in the LNG.

As per Prelude design, the MEG module can be located on the topside. As the MEG module is low in risk it will be located at the aft of the process deck near the living quarters. The MEG module has a produced water handling capacity sufficient for the opportunities considered and has a salt reclamation capacity to cater for produced water from the wells. In case large MEG injection rates are required or deck space is otherwise constrained, the MEG regeneration module also can be situated in the substructure.

For critical cooling duty applications, sea water from 150 metres depth below surface is used (figure 5). Cooling water obtained from these depths is colder allowing an increase in the efficiency and hence capacity of the liquefaction process. For less critical cooling duties, near-surface sea water is used.
TOPSIDES LAYOUT AND WEIGHT

The general topside design philosophy reflects the most important constraints and consequences of the layout on the overall FLNG design. Important areas for consideration are process safety, operations and maintenance, construction and commissioning, not to exceed weight, piping layout and the total available plot space.

For illustration purposes, an image comparing –in side view- the Prelude and FLNG Lean designs is shown below. Similarities in terms of hull, living quarters, flare and safety gaps are apparent. As –compared to Prelude- power generation has moved to the hull, NGL extraction and condensate stabilisation have been simplified and LPG extraction has been eliminated, the utility modules adjacent to accommodation block and the process module closest to the turret are less congested.
Figure 6 – Comparison of FLNG Lean versus Prelude

**SUBSTRUCTURE**

The key premise for the FLNG Lean concept is to maintain and follow the Prelude substructure design. Repeatability of the design will translate into cost and schedule benefits for each subsequent project.

Figure 7 – Overall lay-out of the FLNG Lean substructure
The substructure (refer to figure 7 and table 1) is a steel construction designed to support the production facilities, provide storage for the inventory of LNG and hydrocarbon condensate and refrigerant at ambient pressure. It shall also provide storage for chemicals and solvents. The substructure will provide facilities for mooring and offloading to vessels for export to market. For condensate a tandem offloading configuration is applied. For LNG a tandem and/or side-by-side offloading configuration is applied, depending on the local metocean conditions.

Table 1 - External dimensions of FLNG substructure

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall length</td>
<td>488 m</td>
</tr>
<tr>
<td>Length between perpendiculars</td>
<td>472 m</td>
</tr>
<tr>
<td>Breadth (moulded)</td>
<td>74 m</td>
</tr>
<tr>
<td>Depth (moulded)</td>
<td>43 m</td>
</tr>
</tbody>
</table>

Detailed analysis has been undertaken using the Shell Advanced LNG Supply Chain Application (SALSA) model to confirm the storage requirements from a shipping logistics point of view and ensure optimal product storage tank sizes.

TURRET, MOORING AND RISERS

The turret and mooring system builds upon the knowledge and experience of the Prelude FLNG design concept. The FLNG vessel will be permanently moored with a forward-mounted internal and freely weather vaning turret.

Figure 8 – FLNG Turret and Mooring System

Swivel stack permits fluid transfer from subsea systems to topsides
The turret supports the mooring system and all risers and umbilicals. It contains a fluid transfer system (swivel stack) to safely and reliably convey well stream products, gas for exportation, injection chemicals, water for reinjection, CO₂ for injection and signals/power between the vessel and subsea facilities. The turret structure will be designed to resist loads under the most extreme weather conditions including hull deflections, mooring loads and direct slamming loads.

![Image of turret and risers](image)

**Figure 9 – Free Standing Hybrid riser (left) and Steel Lazy Wave riser (right)**

Up to eight production risers may be required, based on a maximum allowable gas velocity at depletion conditions. For waters deeper than 500m either a free standing hybrid riser or steel lazy wave riser could be selected. A picture showing potential deepwater riser concepts is shown below.

**PRODUCT OFFLOADING**

The side-by-side LNG loading arms have a fixed position (plus or minus 10 metres) about midship at the starboard side of the FLNG facility. As per Prelude, the present design for side-by-side offloading of LNG from FLNG is a double counterweight marine loading arm shown in figure 10 (ref 5).

In the Offshore Loading Arm Footless (OLAF) design, -a co-development between Shell and FMC- a rearrangement of identical and proven components of the current marine loading arm design, the main counterweight has been relocated from the inboard loading arm to its own support. This main counterweight balances the inboard/outboard arm assembly using a rigid pantograph connection. Relocation of the main counterweight eliminates the base riser and enables the use of shorter inboard and outboard arms to reach the required operating envelope. The position is determined by the mooring facilities for the LNG carrier that comes alongside the FLNG facility for loading.

The operating envelope for side by side LNG offloading to a LNG carrier is constrained by the combined effects of wind, wave and current. To allow FLNG to operate in environments where side by side offloading would not provide sufficient uptime, Shell has worked -again in partnership with FMC Technologies- on the development of a hard piped stern to bow offloading system referred to as ATOL (Articulated Tandem Offshore Loader) as per figure 11 (ref5). The ATOL is a system to enable tandem (stern-to-bow) offloading of LNG, between the FLNG facility and specially designed dynamically positioned LNG carriers (DPLNGC).
Just like the OLAF system explained above, the ATOL consists largely of proven components but once more re-arranged differently. Besides a test program that has been executed to demonstrate the suitability of key components of the proposed system, such as swivels, emergency release systems (ERS), and quick connect disconnect (QCDC) systems, a 1:5 scale model has been constructed to demonstrate the functionality of the overall system. Scale model tests of a FLNG Lean type facility and a DPLNGC to assess marine operability of the ATOL – DPLNGC combination for certain defined metocean conditions have been carried out at the MARIN marine testing facilities in the Netherlands, with the conclusion that an ATOL system for the tandem offloading of LNG from a FLNG vessel is technically feasible for the defined metocean conditions.

Condensate will be tandem off-loaded using a floating hose system.
The availability of a FLNG asset depends on a number of aspects. The key aspects are:

- Well and subsea design
- FLNG process equipment
- LNG transfer and shipping
- Mobilization times for services (in case of unplanned outages)
- Maintenance and turnaround philosophy

An assessment was done for FLNG Lean for two potential opportunities based on the extensive Prelude availability models. From that analysis it was concluded that a high availability in terms of stream-days may be obtained for FLNG facilities operating in harsh conditions, and equipped with an ATOL.

**WHAT COULD THE FUTURE FOR FLOATING LNG SOLUTIONS LOOK LIKE?**

In the first instance, Shell considered FLNG as a technology for developing smaller gas-condensate fields (3-5 tcf) at a relatively large distance from shore (> 200 km) which could otherwise not be developed economically. Economic feasibility studies since Prelude FID hint, however, at a much wider application area. To this end, figure 12 shows examples of possible future FLNG application modes. Besides applications that are similar to Prelude or a development where multiple smaller fields are exploited by means of sub-sea tie-backs, internal economic analyses show that multiple FLNG facilities operating on a large field may be a competitive proposition versus an onshore LNG plant.
Accordingly we foresee exiting opportunities for floating LNG facilities, both for the traditional offshore applications with one or more facilities and potentially also for near shore applications.

CONCLUSION

Shell’s approach to FLNG is to design for safety, longevity, applicability over a wide range of anticipated feed gas compositions and met-ocean conditions and along with high reliability and availability. The development of FLNG is complex and we have invested considerable time and money to put ourselves at the forefront of this technology. We believe that our five decades of experience in LNG technology, LNG shipping and offshore operations, provide us with a sound launch pad for commercialising and applying floating liquefaction technology. With the Prelude facility being constructed, we are on a steep learning curve. FLNG Lean is designed based on the same platform as Prelude and incorporating lessons learned, and technology development and other design studies since the start of the Prelude project. Design and construction of FLNG Lean would be executed by the Technip Samsung Consortium as for Prelude.

To create sufficient deck space for the liquefaction trains and process equipment, some utilities have been moved into the hull. Aero-derivative gas turbines will drive liquefaction compressors and generate power. All process heating requirements will be met by waste heat recovery units. Several elements i.e. hull, accommodation, operating and safety philosophies, flare and blow-down system, cooling water systems are replicated from Prelude driving down risks and cost. Besides enlarged operating envelope for inlet gas, enabling technologies have been developed for deepwater applications and offloading in harsher environments.

ACKNOWLEDGMENTS

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