Design Case Study for a 4 MTPA FLNG System for Severe Metocean Conditions
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Abstract

Floating LNG is gaining acceptance as a viable alternative to conventional land based LNG plants. In the past few years, several FLNG projects have become commercial and reached FID. However, most FLNG systems designed to date remain complex, costly and operationally limited to areas with benign to moderate metocean conditions that allow side-by-side offloading of the LNG. This paper describes a “Split Process” FLNG design where primary production and gas treatment functions are provided on a host platform while liquefaction occurs on a separate vessel(s). The arrangement works in moderate to severe metocean operating conditions, such as offshore Western Australia or the Grand Banks of Eastern Canada, and is scalable from 1 – 6 MTPA.

The design and features of a 4 MTPA, deepwater case study are described. Salient features of the concept include:

- Segregation on separate facilities of gas processing/condensate storage from liquefaction/LNG storage
- Improved safety, constructability and overall project schedule
- Use of existing, standard hull designs for host facility and liquefaction vessels
- Pre-cooled Dual N2 expansion liquefaction for safety, simplicity and operability
- Dual fuel diesel electric (DFDE) power to improve fuel efficiency
- No offloading of LNG in open water; all offloading takes place in sheltered water

Process improvements have been made to the Dual N2 expansion liquefaction (DNY) process to reduce the unit liquefaction power. Fuel consumption for liquefaction is further reduced by the higher efficiency DFDE prime movers over gas turbines. The system offers lower capital cost and improved operability over conventional, integrated designs. Eliminating offshore LNG transfer and achieving fuel efficiency on N2 liquefaction similar to mixed refrigerant (MR) processes contribute to reliable/cost effective operations.

The liquefaction vessel is derived from a standard DFDE Moss LNG carrier which is extended 42 ft. at the bow to add a liquefaction module, switchgear and disconnectable turret mooring. Additional power generation is added to drive the 2 MTPA liquefaction unit. The liquefaction vessel disconnects when full and transits to a transfer jetty in sheltered water to offload. A fleet of 3 x 2 MTPA dedicated liquefaction vessels provides continuous operation and total system capacity of 4 MTPA. A host platform, determined by site specific considerations, handles primary production, condensate storage/offloading and treats the gas to an LNG inlet specification. The host may be an FPSO, TLP or fixed platform/FSO depending on upstream field development requirements.

The FLNG concept described offers both schedule and cost advantages through the use of standardized hull forms and repetitive, standardized design.
Introduction

The global demand for LNG in 2015 was 256 MTPA. This is projected to nearly double to by 2030. Traditionally, LNG has been dominated by IOC’s and large government utilities. However, as the market grows, the composition and characteristics of demand are changing, providing greater opportunity for small to mid-scale LNG developments. Costs for conventional onshore, base loads plants declined in the 1990’s as larger capacity trains were introduced, but this trend was reversed in recent years, particularly in Australia where baseload LNG plant costs have exceeded $3000/TPA due to high labor costs and construction in remote locations. Floating LNG offers the potential to unwind the cost spiral by shifting most of the construction work to shipyards and fabrication yards, while eliminating the cost for long pipelines to shore and extensive civil works and large scale construction housing on site.

Today, FLNG is generally accepted in the industry as feasible. The focus is now on technology selection, liquefaction & storage capacity, and safe operational considerations, particularly with regard to LNG offloading (Refs. 4,5,6,7,8,)

Concerns typically raised with proposed FLNG schemes include:

1. Size, weight and complexity of topsides
2. Topsides hydrocarbon inventory and impact on safety design
3. LNG offloading method and sea-state limitations
4. Overall project cost, schedule and uncertainty
5. Design for generic application/residual value

Additional general considerations, not unique to FLNG, include:

1. Method and cost for well drilling, completion, workover
2. Subsea architecture
3. Exposure to cyclonic storms or other extreme metocean conditions

FLNG System Configuration – Integrated Arrangement

Most FLNG concepts on the market utilize an integrated FLNG vessel that incorporates all functions into a single vessel: primary processing, gas treatment, NGL fractionation, liquefaction, storage of condensate/NGL/LNG, and offloading of each product from storage (Fig. 1). This approach leads to very large and complex purpose built vessels.(Ref 1) Other cost and design factors in FLNG include the use of proprietary liquefaction technology (licensing fees), topsides weight, layout congestion & safety hazards due to hydrocarbon inventory/explosive overpressure, and limitations on LNG offloading operations in moderate to severe metocean conditions.

Processing requirements for treating wellhead gas to LNG inlet quality vary considerably from field to field depending on

- condensate/gas ratio
- acid gas and nitrogen levels
- ethane, propane and butane content & LPG marketing
- method for hydrocarbon dewpointing

It is not practical to design a single generic topsides process scheme to deal with the range of conditions that may be encountered if the FLNG vessels has to produce two, three or more fields over its useful life. However, once the gas is rendered suitable for liquefaction , with water, acid gas, contaminants and heavier hydrocarbons removed, the facility requirements for liquefaction, storage and offloading of the LNG are the same from one field to another, varying only according to capacity.

FLNG System Configuration – Segregated Arrangement

The FLNG concept described in this paper (Ref 2,3) was designed to circumvent many of the cost and design concerns of the conventional, “integrated”, FLNG concepts. The primary assumption is that de-integrating or splitting the system between 1) a field specific host facility to provide primary processing, liquid handling and gas treatment and 2) a generic LNG liquefaction/storage/offloading vessel provides

- an overall reduction in complexity and cost
- an increase in design flexibility and residual value for re-deployment.
Design features of the split system (Fig. 1) include:

1. Standard, proven, “off-the-shelf” hull designs for both host facility and liquefaction vessel
2. Segregation of functions between FPSO & Liquefaction
3. DNX expander liquefaction process with CO2 pre-cool cycle for compactness, safety and simplicity
4. DFDE prime movers for liquefaction for improved efficiency
5. Wider selection of yards, multiple parallel construction paths, modularized and repetitive design/build

Segregating the FLNG functions between different vessels provides several benefits for cost, safety, project schedule and operations as described further below.

Discussion

Selection and Function of Host Platform

For the segregated FLNG concept, the host facility is selected based on site specific field development conditions as per any other offshore field development. Functionally, the host provides primary separation, depletion compression, gas dehydration, condensate/oil treatment & stabilization, and in some cases drilling platform or well bay.

Modifications to the host facility for FLNG involve replacing or adding the following equipment to the gas process system:

- mole sieve dehydration (replaces glycol gas dehydration)
- mercury absorption beds
- amine unit for acid gas removal
- hydrocarbon dew point system for removal of C5+ components
- heat integration for export gas pre-cooling

Host facilities considered in general include fixed or self-installing platforms in shallow water, concrete gravity base platforms for ice prone waters, Tension Leg Platforms (TLP) for moderately deep water subject to tropical cyclonic storms, FPSO’s (circular, spread moored or ship shaped, turret moored), production semi-submersibles for deep water or MODU semi-submersibles for small scale, mobile systems.

An example FPSO type host facility for moderately deep water in non-cyclonic areas is shown in Fig 2. The FPSO is based on a Sevan 650 hull. Several hulls of this type have been built for MODU and FPSO service. The circular hull can be spread moored, eliminating the cost and complexity of a large turret. The FPSO topsides consist of 2 x parallel process trains of 300 MMSCFPD capacity each. The 600 MMSCFPD capacity is sufficient to feed 4 MTPA of LNG liquefaction capacity.

Each train is arranged in three standardized modules:

- primary separation
- gas treatment
- export compression/liquids treatment

LNG inlet quality gas is pre-cooled to –20F @ 1400 psi and exported from the FPSO to the liquefaction vessels via a flexible riser connected to a disconnectable turret.
Design of LNG Liquefaction Vessel

The liquefaction vessel is based on a Moss type LNG carrier of 155 – 170,000 m³ capacity and equipped with Dual Fuel Diesel Electric (DFDE) propulsion. The Moss containment system eliminates risk of damage from sloshing in slack tanks during filling. There is no documented evidence of sloshing damage to the tanks in a Moss type LNG containment system although some early designs required reinforcement of the pump tower foundations.

A standard LNG carrier with DFDE power plant will have 25 – 30 MW of installed power. This is increased to 108 MW of installed power by using 6 x MAN V18 DF 51/60 engines in two engine rooms (Fig. 3). The power required to drive a 2 MTPA liquefaction plant is approximately 70 MW, depending on gas composition and cooling water temperature. Six engines provide an N + 2 sparing. DFDE engines should achieve 30,000+ hours between overhauls, thus allowing duty hours to be shared between engines so that they can be overhauled in conjunction with the 5 year dry dock interval of the vessel. Normally, it should not be necessary to overhaul an engine in the field.

At the bow, a 42 ft. long “sandwich” section (Figs. 4, 5 & 6) is spliced in just forward of the cargo compartment to house:

- disconnectable turret, turret trunk & auxiliaries
- switchgear including transformers, variable frequency drives & magnetic bearing controls
- seawater/freshwater heat exchangers & cooling water pumps
The turret contains a single 10 in. NB, ANSI 900 gas swivel to deliver pre-cooled gas to the liquefaction vessel from the host platform. The turret contains an additional swivel for a deep seawater intake hose to provide cold seawater for process cooling. At a depth of 1500 ft., typical seawater temperatures will be 48 – 50 F (Fig. 12).

The turret is designed for quick connect/disconnect (< 8 hours). Maximum seastate for turret connection is Hs≤4 m and for disconnect Hs ≤5.5 m. Once the turret is connected, the liquefaction vessel can remain on station in any weather condition subject to design of the buoy mooring system, although it would not be planned to remain on station for extreme weather such as tropical cyclonic storms or severe winter storms at high latitudes.

The sandwich piece provides a footprint for the liquefaction module (Fig. 6). The liquefaction module contains 2 x 1 MTPA liquefaction trains arranged port and starboard. Each train consists of:

- 1 x Cold Box containing 5 x Braised Aluminum Heat Exchanger (BAHE) cores
- 1 x “Warm Loop” and 1 x “Cold Loop” Turbo Expander/Compressors
- 3 x Integral Sealed N2 compressors (ISC)
- Printed Circuit Heat Exchanger (PCHE) inter-stage coolers
- 1 x Boil-off Gas (BOG) compressor
- 1 x Liquid Expander

ISC compressors are directly driven by a high speed electric motor which is housed within the compressor body. The motor and impellers are installed on a common shaft supported on magnetic bearings and is cooled by a slipstream of the gas being compressed. The entire assembly is hermetically sealed within the compressor body with no external shaft seals. Benefits of the ISC include:

- extremely compact footprint
- no shaft seals or seal gas system
- no lube oil system
- no gearbox

ISC’s were originally developed for remote, unmanned pipeline booster stations. In recent years, they have been selected for seabed compression. The use of ISC’s and the elimination of nearly all hydrocarbon inventory in the liquefaction system enables the liquefaction module to be extremely compact (Fig. 7) and lightweight. Overall dimensions of a 2 MTPA liquefaction module are estimated at 40 ft. long x 50 ft. high x 125 ft. wide with a dry weight of 2800 ST.

In contrast to most FLNG vessels, because the liquefaction vessel described here is simply a modified ship, it remains classed, flagged and crewed as a ship and it would periodically dry dock for repair and maintenance. This operating philosophy is expected to significantly reduce capex and opex compared to a liquefaction vessel which must be designed to remain on station indefinitely and which much be crewed as a production unit.
For a 4 MTPA system in a severe metocean environment, there are 3 liquefaction vessels and 3 disconnectable buoys in the system (Fig. 8). At any time, there are two vessels on station in the field liquefying gas, with one vessel in transit to a discharge point in sheltered water. Thus, the offshore transfer of LNG cargo from the FLNG vessel to an LNG carrier is avoided. The liquefaction vessel remains mobile by disconnecting the turret and transiting to a safe, sheltered location for ship-to-ship transfer of cargo in the conventional manner at a transfer jetty or existing LNG storage terminal.

**Process Optimization - Dual N2 Expansion Liquefaction**

Dual N2 Expansion liquefaction (DNX) was selected for liquefaction because of the following advantages:

- compact/lightweight
- intrinsically safe
- convenient refrigerant makeup
- simple operability/restart/maintenance
- proven track record on LNG carriers

The primary concerns or drawbacks typically cited against DNX are:

- process efficiency/fuel consumption
- lack of large scale plants

There are several variations on DNX processing in the industry, primarily around the manner in which the N2 is routed to the cold box, expanders and compressors for pre-cooling, expansion and refrigeration duty. The PFD for the particular DNX process scheme used is shown in Fig. 9.

In the Base Case, the N2 discharge pressure from the main compressor is approximately 900 psig and interstage cooling temperature is 100 F. The feed gas pressure is 900 psig @ 80 F. Unit power for the Base Case is 453 KW-hr/Tonne LNG based on the Lean Gas composition shown in Table 1. Several process improvements were tried to reduce the unit-power.
Through a series of process improvements, it was found that unit power could be reduced about 6% to 425 KW-hr/Tonne LNG by increasing feed gas pressure and N2 discharge pressure to 1300 psi (Fig. 10). Smaller improvements from additional pressure increase were observed, but it was desired to stay within the capability of an ANSI 600# BAHE in order to achieve a more efficient heat transfer design.

Unit power is reduced by 20% from the Base Case by further lowering the interstage cooling temperature on the N2 compressors from 100 F to 60 F. In practice, this would be achieved by a deep seawater intake hose – seawater at 1500 ft. depth is 47 – 50 F, with little sensitivity to surface temperature. (Fig. 12). A further reduction of overall unit power to 325 KW-hr/Tonne LNG, (28% less than the Base Case) is achieved by pre-cooling the feed gas from 80 F to -20 F. The pre-cooling is achieved by heat integration with the hydrocarbon dewpointing system on the host facility and increasing export compression power on the host, which is included in the total liquefaction power.
The unit power cited above includes the power on the host facility for both feed gas booster compression and pre-cooling on the host plus the liquefaction power on ship. Focusing on the latter, the power required to drive the liquefaction plant on board the ship is reduced by 34% compared to the Base Case, from 64,500 HP to 42,500 HP (Fig. 11) for each 1 MTPA train. The ship power is mainly for N2 compression, but also includes BOG compression and a power “credit” from the liquid expander. Total fuel consumption (host facility + ship) for liquefaction power is reduced from 7% of feed gas in the Base Case to 5.2% in the Optimized Case (Table 2).

Unit power in the Optimized Case for DNX is still higher than typical values for Single Mixed Refrigerant or Dual Mixed Refrigerant processes. The higher thermal efficiency of the DFDE power plant, 44% net of switch gear losses vs. 38% for an aero-derivative gas turbine, compensates this difference in unit power. Thus, the Optimized DNX liquefaction process with DFDE power achieves near parity in fuel efficiency compared to mixed refrigerant processes, but retains the benefits of safety, compactness, lightweight and operational flexibility which are intrinsic to N2 liquefaction processes.

The final remaining concern raised in regard to N2 liquefaction is the absence of large scale LNG plants in operation that utilize this process. There have been dozens of “peaking plants” installed over the past several decades based on N2 liquefaction and there are over 50 LNG vapor re-liquefaction plants in service on board LNG carriers based on N2 liquefaction, but these are typically small scale, single expander processes with much higher unit power than DNX systems. On the other hand, DNX is the standard process used in the air separation industry to fractionate liquid oxygen (LOX) from the atmosphere. Fig. 13 shows that over 80 DNX air separation units (ASU) were installed over the past 35 years by one of the large air products suppliers and that 40% of these units had a LOX capacity of 1 MTPA equivalent or greater.

The DNX liquefaction module with ISC N2 compression is compact and lightweight enough to fit onto the extended bow of a standard Moss carrier. By expanding the capacity of the DFDE power plant, a 2 MTPA liquefaction unit can be driven using ship power with an N + 2 engine sparing. The DNX liquefaction module offers further advantages in safety and operational simplicity, and smaller single N2 cycle plants are currently in operation on LNG carriers. The higher unit power of the optimized DNX liquefaction process compared to mixed refrigerant processes is offset by the higher efficiency of the DFDE power plant compared to aero-derivative gas turbines.

**System Arrangement & Application**

The Split FLNG concept can be adapted to a wide range of applications by selecting a host facility suitable for the site specific gas composition, water depth, metocean conditions, well drilling and intervention method, condensate storage & handling, etc. Fig 14 shows a variety of host facilities that have been considered for various cases including:

- FPSO – circular, spread moored
- FPSO – ship shape, turret moored
- Fixed Platform – conventional or self-installing
- Concrete Gravity Base Platform (GBS)
- Tension Leg Platform
- Production Semi-submersible
- MODU Semi-submersible

Two harsh environment case studies are considered in more detail below.
The Grand Banks fields lie in the North Atlantic about 200 miles east of St. Johns, Newfoundland. Several oil fields produce in the area and WD ranges from 300 – 500 ft. The metocean conditions are severe with 100 year return winds = 70 knots (1 hr.), $H_s = 50$ ft., seasonal sea ice from Jan – May, and occasional icebergs. Annual median wave height is $H_s$ 8 – 10 ft. A concept was devised to process and liquefy associated gas which is currently being re-injected into the reservoir.

A concrete GBS was selected for the host facility to provide an ice resistant, stable platform for gas processing. The GBS is relatively insensitive to topsides load and allows for local content during construction. A 3-level integrated topsides (Fig. 16) provides the following gas processing functions, arranged in 2 trains x 300 MMSCFPD:

- Amine Unit for acid gas removal
- Mole Sieve dehydration
- Mercury Absorption Beds
- Turbo-expander for hydrocarbon dewpointing
- Fractionation Tower for separation of C1 – C4 from C5+ components

The gas composition approximates the Rich Gas shown in Table 1. Propane and butane components are left in the LNG stream in order to simplify the offshore processing and export scheme. The 2 MTPA liquefaction vessel is designed as described previously, except that a 165,000 m$^3$ Moss carrier design with continuous tank cover (Fig. 15) is selected to improve global strength and fatigue performance and minimize accumulation of snow and ice on the vessel.
LNG export is assumed to Milford Haven in the UK, a distance of 1700 nautical miles. Using 4 x 2 MTPA liquefaction vessels, with 2 on station in the field (Fig. 17) and 2 in transit, a nameplate capacity of 4 MTPA is achieved. The transit time @ 16 kts. is less than the fill time of the sister vessel. Because of the severe winter storms on the Grand Banks, it was assumed that liquefaction operations would be suspended and the ships would seek sheltered waters in seastates ≥ Hs 20 ft, which would provide average annual availability of 90 – 95%.

**Deepwater – Western Australia**

A concept was investigated for dry gas fields in 2500 – 4000 ft. WD offshore W Australia. The metocean conditions are moderate to severe with 100 year cyclone winds = 105 knots (1 hr.) and Hs = 55 ft. Annual median wave height is Hs 8 – 10 ft. with associated periods of 12 – 16 seconds. A concept was devised to process and liquefy associated gas for non-associated gas fields.

A TLP was selected for the host facility (Fig. 18) to provide cyclone resistant, stable platform for gas processing and well completion/workovers. Gulf of Mexico experience shows that TLP’s are proven for withstanding tropical storms in these water depths. The TLP hull has 4 x 62 ft. OD columns on 203 ft. spacing with 100 ft. draft. Operating weight of the integrated topsides is 18,300 ST and the hull displaces 53,000 ST. These dimensions are similar to deepwater Gulf of Mexico TLP’s.

The TLP hull and topsides would be mated at the fabrication yard and dry towed to a nearby port. The 2-level integrated topsides provides the following gas processing functions, arranged in 1 train x 300 MMSCFPD, sufficient for 2 MTPA.

- Amine unit for acid gas removal
- Mole sieve dehydration
- Mercury absorption beds
- Turbo-expander for hydrocarbon dewpointing
- Fractionation Tower for separation of C1 – C4 from C5+ components

TLP hull sizing is sensitive to topsides weight, so wells would either be pre-drilled using a MODU or drilled from the TLP using Tender Assist Drilling. The gas composition approximates the Lean Gas shown in Table 1. The 2 MTPA liquefaction vessel is designed as previously described.

LNG export to Singapore is assumed, a distance of 1700 nautical miles. Using 2 x 2 MTPA liquefaction vessels, with 1 on station in the field (Fig. 19) and 1 in transit, a nameplate capacity of 2 MTPA is achieved. Depending on field size, additional TLP units would be installed in a phased development approach to increase overall capacity to 4 or 6 MTPA. Because of the severe seasonal cyclone storms in the region, it is assumed that liquefaction operations would be suspended and the ships would seek sheltered waters in advance of an approaching cyclone.
Conclusions

The following conclusions may be drawn regarding the Split FLNG Concept:

• By separating the LNG liquefaction/storage/offloading function from the primary production processing/gas treatment facility, the Split Process arrangement offers advantages in concept design flexibility, liquefaction vessel redeployment and residual value, and improved project execution through wider choice of yards, use of standard hulls, and parallel construction activities.

• Site specific development considerations can be accommodated through host facility selection with little impact on liquefaction vessel design. Host facility can be designed for extreme metocean conditions utilizing existing, proven concepts.

• Because gas processing is performed on the host facility, the liquefaction vessel merely has to provide liquefaction/storage/offloading, which greatly simplifies its design.

• Because the liquefaction vessel remains classed as a ship it remains mobile; it can avoid severe weather and can dry dock for planned maintenance or repairs.

• Dual N2 liquefaction is preferred for FLNG due to its compactness and light weight, safety benefits & ease of refrigerant makeup with N2, easier operability, and proven track record on LNG ships of similar systems.

• Process improvements to the DNX liquefaction process reduce total power by 28% compared to a typical base case. Liquefaction power on the ship has been reduced by 34% which enables a simplified liquefaction vessel based on a modified Moss LNG carrier with DFDE.

• Use of modified Moss carriers as liquefaction vessels on disconnectable turret circumvents the limitations of offshore LNG transfer; rather, the liquefaction vessel remains mobile when disconnected from the turret and can transit to a sheltered location to offload its LNG cargo.

The combined impact of the Split Process concept not only reduces the capital cost of the FLNG system, but also expands the envelope of application for FLNG to fields in severe metocean environments that are currently beyond FLNG development.

Acknowledgements

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References

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### Table 1 – Nominal Gas Compositions

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<th>Lean Gas(%)</th>
<th>Rich Gas(%)</th>
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### Table 2 – Process Optimization Parameters: Lean Gas Composition

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<th>Case Number</th>
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<th>Feed Gas Temp to Cold Box F</th>
<th>Cold Box U.A. MM BTU/ft-hr</th>
<th>Cold Box Approach Temp F</th>
<th>Cold Box Approach Temp F</th>
<th>N2 Compressor Discharge psig</th>
<th>N2 Interstage Cooling F</th>
<th>Single Train Power - Host HP</th>
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|                        |             |             |                           |                           |                           |                           |                           |                           |
| Single Train Power - Total HP/MMSCFPD | 68,189 | 67,292 | 64,416 | 55,539 | 50,392 |
| Unit Power HP/LNG       | 486.91     | 479.01     | 456.79 | 388.98 | 349.96 |
| Unit Power KW-hr/tonne  | 452.6      | 445.2      | 424.6  | 361.5  | 325.2  |

| Host Fuel Gas (MMSCFPD) | 38.0% | 0.65   | 1.13   | 1.13   | 1.13   | 1.39  |
| Ship Fuel Gas (MMSCFPD) | 44.0% | 9.83   | 9.27   | 8.84   | 7.48   | 6.47  |
| Total Fuel Gas (MMSCFPD) | 10.48 | 10.41 | 9.97 | 8.62 | 7.87 |
| Total Feed Gas (MMSCFPD) | 150.52 | 150.89 | 151.10 | 150.99 | 151.25 | 6.96% | 6.90% | 6.60% | 5.71% | 5.20% |