AN OPERATOR APPROACH TO THE FLOATING LNG: PROCESS SELECTION and RISK MANAGEMENT

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Abstract – Background

Gas from remote offshore fields may be difficult to exploit when technical difficulties or high costs prevent the installation of an onshore pipeline. Offshore liquefaction on a floating unit may then be a viable alternative.

Over the past five years, Total has developed an FLNG concept with emphasis placed on safety for the selection of the major options.

The selection of the liquefaction process is a major factor for risk reduction, but also on the overall lay-out, the loading system from the floating unit to the LNG carrier, the driving mode of the rotating machines, and the LNG storage technology.

Two liquefaction processes were compared: the pre-cooled nitrogen expansion loop and the Dual Mixed Refrigerant (DMR) process. Although the nitrogen pre-cooled process presents a slightly lower efficiency than the DMR process, it shows other advantages which offset this drawback, the most important among them being the safety and operability. The nitrogen pre-cooled process looks to be an excellent compromise between safety, profitability and operability, and is considered by Total as a viable option for future F-LNG projects.

Following a Risk Management study, the following design criteria were selected

The lay-out study results in locating the living quarter at the bow of the FLNG (up-wind).

Tandem offloading is preferred to side by side offloading in order to prevent collisions since the distance between the liquefaction vessel and the LNG carrier during tandem offloading is larger than with side-by-side offloading.

Membrane storage tanks are selected based on forty years experience of this proven technology and on cost consideration. However, some precautions are taken to mitigate the sloshing effect at any liquid level in the tank.

With all these design criteria, Total aims to minimize the risk inherent to a gas processing unit particularly for offshore operation.

Introduction

Gas from remote offshore fields may be difficult to exploit when technical difficulties or high costs prevent the installation of an onshore pipeline. Offshore liquefaction on a floating unit may then be a viable alternative.

Offshore liquefaction is a relatively new concept which has not yet been implemented. It is recognized to be potentially more dangerous than the oil Floating Production Storage Offloading units (FPSO) that Total has been operating for the last decades.

Taking advantage of its experience in offshore operation (Total operates 8 FPSO's), Total has developed, over the past five years, an FLNG concept with emphasis placed on safety when selecting the major design options.

The key facilities which have a significant impact on the safety are the process, lay-out, the LNG offloading system, the gas turbines and their associated hazards, and the LNG storage facilities.

Each of these facilities was carefully studied from operational, economical, and most importantly, safety points of view. For the overall FLNG and in particular for these sensitive items, a risk analysis was carried out in addition to the economical and operational aspects.

The safety studies included two steps: hazard identification and risk management analysis.

Hazard Identification: the first step in effective risk management approach.

In the confined space of an FLNG vessel, living quarters are adjacent to operations (liquefaction, storage, offloading) that involve large inventories of flammable gas. The major risk is a blast that could set off other explosions by a domino effect.

To define an effective risk management strategy, Total first carried out an in-depth study to identify the hazards of liquefaction at sea. The ultimate aim was to make sure safety performance would be similar to that achieved on Total-operated FPSO vessels.

Risk management

Total based its FLNG design on the most extensive safety analyses carried out in the area of offshore liquefaction. The main studies consisted of:

- Consolidation of feedback reports on hundreds of incidents involving FPSO vessels, LNG carriers and liquefaction plants,
- A systematic Hazard Identification study (HAZID),
- A risk analysis taking more than 300 major accident scenarios into account,
- Three-dimensional modelling to assess ventilation of the installations, dispersion of a cloud of flammable gas, fires and explosions
- Failure Mode Effects and Criticality Analysis (FMECA) for the tandem offloading system.

This Safety approach leads to the selection of some options which may not be the most economical, but guarantee the operability and the safety of the operators and the asset.

Basis for the F-LNG

The risks identified through these studies led to a decision with significant repercussions on the entire design: namely the selection of an inert-gas liquefaction cycle. This option proves to be much less dangerous than alternative processes that involve large inventories of hydrocarbon refrigerants. There are fewer possible accident scenarios, and the consequences of each one are less severe.

To approve this choice of an Inert gas cycle solution, a comparative study was carried out covering the process, safety, layout and the operating aspects for each process. The study was generic, not being linked to a specifically identified gas field.

The selected production is 3.5 MMTPA of LNG and 20 000 barrels per day (bpd) of condensates. There is no LPG recovery and after extraction of the NGL (for the BTX removal) all LPG is re-injected into the gas prior to liquefaction. This consequently results in LNG with High Heating Value (HHV), but it appears that this is compatible with most markets.

The gas composition at liquefaction inlet is given in Table 1. The gas is relatively high in light ends because the heavier components are extracted upstream of the liquefaction unit in a turbo-expander refrigerated unit. The NGL is re-injected into the gas upstream of the liquefaction while the condensates containing aromatics, which are subject to freezing in the cryogenic unit, are mixed with the upstream condensates. The Nitrogen content is moderate and does not necessitate the implementation of a nitrogen rejection unit.

Component	Mole fraction
N2	0.00036
CO2	0.0505
C1	0.91625
C2	0.0604
C3	0.0169
IC4	0.00278
NC4	0.003
IC5	0.00019
NC5	0.00007

Table 1

For this study, the environmental conditions selected are those of the Gulf of Guinea, which are relatively mild.

Process

Description of the selected processes

Both processes (DMR and Nitrogen Refrigerant) are designed on the same basis and are shown in block diagram in Figure 1.

In both processes, the NGL is extracted upstream of the liquefaction unit. The condensates are routed to the inlet facilities while the NGL is injected back into the gas prior to liquefaction. The natural gas is compressed to 80 bars at the liquefaction inlet to ensure a sufficient margin above the gas critical pressure for stable operation.

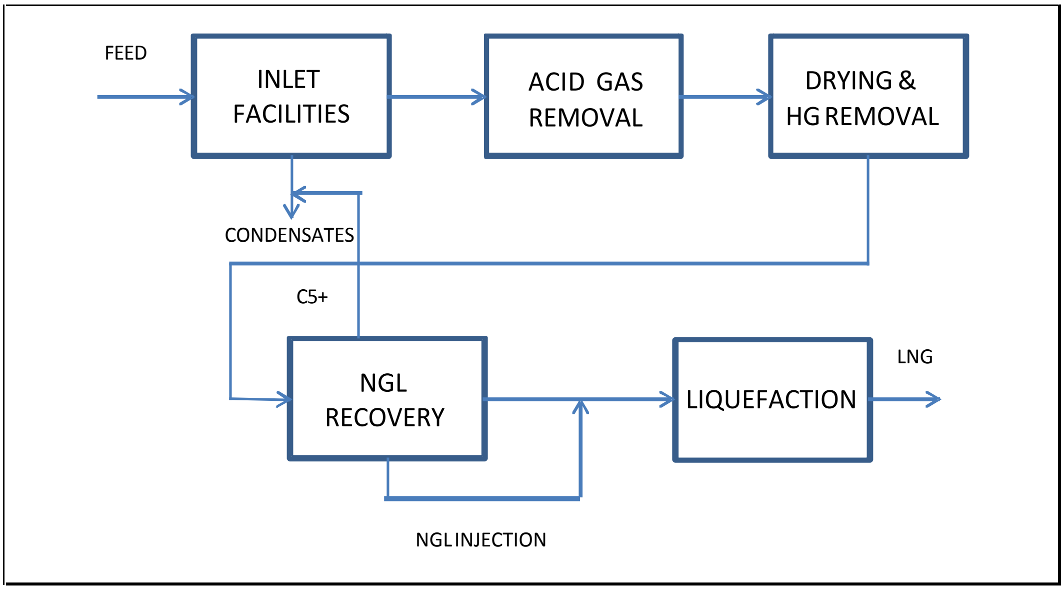


Figure 1

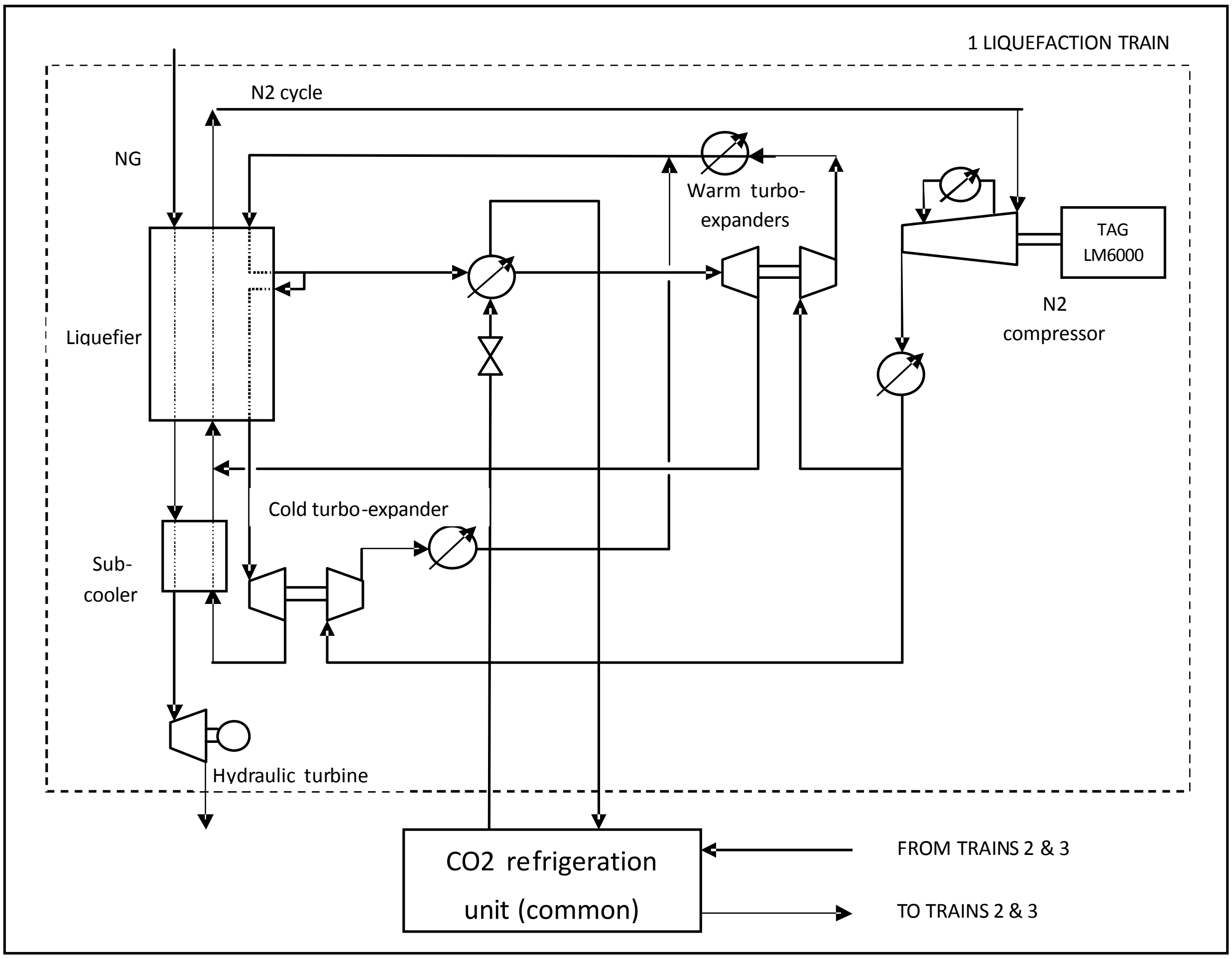


Figure 2

The nitrogen pre-cooled process is shown in Figure 2. It consists of a nitrogen refrigeration loop with two expanders at different temperatures for energy optimization. Both expander discharge pressures are the same. The inlet of the warm expander is cooled to -40°C by a refrigeration unit, preferably using CO2.

Figure 3 shows the selected DMR process. The pre-cooling cycle (warm MR) operates with two evaporating pressures and consequently there are two Spiral Wound Heat Exchangers (SWHE) in series.

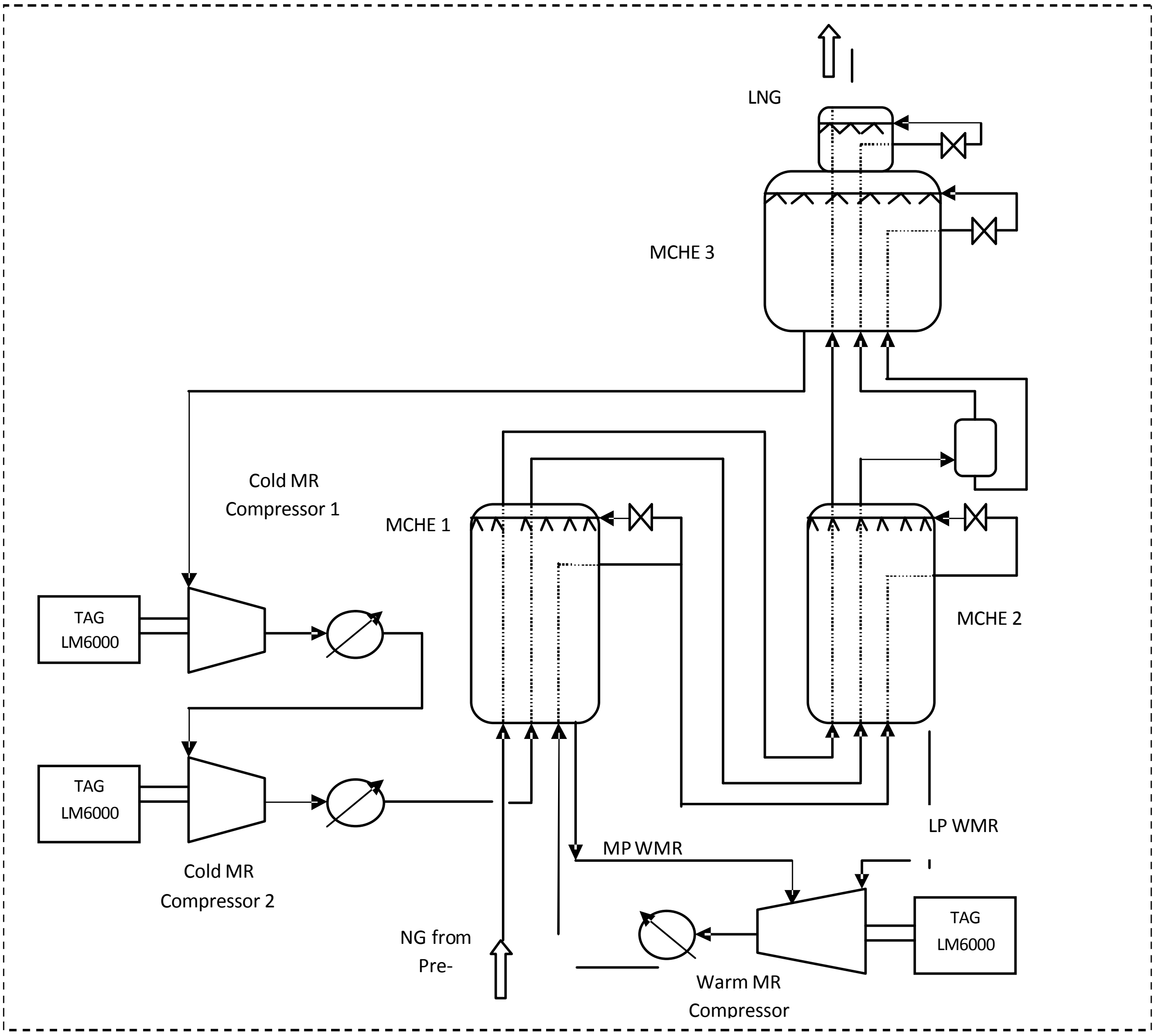


Figure 3

The performances and overall weight / layout of the installed facilities are determined for both processes.

Process comparison

The specific power consumptions are 227 kWh/t for the DMR and 262 kWh/t for the nitrogen pre-cooled process. These relatively low consumptions can be explained by the low sea water temperature and the high pressure of liquefaction. This highlights an energy efficiency advantage of 13 % for the DMR process which is in line with the literature. However, the difference in overall FLNG power requirement between each process is less than 10 % when considering the other consumers, corresponding to a fuel gas consumption difference of less than 1 % of the feed gas flow rate.

The cooling water flow rate is 56,000 m3/hr for the nitrogen pre-cooled process and 53,500 m3/hr for the DMR process. The difference comes from the relative efficiencies of the two processes, and is about 8 % power difference mentioned above because of the impact of other cooling water consumers, in particular the acid gas removal unit.

The cryogenic heat exchangers are of different designs: SWHE for the DMR and Plate Fin Heat Exchanger (PFHE) for the nitrogen pre-cooled process (base case). However, part of the cryogenic duty for the nitrogen process can be performed by a SWHE.

The evaporation of the Mixed Refrigerant (MR) takes place in the SWHE and this two-phase process is sensitive to motions. In contrast, in the nitrogen pre-cooled process the nitrogen always remains in vapour phase and is intrinsically insensitive to motions. Although vendors have extensively studied the behaviour of the SWHE with regards to motion, the DMR process leads to management of the risk while the nitrogen pre-cooled process eliminates it.

Similarly, the tubes of the SWHE face accelerations due to motions of the vessel and are subject to fatigue. From this point of view, even if fully studied, it is not yet sea proven. At the same time, 40 PFHEs have been in operation for some years for Boil Of Gas (BOG) liquefaction aboard the Q-flex and Q-max LNG carriers with good mechanical records.

The liquefaction pressure of 80 bars ensures a sufficient safety margin above the critical pressure. SWHEs are referenced up to 65 bars in operation while PFHE vendors have about 30 references with a design pressure of 88 bars or above in operation for large size cores.

There is one major vendor for the SWHE while the PFHE can be supplied by 4 or 5 competitors.

The PFHEs show advantages which lead Total to consider them as a viable option. Alternatively, part of the cryogenic duty, in particular the condensation of the natural gas, can be performed in a SWHE for which it is well referenced.

All the DMR compressors are well known and similar to other compressors in operation in different LNG plants. The nitrogen compressors are similar, yet smaller, to those in operation in Qatar for the APX^{TM} process. CO2 compressors already exist and CO2 refrigeration units are in operation in smaller commercial scale units.

In summary, the DMR process has a clear advantage in term of performance. The primary difference concerns the power generation unit where one additional gas turbine is necessary for the nitrogen pre-cooled process. The cooling water flow rate is slightly lower for the DMR process. On the other hand, the design of the nitrogen pre-cooled process is simpler and eliminates all concerns related to two-phase operation; while the referenced PFHE's closely match the design criteria required for this application.

Operation

The operation of the processes results from their designs and there are some differences between the two.

The nitrogen pre-cooled process uses a pure component which always remains in vapour phase. There is, consequently, neither two-phase flow management nor refrigerant mixture composition to monitor. From this point of view the operation is simpler than that of a DMR.

The simplicity of the nitrogen pre-cooled process is also apparent in the start-up procedure. Start-up of a DMR unit from a warm stand-by position takes between 1 and 1.5 days while the start-up of a nitrogen pre-cooled process is estimated at about 6 hours. This difference has an impact on the availability of the plant and the overall yearly production (see below).

The nitrogen pre-cooled process is also more flexible and offers a shorter response time to production changes than the DMR process. The time required to reduce the production from 100 % to 50 % is in the range of 2 to 4 hours for the DMR process while it is estimated to require less than one hour for the nitrogen pre-cooled process.

The DMR mixture consists of hydrocarbons and requires ethane and propane make-up. A fractionation unit becomes necessary for the production of these pure components. This includes distillation columns which could be subject to upset conditions while in motion. Furthermore, the availability of make-up components necessitates storage with associated hazards. In the specific case studied by Total the fractionation unit is only required for the removal of BTX as there is no LPG production. If there is no need to supply mixed refrigerant makeup the NGL recovery unit can be simpler.

In summary, the nitrogen pre-cooled process is more flexible and easier to operate than the DMR process, and shows significant advantages for a remote and isolated plant.

Availability

The availability of the plant is a function primarily of the rotating machinery and to a lesser degree the heat exchangers.

The availability study was performed prior to the final selection of the all electrical drive option when the cycle compressors were directly driven by the Gas Turbines. The results have consequently to be updated in a future phase. However, it is anticipated that the results should be qualitatively similar.

In the nitrogen process, there are 3 liquefaction trains in parallel and the shutdown of one nitrogen compressor does not result in an entire plant shutdown.

In the DMR process, the compressors are in series and the liquefaction train needs to be shutdown in case of shutdown of one compressor.

The power generation and the end flash system are common systems which have different impacts on the availability and therefore have to be considered. The other systems (utilities, etc) should not affect the availability of the plant any differently as they are identical for each process considered.

The availability of the liquefaction units is calculated in each case taking into account its specific configuration. This calculation covers the liquefaction unit and the power plant.

The calculated availability of the pre-cooled nitrogen process is 96.07 % while that of the DMR is 95.35 %. This result can easily be explained by the configuration of the rotating machines which are in parallel for the nitrogen process and in series for the DMR process.

The availability of the nitrogen process is anticipated to be slightly better than that of the DMR.

Weight and lay-out comparison

The weight and layout requirements are compared for both options including the impact on the utilities.

The difference in deck layout in the liquefaction unit is itself not significant. In particular, the number of modules does not change. There is one additional Gas Turbine Generator in the nitrogen pre-cooled process for power generation.

The length of the hull is determined by the topsides. There is consequently some room available in the hull to accommodate the cooling water system - which is a safe and inert system. The larger size of this system for the nitrogen pre-cooled process has no consequence on the lay-out.

The overall weights for both options are similar, with a difference of 4 % in favour of the DMR.

Safety

Onboard an FLNG safety is a key issue because of the congestion of the facilities. Any incident or fire may rapidly induce a domino effect which could lead to asset damage or even fatalities.

Risks of leakage and consequent severity in case of explosion are directly proportional to the hydrocarbon inventory. The overall inventory of hydrocarbons in a liquefaction unit using the DMR process is about 250 to 300 t while it is only about 30 t for the nitrogen pre-cooled process.

The difference in total hydrocarbon inventory has the following consequences:

- The peak flow rate to the flare increases from 1350 t/hr for the nitrogen pre-cooled process to 4000 t/hr for the DMR process. Unless important derogations to the API recommended practices are accepted, no flare can be built on the FLNG to accommodate the latter. Assuming a 150 m flare height and a blow down time of 15 minutes as per the API recommended practices, the number of depressurization zones is 3 for the N2 pre-cooled cycle and 7 for the DMR.
- The risk of a domino effect is much more important with the DMR than with the nitrogen pre-cooled process. Total performed a Risk Assessment considering about 300 possible scenarios for the entire FLNG taking into account the risks of fire and explosion, structure embrittlement, BLEVE, rapid phase transition and personnel asphyxiation.

The main outcome of this study is that the risk differences between N2 and DMR processes come from the liquefaction unit due to the hydrocarbon inventory in the DMR loops. The effects of an accident on a FLNG using a DMR process would lead to more severe consequences for the following reasons:

- Larger flammable gas cloud in case of leak,
- Higher reactivity of product in case of explosion, leading to greater damage on topsides,
- Higher risk of escalation due to more equipment containing flammable inventories. This in turn leads to a higher risk of asset losses. The overpressure generated by the explosion of a MR is greater than that generated by natural gas because the reactivity of the components is much higher. In consequence, the risk of domino effect is higher considering the congestion of the process area.

For more details on this safety study please refer to the publication “Total’s approach to selecting the liquefaction process for FLNG”, GPA Europe, Prague, September 2011.

There is consequently a major risk difference to lose the asset between both processes, the DMR process being by far the more dangerous for offshore applications.

Conclusion for the process

Considering above risk reductions, the nitrogen pre-cooled process is an excellent compromise between safety, profitability and operability and is considered by Total to be a viable option for the FLNG projects.

Lay-out

Because of the congestion of the facilities on the deck, the lay-out is of major importance for the safety.

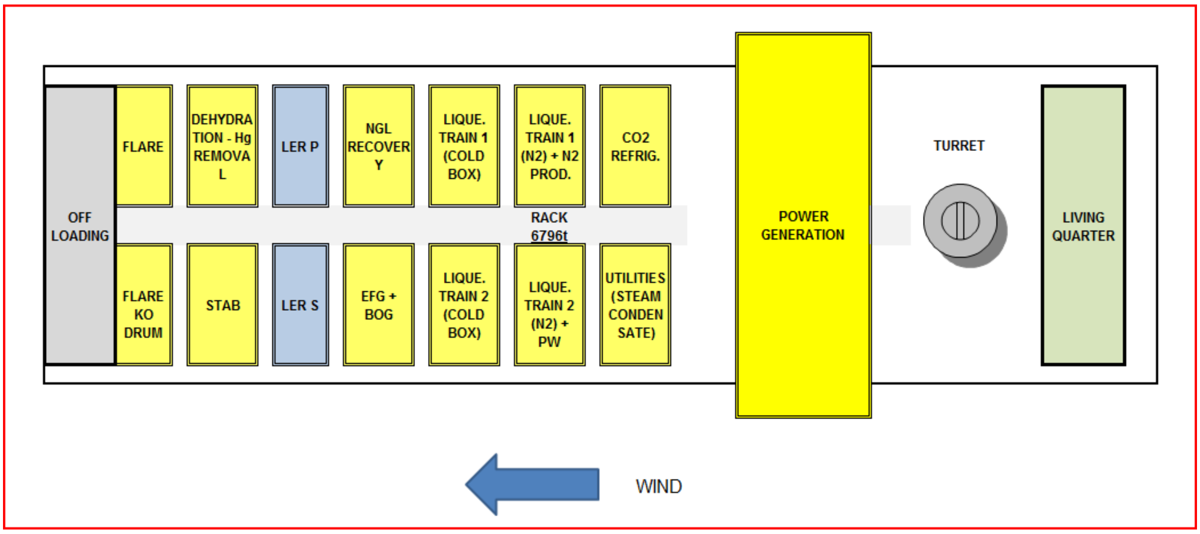
One of the most sensitive items is the living quarter (including main control room, offices and recreational areas) where most of the crew are located. It is then fundamental to keep the living quarters as far as possible from the processing areas.

Natural ventilation of the process facilities is the most efficient way to prevent any gas accumulation. A ventilation study was performed on the overall layout and it confirms the air replacement ratio for each module of 12ACH95%. . As mentioned above, the living quarters are located up-wind of the processing facilities. In addition, the hull will be naturally oriented by the wind (few degrees) and it can also be dynamically oriented at higher angle in order to increase the ventilation of the facilities by using hull thrusters.

The consequence of selecting the nitrogen cycle is that the main gas inventory is no longer located in the liquefaction unit (as is the case with a DMR process due to hold-up in the refrigeration loop) but in the Acid Gas Removal Unit (AGRU). Accordingly, the AGRU is located at the stern, far from the living quarters. The liquefaction units are then located in between.

The turret is located at the stern, downwind of the Living quarter and the lay down area. It makes hull orientation easier than a turret located closer to the centre of the vessel (and minimizes the tracing forces on the anchoring chains). The power generation, with hot exhaust is located between the turret and the process facilities.

The flare and vents are located at the stern, down-wind of all process facilities, near the LNG offloading system



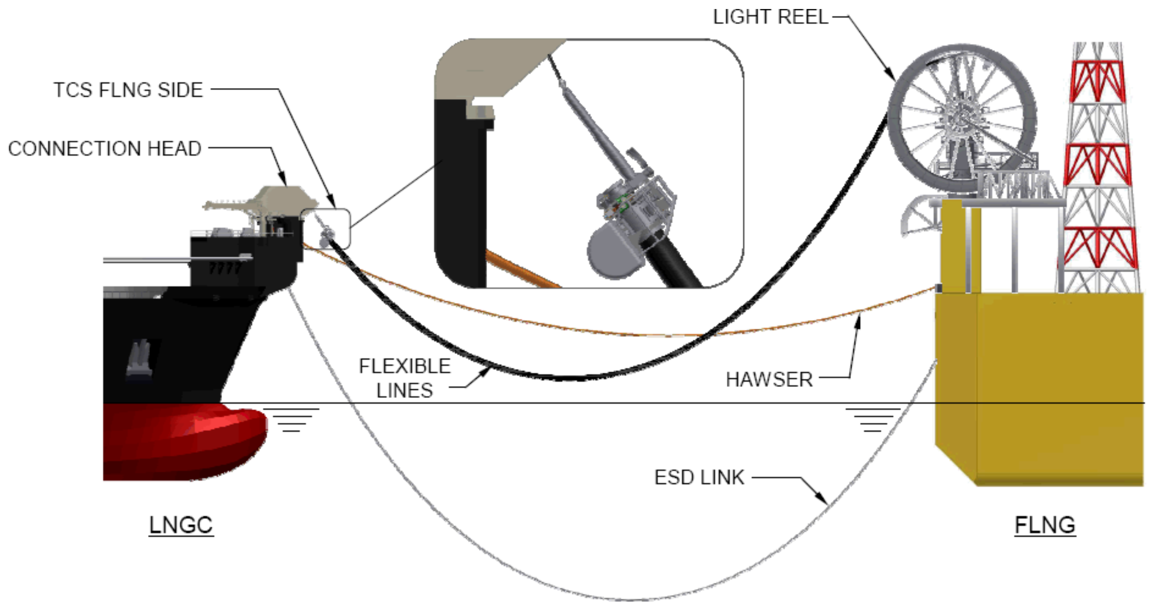
LNG Offloading system

A tandem offloading configuration was selected for the ship-to-ship transfer of LNG.

One of the advantages of the tandem configuration is that it uses flexible hoses instead of loading arms. The vertical and horizontal amplitudes of motion between the FLNG and the

LNG carriers, as well as the acceptable accelerations, are larger with the flexible hoses than with the loading arms. This improves the availability of the offloading system..

The main incentive for the selection of the tandem offloading is safety. The distance between the LNG carrier and the FLNG is always about 100 m for the tandem configuration while it is only a few meters for the side-by-side configuration, reducing the collision risks accordingly. The naval operations in tandem mode are simplified in the approach, berthing and residence phases as is commonly performed in the North Sea. For side by side positioning, mooring of the LNG carrier to the FLNG requires the assistance at least four tug boats



Amplitude LNG Loading System (ALLS) developed by Technip

Rotating Machinery Drivers

The choice of electric-only drive systems enhances the operating flexibility of power generation. All electricity requirements are generated by GTGs. This is in sharp contrast with direct-drive compressors, which have their own turbines. This electric-only option is already being applied on one of Total's FPSO vessels (Akpo, Nigeria) which can provide the experience in design and operation of such systems.

To operate gas compression in the liquefaction process, electrically driven motors using variable speed drives (VSD) are easy to accommodate, providing operational flexibility which is not easy to achieve using directly driven gas turbines. The aero-derivative gas turbines can provide variable speed to a certain extent but at low rotation speed the torque is generally insufficient.

Unlike direct-drive configurations, an electric motor has high enough torque to be able to restart at the compressor settle out pressure without prior depressurization of the liquefaction loops. Therefore, the overall availability of the plant is improved.

The availability of the plant factors in the installation of N+1 GTGs. With this configuration, the refrigeration cycle compressors take advantage of the spare generator and the overall availability of the plant is improved accordingly.

The use of electrical motors also has a positive impact on safety. All the gas turbines are located together, up-wind of the process facilities. There are consequently neither hot points nor flames in the process area where leakage is most likely to occur. Additionally, a centralized power plant makes the steam production by heat recovery easier to implement than if the gas turbines were spread out in the process area. This design allows the removal of all boilers with associated ignition sources.

Conclusion

With respect to safety, Total has decided upon some options in the design of the FLNG:

Despite lower efficiency, the liquefaction process based on the use of inert gas is preferred to the DMR primarily for safety and operational reasons related to a dramatic reduction of the MR hydrocarbon inventory in the liquefaction units and in storage.

The design of the lay-out aims to remove the living quarters from the process facilities and any potential source of ignition. In the same way, the power generation is separated from the process facilities to distance the hot exhausts and ignition points which may be a hazard in the process facilities.

The advantage of tandem over side-by-side offloading systems is not only that it allows the transfer of LNG in rougher seas, but most importantly that the distance between the LNG carrier and the FLNG is much larger, reducing the risk of collision.

The preference of the electrical motors over directly driven gas turbines presents some operational advantages such as the restart of compressors at settle-out pressure. The electric drive system is also intrinsically safer since the gas turbines, which are potential sources of ignition, are not located in the process area subject to leaks, but in a separated and dedicated area.

Safety is a major priority for Total. Even if some options are less economical, Total considers that these are necessary costs to ensure the safety of the asset and, most importantly, of the operators.