ZR-LNG Innovative Self-Refrigeration Technology for LNG with Integrated Liquids Removal

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Abstract

ZR-LNG, an innovative self-refrigeration liquefaction technology, provides multiple benefits;

- Reduction in CAPEX, $/tpa
- Reduced equipment count
- Improved safety profile
- Opportunities for standardisation
- Simple and flexible operation

The patented ZR-LNG dual methane expander process requires no external gaseous or liquid hydrocarbon refrigerants, no refrigerant extraction, import system or storage facilities and no ongoing refrigerant make-up. It provides a simpler and safer low-cost liquefaction solution whilst achieving an energy efficiency comparable to competing hydrocarbon based refrigerant processes. This development results in a concept well suited to standardisation in 1.0 and 1.5 Mtpa modules for application offshore where weight and space constraints and emphasis on safety are key design drivers.

The recently patented IHR (Integrated Heavies Removal) variant processes heavy components, BTX and ethane within the expander-based ZR-LNG liquefaction unit, without need for a scrub column, stand-alone upstream turbo-expander NGL recovery unit or separate cryogenic ethane recovery unit, thus significantly reducing investment cost and footprint.

The paper will provide data on a 1.5 million tpa modularised unit and data on the performance of the IHR system in respect of benzene removal and ethane recovery integral within the ZR-LNG configuration.

ZR-LNG Innovative Self-Refrigeration Technology for LNG with Integrated Liquids Removal

1. Introduction

Gasconsult Limited has developed and patented a mid-scale Liquefied Natural Gas (LNG) liquefaction technology termed ZR-LNG. The technology uses a dual methane expander configuration with a number of innovative features. Safety, simplicity and low power demand were key drivers in developing the process configuration.

ZR-LNG is well suited to land-based application but its benefits are significantly amplified on Floating Liquified Natural Gas (FLNG) schemes. A design development programme was undertaken by CB&I (now McDermott) to confirm the technical viability and quantify the benefits of the system. This work was undertaken for a standardised FLNG liquefaction module. A principle behind the design development was that the standard modular design could remain unchanged and be deployed in alternative locations where differing factors would impact available gas turbine power and LNG production capacity. The benefits of this standardisation include a reduction in ongoing engineering costs and project schedules.

The process equipment and piping were designed for an LNG output of 1.5 million tonnes per annum (Mtpa) of 365 days under the Basis of Design (BoD) defined in Tables 1 and 2 below. The actual LNG output will depend on the feed gas composition/pressure, the ambient air and seawater temperatures and on the power available from the selected gas turbine under specific site conditions.

The main refrigerant compressor was assumed to be driven by either a BHGE LM6000PF+ or Siemens SGT-A65 gas turbine. At the time of the engineering development, the 46-47 MW power from the gas turbines under the BoD conditions limited the LNG production to circa 1.4 Mtpa. With subsequent development of higher power outputs by BHGE and Siemens (see Table 3) the full 1.5 Mtpa LNG production is now feasible, justifying the decision to size the standardised module for 1.5 Mtpa.

2. Basis of Design

To provide a reference point for the data presented in this paper the BoD is provided as detailed in Tables 1 and 2. The basis includes the specific inputs to the liquefaction module design and a generic FLNG vessel incorporating the installed modules.

The FLNG vessel was assumed to be located in deep water off the West African coast with warm ambient air and seawater temperatures. The metocean data has been selected to be typical for the environment and the accelerations imposed upon the liquefaction module are based on the sea state typical for such a location.

TABLE 1 BASIS OF DESIGN SUMMARY		
Parameter	Unit	Basis Value
Feed Composition		
Nitrogen	Mol %	0.50
Methane	Mol %	96.04
Ethane	Mol %	2.80
Propane	Mol %	0.40
C4+[1]	Mol %	0.26
Feed Gas Arrival Temperature	°C	27
Feed Gas Arrival Pressure	barg	65
Target Production Rate	Mtpa	1.5
Ambient Air Temperature	°C	25
Cooling Water Loop Supply Temperature	°C	23
Process/Cooling Water Approach	°C	4

1 Composition is based on feed gas having been treated by upstream NGL extraction

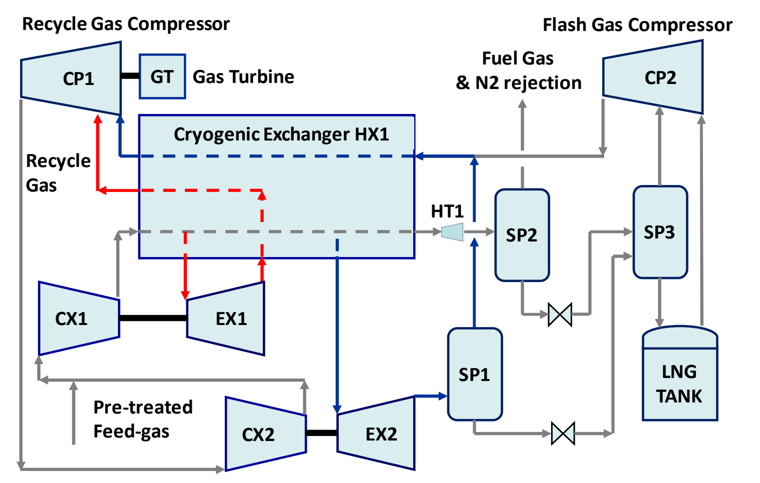
TABLE 2 BASIS OF DESIGN SUMMARY KEY LOCATION & FLNG ASPECTS		
Parameter	Unit	Basis Value
LNG Storage Capacity[2]	m³	210,000
Condensate Storage Capacity	m³	50,000
Seawater Temperature	℃	20
Guide Module Envelope	L x B x H	45 x 24 x 30
FLNG Dimensions	L x B x D	380 x 65 x 33
Maximum Operating Sway on Module	G	0.2

2 Membrane type storage containment

3. The ZR-LNG Process

3.1 Process Configuration

Fig 1 Basic ZR-LNG Flow-scheme



The basic ZR-LNG flow-scheme is shown in Fig 1. Liquefaction of the natural gas is achieved through the use of two expander-compressor circuits providing two temperature levels of refrigeration with heat exchange across a manifolded plate fin heat exchanger block located in a single cold box structure.

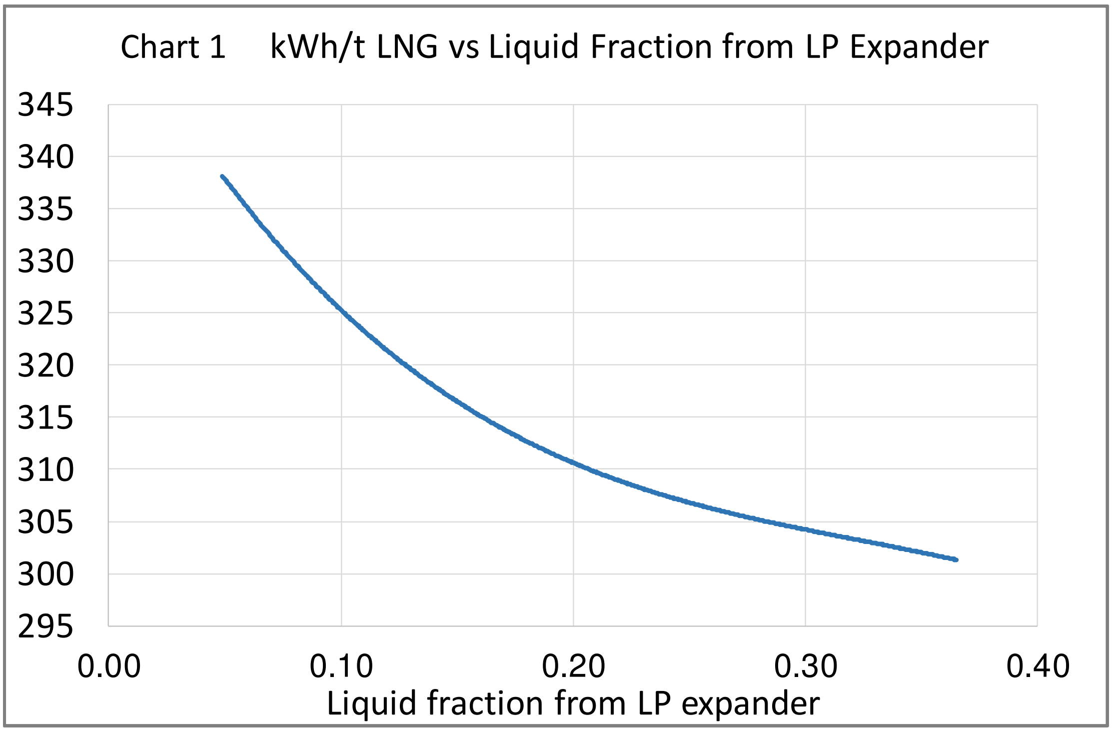
The High Pressure (HP) expander EX1 provides a warmer level of cooling of the feed gas, with the expander outlet stream reheated and returned to the suction of the recycle compressor. The shaft power produced by EX1 is typically used in an expander-driven compressor CX1 to compress the feed gas to a higher pressure than the feed gas; improving the efficiency of the liquefaction process. The Low Pressure (LP) expander EX2 provides a partially condensed stream from which the vapour is separated and used as a lower temperature, lower pressure refrigerant to condense the feed gas to LNG. The shaft power produced by EX2 is typically used in a second expander-driven compressor CX2 to compress the recycle gas stream discharged from the recycle compressor prior to mixing with feed gas.

The mixture of feed gas and recycle gas typically exits the cold box HX1 as a dense phase at around -110℃ and is then let down to an intermediate pressure across a hydraulic turbine HT1 (or optionally, across a Joule-Thomson (JT) valve) before being further reduced in pressure prior to LNG storage. Flash gas generated at both of these pressure let-down stages is used to provide additional refrigeration and to facilitate nitrogen rejection. Gasconsult's analysis has shown that with the ZR-LNG process this pressure let-down approach is as efficient and more cost effective than provision of a sub-cooling arrangement to cool the liquefied product to the temperature of around -150℃ typical of conventional LNG liquefaction practice.

ZR-LNG is similar in operating principle to nitrogen expander schemes. However, it enjoys certain advantages over nitrogen. Methane has a higher specific heat - this significantly reduces circulating flows, reducing power consumption and pipe sizes. Moreover, methane is more compressible than nitrogen at the typical compressor discharge pressures.

A patented feature is the partial liquefaction that takes place in the LP expander EX2 – this very efficiently converts latent heat directly into mechanical work and also permits a reduction in heat transfer area and cost of the main cryogenic heat exchanger HX1.

The power demand reduction arising from liquefaction in EX2 is shown in Chart 1.



3.2 Process Performance

The features described in the ZR-LNG process configuration make for a highly efficient system, with a simulated specific power of 313 kWh/tonne under the BoD conditions. Table 3 provides the key process performance parameters for the BoD specified in Table 1.

TABLE 3 PROCESS PERFORMANCE	
Power Demand kWh/tonne	313
LNG Production Mtpa	1.5
GT Power Output MW	51.1
HT Expander(s) Power Output MW	2 x 7.5
LT Expander Power Output MW	9.6
Recycle Compressor polytropic efficiency %	86.9
HT Expander adiabatic efficiency %	87.0
LT Expander adiabatic efficiency %	86.3
Flash Gas Compressor MW	3.1
Hydraulic Turbine MW	-0.6

3.3 Process Sensitivities

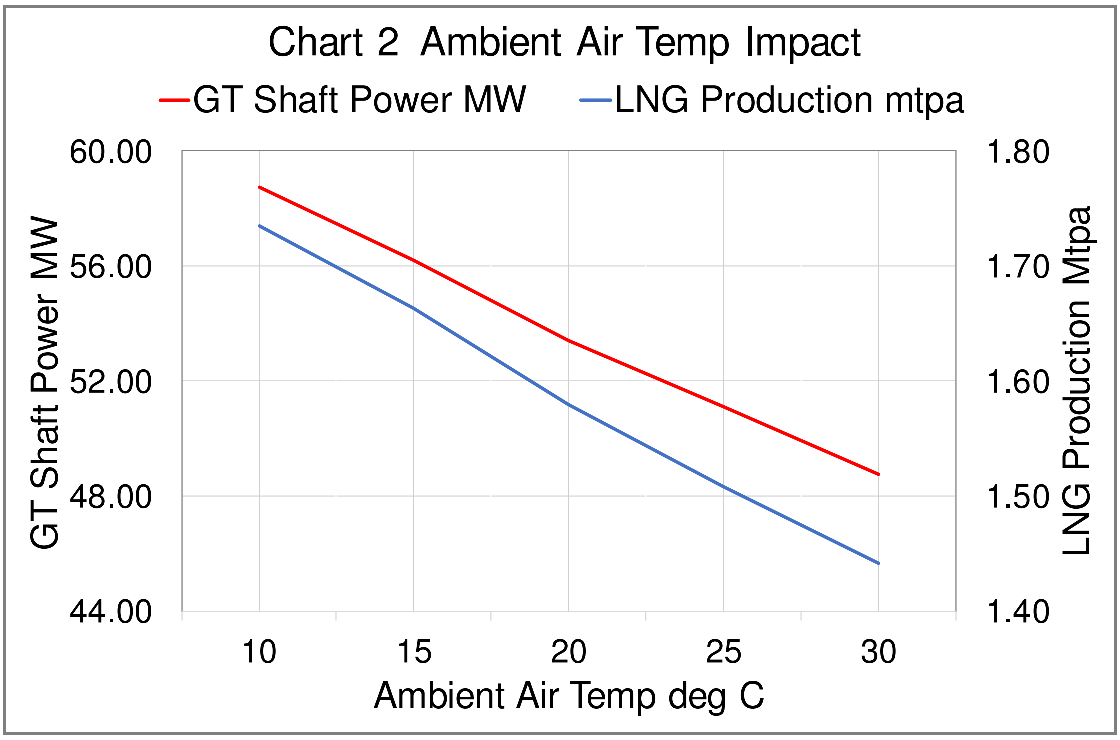
Due to condensation of the C2+ components of the feed gas at the cold end of the process, the composition and flowrate of the recycle gas are little affected by changes in composition of the feed gas; the recycle gas consisting mainly of methane with some accumulated nitrogen. As a result, the requirement to monitor and adjust the refrigerant composition for changes in feed composition is eliminated, a significant operational advantage over Mixed Refrigerant (MR) processes. LNG production in actual operation can be maximised by minor adjustments in the flow ratio between the expanders.

An increase in the C2+ content of the feed gas can be expected to reduce the compression power within the same equipment due to the higher overall condensing temperature. The required gas turbine power demand will therefore be reduced, and, as this is the limiting equipment item in the 1.5 Mtpa standard design, the LNG production may increase within the limits of the available gas turbine power. Conversely, a reduction in C2+ content results in an increase in the specific power and so a reduction in the LNG production rate.

An increase in feed gas nitrogen also increases the liquefaction specific power, resulting in a reduction in LNG production for a fixed gas turbine available power. The recycle loop concentrates the nitrogen so the specific compression power increases. Typically, 3 - 4 % N2 in the feed gas can be accommodated, the limitation being the nitrogen content acceptable in the gas turbine fuel gas. However, the process naturally removes nitrogen as part of the fuel gas bleed which ensures that the product LNG specification is robust to increased nitrogen without a change to the design.

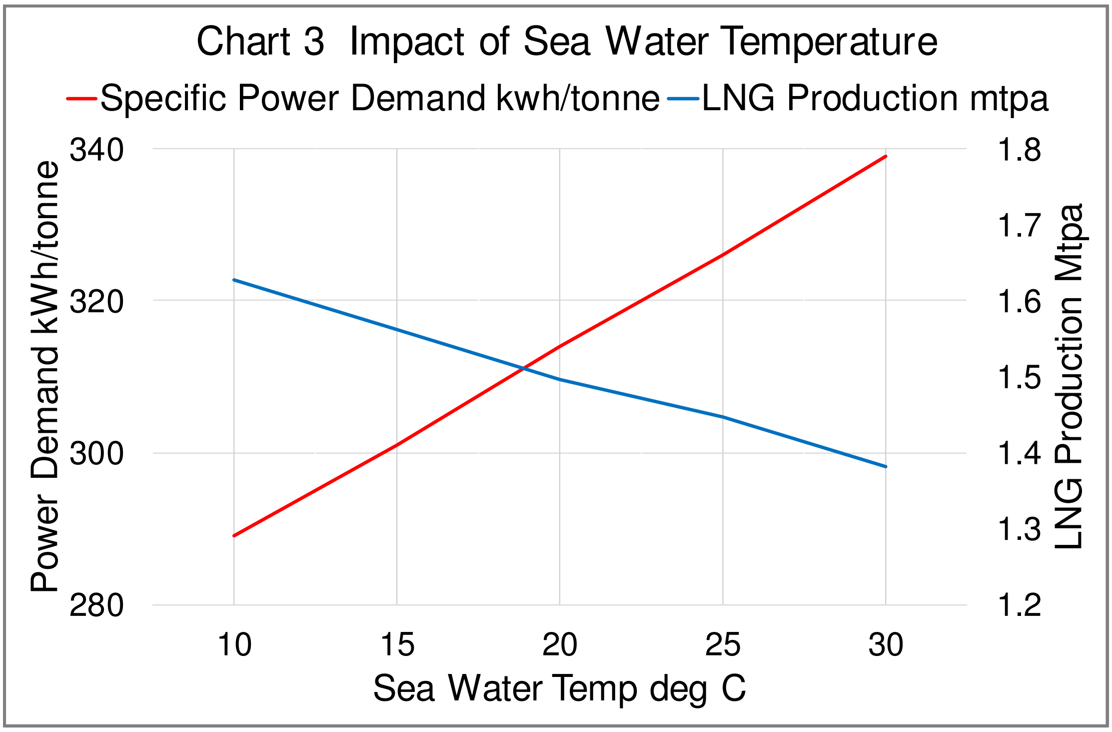
3.3.1 Impact of Ambient Air Temperature

The impact of ambient air temperature is similar to that on other gas turbine driven liquefaction processes in that the available power for the main recycle compressor falls at increased ambients so reducing the LNG production rate. Conversely, reduced ambients allow the gas turbine to deliver increased power and production can be increased up to and potentially in excess of the maximum of the standardised equipment capacity of 1.5 Mtpa. The impact of ambient temperature on LNG production and GT shaft power is shown in Chart 2.



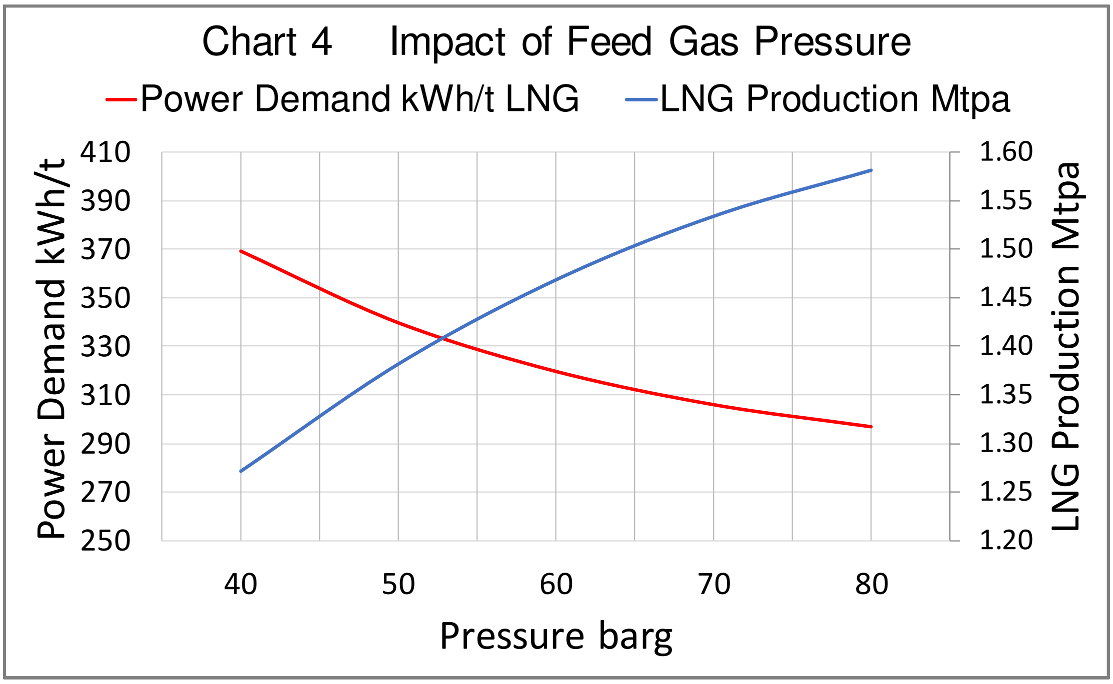
3.3.2 Impact of Sea Water Temperature

There will be an increase in liquefaction efficiency if the cooling water loop is able to provide more cooling due to colder seawater than design. The impact will be the opposite with warmer water. Quantification of the effect of seawater temperature on Specific Power Demand and LNG production is shown in Chart 3.



3.3.3 Impact of Feed Gas Pressure

All liquefaction technologies consume more power at lower feed gas pressures. Chart 4 details the impact on ZR-LNG power demand and LNG production against feed gas pressure based on the BoD in Table 1 (BoD feed gas pressure 65 barg).



3.4 Dynamic Analysis

A dynamic simulation of the liquefaction unit was performed to validate the robustness and integrity of the process configuration and equipment for normal operating and transient conditions such as start-up, shut down and trip scenarios. The dynamic model was initially configured to operate at steady state conditions (1.5 Mtpa) to confirm functionality and to develop the control scheme. Following this, a number of transient cases were analysed to assess performance of the module equipment and controls during unsteady conditions. The following transient cases were reviewed:

- Trip of one or two of the HP expander-compressors
- Trip of the LP expander-compressors
- System start-up

The completed dynamic simulation demonstrated that ZR-LNG operates stably in steady state operation. The expander trip cases were all found to be survivable with simple trip sequences incorporating feed forward step reductions in LNG and refrigerant flows and in the extreme case of both HP expanders tripping, keeping the HP JT valve closed until a suitable temperature profile across the cryogenic exchanger is achieved.

The start-up sequence developed demonstrated the simplicity of the system and introduced a number of control elements required for start-up. The sequence indicated that full production could readily be reached in 12 hours from start-up from "warm". This time is well within the cooldown and operational constraints of the ancillary equipment, so substantial improvements to this time-scale are considered possible.

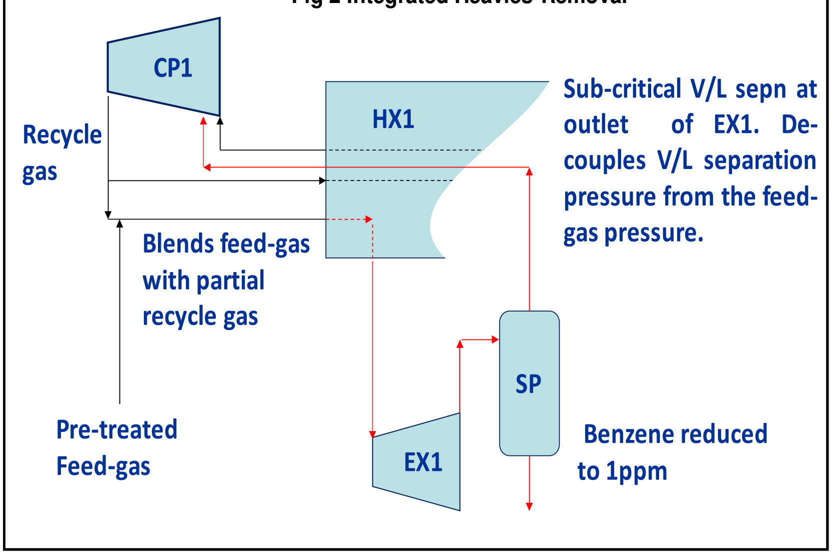
4. Alternative Process Configurations

As an open methane cycle process ZR-LNG lends itself to three interesting process configurations not possible with MR or nitrogen expander schemes.

4.1 Integrated Heavies Removal

Liquefaction systems require removal of C5+ and aromatics to avoid freezing and plugging of the main cryogenic exchanger and ancillary equipment. This heavies removal is widely carried out in a scrub column upstream of liquefaction and heat integrated with the liquefaction system. For feed gases close to their critical pressure achieving satisfactory operation of the scrub column and effective vapour/liquid separation may be problematic and may require operation of the scrub column at a pressure sub-optimal for liquefaction. Leaner feed gases with reduced levels of C_2 and C_3+ can also create instability in the scrub column due to lack of liquid reflux. Faced with either of these scenarios a typical solution is to install an upstream NGL recovery unit, expanding the feed gas to a sub-critical pressure, condensing the liquids and recompressing the depleted gas to recover liquefaction efficiency. This adds cost and complexity to the overall liquefaction scheme. At its simplest it requires additional heat transfer equipment and turboexpander with recompression of the feed gas to liquefaction pressure.

Fig 2 Integrated Heavies Removal



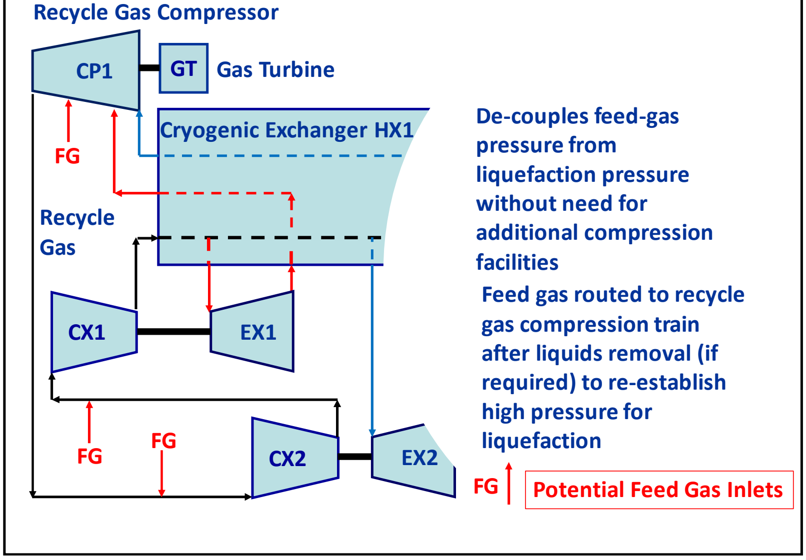
With the ZR-LNG process heavy components can be removed by passing the feed gas plus a portion of recycle gas through the high-pressure gas expander EX1 and separating the condensed liquids from the expander outlet at sub-critical pressure, typically around 15 bar. See Fig 2. This solution de-couples the vapour/liquid separation and feed gas pressures and saves a large part of the equipment and cost of a separate expander based NGL removal unit. Specifically, the expander and re-compression facilities already exist in the basic ZR-LNG configuration. In addition to cost, the weight and footprint reduction is particularly relevant to FLNG applications.

Simulations performed in the CB&I study indicated that benzene, toluene and xylene concentrations up to 500 vppm can be reduced to 1ppm in the LNG product when using IHR with use of a simple vapour/liquid separation system. It is also feasible to remove these components from lean feed gases containing < 100 ppm benzene - a difficult operation using existing technology.

4.2 Integrated Pressure Liquefaction

Chart 4 details the impact on ZR-LNG power demand and LNG production against feed gas pressure. ZR-LNG provides an elegant solution for lower pressure feed gases which can be routed after liquids separation back to an inter-stage point in the recycle gas compression train. See Fig 3. This allows consolidation of all compression power input into the liquefaction scheme itself, simplifying the configuration. By optimising the pressure parameters of the compressors CX1, CX2 and CP1 a higher liquefaction pressure decoupled from the feed gas pressure can be achieved, enhancing liquefaction efficiency without need for a separate feed gas compression plant.

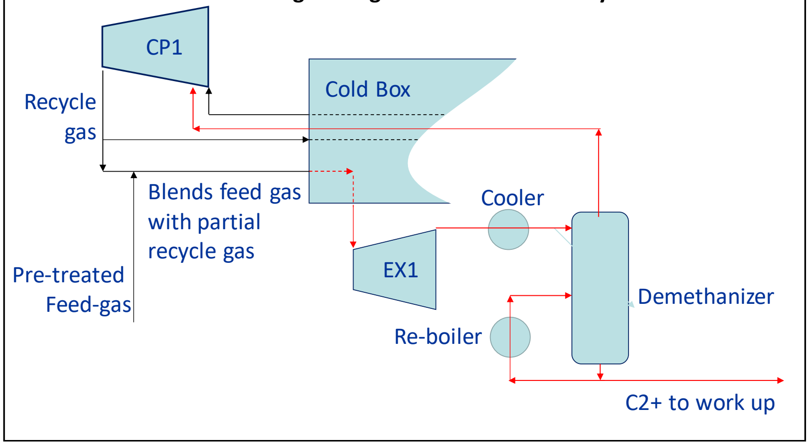
Fig 3 Integrated Pressure Liquefaction



4.3 Integrated Ethane Recovery

Fig 4 outlines an adaptation of the Integrated Heavies Removal flow scheme shown in Fig 2, recovering a significant fraction of the ethane content of a feed gas. The outlet stream from expander EX1 is further cooled in a heat exchanger to a temperature at which most of its ethane content condenses. The 2-phase stream leaving the cooler flows to the top of a demethanizer column. The bottom product stream from the demethanizer flows to a conventional fractionation unit in which the C2, C3, C4 contents are separated as required. The demethanizer overhead vapor is reheated and recompressed by CP1. The cooler and reboiler would be integrated with the main heat exchanger HX1. By performing the separation and recovery of an ethane-rich stream at a pressure much lower than the critical pressure of methane, it is possible to recover approximately 75 to 80% of the ethane content of a feed gas containing 9% ethane without need for a separate ethane recovery facility.

Fig 4 Integrated Ethane Recovery



5. Operability

5.1 RAM Analysis

A Reliability, Availability and Maintainability (RAM) analysis was performed to assess the on-line availability of the ZR-LNG process. To carry out the RAM analysis the unscheduled outages were calculated based on estimated production possible without each equipment item. For example, the loss of the gas turbine or recycle compressor would reduce production to 0%; but the expander-compressors are provided with JT valves and bypasses which would be expected to allow operation at 50% in the event of an expander-compressor trip.

The Mean Time Between Failure and Mean Time to Repair were taken from Offshore Reliability Data (OREDA) Handbooks for unplanned unavailability. The minimum outage time for any process trip was conservatively assumed as 8 hours. Planned maintenance was based on CB&I's past project data as provided by equipment suppliers.

A Monte-Carlo simulation was used to model the predicted plant unscheduled outages. Combining these outcomes with the scheduled outages results in a predicted plant availability of 96% in terms of total LNG production. This predicted availability for the ZR-LNG concept is equivalent to the availability of the liquefaction unit of a baseload onshore LNG facility.

The gas turbine is a major contributor to unavailability. It accounts for approximately 40% of the downtime for planned and unplanned maintenance. The HP expander-compressors account for approximately 25% and the LP expander-compressor accounts for approximately 12% of the downtime for planned and unplanned maintenance.

5.2 Safety

The key safety differentiator for ZR-LNG is that the refrigerant is feed gas, essentially methane with minimal LPG components. The cold box operates in the vapour or dense phase with no internal liquid inventory. Unlike MR processes the only liquid within the liquefaction module is LNG product so resulting in a lower inventory of flammable fluid. There is also no requirement for liquid refrigerant storage, import or transfer which reduces the liquid hydrocarbon inventory in other areas of the FLNG facility.

These factors directly reduce the inherent risk for an FLNG facility using ZR-LNG technology as there are reduced consequences of loss of containment when compared to MR processes. Similarly, when considering a loss of containment, the flammable gas cloud formed due to methane release is approximately half that of MR or propane, resulting in reduced overpressure design loads.

Another benefit of feed gas as the refrigerant is that, on shutdown, the majority of the liquid inventory can potentially be recovered as LNG. This minimises hydrocarbon loss to flare and reduces the lifetime emissions of CO_2 per tonne of LNG compared to other liquefaction technologies.

6. Equipment

Major equipment evaluated and costed in the design is detailed below. Appropriate references were sought and received from vendors for equivalent capacity and operating conditions for all equipment.

6.1 Main Recycle Gas Compressor and Gas Turbine Driver

For the specified feed gas and site conditions, approximately 50 MW of shaft power is required to drive the refrigerant compressor for the required LNG output of 1.5 Mtpa.

The largest available aero-derivative gas turbines in this range were selected to define the achievable LNG capacity and to select appropriate recycle compressors. Both BHGE and Siemens were approached to provide performance and cost data for the LM6000PF+ and SGT-A65 respectively. Either gas turbine or an electric motor drive is suitable for a modular design execution strategy.

6.2 Expander-Compressors

The expander-compressors units are key to the performance and layout of the liquefaction module. Both BHGE and Mafi-Trench (Atlas Copco) were approached for budgetary selections with a 2 x 50% arrangement for the HP units and a 1 x 100% arrangement for the LP units.

Concerns have been raised in the past concerning the concept of performing a partial liquefaction in the LP expander. Both vendors advised numerous references for units running with up to 40% liquids in the expander outlet.

6.3 Main Cryogenic Heat Exchanger

The ZR-LNG technology includes an LNG exchanger comprising several brazed aluminium heat exchangers (BAHX), manifolded together and supplied as a package in a cold box. The ZR-LNG cold heat exchanger group is designed to operate in dense phase which simplifies the cold box design due to the lack of any separate liquid phases and associated concerns over internal fluid distribution. This provides greater robustness than may be the case with other hydrocarbon-based liquefaction technologies. There are a number of suppliers of cold boxes. Data was obtained from Chart Industries per Table 4.

TABLE 4 BAHX DATA SUMMARY		
Parameter	Units	Chart Energy and Chemicals Inc.
Number of Cores	-	6
Height	m	14.2
Depth	m	7.0
Width	m	7.0
Weight	tonnes	280

Chart have supplied cold boxes with similar dimensions and with the same number of cores, as well as lighter and smaller cold boxes in LNG service. Chart have also supplied cold boxes of approximately double the weight and larger dimensions than described in Table 4, mostly for use in ethylene purification and natural gas processing facilities, the largest being a single cold box of over 500 tonnes weight containing 18 core brazed aluminium exchangers with overall dimensions of 28 m x 10.5 m x 7.3 m (H x D x W). These exchangers are deemed appropriate references as they have been produced by the same manufacturing process.

7. Module Design

The ZR-LNG concept is simple with a relatively low equipment count, allowing a standardised and compact module design. The process equipment was planned as a single module over three decks with a module frame size of 40 m x 18 m x 22.5 m (L x W x H). A half deck is included on the top of the module for the gas turbine driver and associated compressor, with the top of this structural frame at 30.5 m. The overall weight of the module is estimated to be 4,500 tonnes, which is within the limits of lift capacities of floating cranes expected to be available at FLNG integration yards. A summary weight breakdown is provided in Table 5.

TABLE 5 ESTIMATED WEIGHTS	**Equipment Gross Dry Weight (tonne)**	**Bulks Gross Dry Weight (tonne)**	**Structural Gross Dry Weight (tonne)**	**Total Dry Weight (tonne)**
Module Total	1250	1050	2200	4500

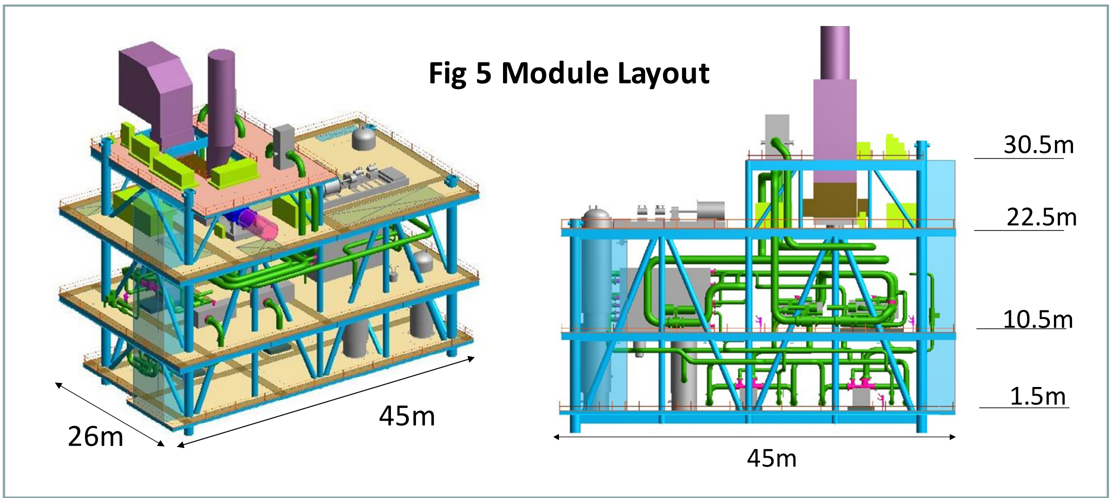
A structural analysis was carried out to prove the layout works for the operating loads and motions experienced on a typical FLNG. The structural analysis also provided the basis for the Primary Steel weight.

The structural model was built using STAAD Pro. The module was checked for three design scenarios:

(i) normal operation including 100 yr. return period wind and sea motions
(ii) transportation from fabrication site to the operating location including 10 yr. return period
(iii) lift of the module from ground or water level to the top of the FLNG hull at the fabrication yard.

Multi-disciplinary reviews on the module layout were performed to confirm safety requirements were met and that sufficient access and flexibility was provided for commissioning, maintenance and operation of the unit.

Fig 5 Module Layout



One key factor considered in detail was the optimum location for the gas turbine/recycle compressor unit with its associated ancillary packages. The module concept is such that the gas turbine driver/recycle compressor assembly could be designed as a separate sub-module giving the option to build this sub-module at a separate location, so providing flexibility in the execution strategy. The 'process sub-module' would then be a standard module, capable of producing LNG to the limits of the selected driver. Splitting the modules in this way results in a 'process sub-module' overall weight of approximately 3,500 tonnes and a 'gas turbine/recycle compressor sub-module' weight of approximately 1,050 tonnes. This configuration allows both modules to be lifted at most yards in South East Asia by enabling the lift of the larger 'process sub module' with two smaller floating cranes if necessary.

This concept had a number of benefits:

- The split leads to the gas turbine with its driven recycle compressor, the heaviest equipment item, being in its own module, whilst creating minimal piping interface points with the process module.
- Splitting the gas turbine with its driven recycle compressor onto its own small module allows a pallet type structure, which then makes it easier to lay out the gas turbine and compressor 'across the module' which is viewed as the most efficient use of space and allows better maintenance access.
- As the gas turbine/recycle compressor tends to be a long lead equipment item its availability in its own module for final installation on top of the process module de-risks the construction critical path.
- By splitting in this way, it allows the 'process module' to be 'standardised'. The 'gas turbine/recycle compressor sub-module' is then designed depending on the driver and compressor selected and is potentially fabricated and tested at facilities owned by the vendor.

Ultimately it was deemed more flexible to follow a concept where the module could be designed either as one large module or as two smaller modules depending on project requirements and fabricator capability. As a result of this, the ''gas turbine/recycle compressor sub-module' was placed on top of the 'process module' to provide the most flexible solution.

The final concept (Fig 5) is shown as a single module but could readily be configured as a two-module concept utilising a separate 'driver module'.

The only concern raised with this concept was whether having the gas turbine and the recycle compressor at an elevated level would create any issues with respect to accelerations being outside the limits of manufacturer's design envelope. This concern was raised with the manufacturers and the accelerations set out in the project BoD were found to be acceptable.

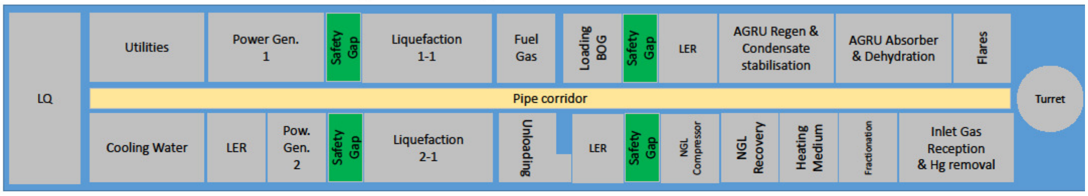
8. FLNG Vessel Layout

The design of an FLNG vessel is structurally distinct from an LNG carrier as it needs to support the process equipment and structural weight on the deck. As a result, the design of the hull and deck space is designed to suit the FLNG facility needs. The overall dimensions are, however, limited by the maximum size shipyards can build.

The basis for the generic FLNG design is to produce up to 3 Mtpa LNG which fits the design capacity of two ZR-LNG liquefaction modules.

The liquefaction modules have been sized to fit on a purpose built FLNG with a length of 380m and breadth of 65m which is estimated as the minimum required for the topsides, assuming a turret within the hull structure and is sufficient for the design LNG storage capacity of 210,000 m³. See Fig 6.

Fig 6 Overall FLNG Layout



Key aspects of the layout are:

- Central 7 m wide piperack running longitudinally at the centre of the FLNG, supported via grillage to strong points on the hull structure.
- Process and utility modules ranging in size up to potentially 6000 tonnes arranged either side of the piperack
- Flare boom and turret at the bow
- Safety gradient from the turret to living quarters at the stern
- Offloading of LNG and Condensate on the side utilizing arms.

The process units are, as far as possible, arranged to minimise the piping by flowing through the sequence of treatment units from inlet at the turret through to liquid closer to the stern. The process unit modules are sized based on typical equipment size and count but footprint is governed by the assumption that each module will have a similar truss line spacing to the liquefaction or half of that value to allow consistent design. For the liquefaction modules a structural frame spacing of 18 m allows for up to a 4 m gap between the edge of the piperack and module framings. This allows for perimeter walkways on the modules and pipe bends as pipes enter and leave the main pipe rack and results in an overall footprint of 26m x 45m.

9. Cost Estimate

A cost estimate was developed for the module. The inputs to this estimate were:

- Sized Equipment List
- Weight Report
- Supplier Pricing Data
- Preliminary Structural Material Take Off (MTO)
- Preliminary Piping MTO

The cost estimate for the 1.5 Mtpa production module is US$195 million based on a 1Q2018 instant execution basis. A summary breakdown of this cost is provided in Table 6.

TABLE 6 COST ESTIMATE BREAKDOWN	
ITEM	US$ (million)
Home Office	25
Mechanical Equipment	80
Bulk Material	30
Shop Fabrication/Freight/Spares	60
TOTAL	195

The following methodology was applied to develop the cost estimate.

Home Office Engineering

Engineering costs were developed from typical manhour ratios from relevant reference projects. The costs comprise home office project management services, procurement and subcontracts management for a single module.

Mechanical Equipment

A costed equipment list was developed for the estimate. The majority of equipment items were costed based on budget proposals received from equipment suppliers.

Budget proposals from suppliers were benchmarked against proposals and actual costs from other projects to arrive at an overall anticipated cost. An allowance for 2 years' spares and an allowance for first fill of lubricants were also included in the mechanical equipment cost.

Bulk Materials

Bulk materials costs were developed from estimated weights included in the weight report. Primary structural steel and large bore piping weights were developed from the MTOs, giving an increased confidence in these quantities. The primary steel MTO was generated from the structural analysis software. The piping MTO was generated from the 3D model including a split between carbon steel and stainless steel. Other weights were factored using in-house benchmarks.

Freight

Freight and Logistics costs were calculated on a percentage of the mechanical equipment and bulk materials costs.

Yard Fabrication Costs

The direct fabrication cost estimate was obtained by using an All-In Rate (USD/MT) applied to a total number of man-hours derived from key quantities. Indirect costs for supervision and pre-commissioning were factored from the direct costs. The All-In Rate was based on labour rates and productivity factor data in South East Asia.

Estimate exclusions

- E&I Equipment related to Power Generation, Distribution and Control Systems are excluded
- Cost Prior to FID
- Owners Costs
- Cost for fees, licences and permits
- Cost of Finance and Finance Costs
- Insurance Costs
- Customs and Import Duties
- Taxes
- Transportation costs of the module from the yard in which it is fabricated
- Final Installation

- Load out and sea fastening.
- Forward Escalation
- Contingency and Contractor’s EPC Margin
- Gasconsult licence fee

10. Conclusions

At the time of writing LNG schemes face difficult financial hurdles arising from low energy prices and expanding LNG production capacity. This difficulty is exacerbated for mid-scale and FLNG schemes as, by their nature, they are lower capacity than current base load plants, introducing a further challenge in the form of economy of scale.

The methane expander based ZR-LNG process with its high efficiency and elimination of the complete refrigerant infrastructure (storage, blending, transfer and extraction) offers a low capital cost solution. Indications are that weight/footprint can be reduced significantly relative to MR schemes. Further substantial savings may be secured when the Integrated Heavies Removal variant allows elimination of a conventional expander based NGL removal unit. ZR-LNG combines these advantages with the following safety, operations and logistics benefits:

- No liquid refrigerants are required, the only hydrocarbon in the liquefaction module is the feed natural gas itself. This provides an intrinsically safer scheme than MR processes.
- There are no refrigerant make-up costs.
- There is no need for ongoing refrigerant composition adjustment.
- There is no requirement to import refrigerant components such as ethylene or isopentane required to optimise the refrigeration system and ensure maximum liquefaction efficiency.
- The methane refrigerant is always in a single-phase providing advantages over MR schemes on floating facilities subject to motion.

The level of engineering performed during the CB&I development has demonstrated the commercial readiness of the ZR process. Quality data is now available to allow detailed assessment of ZR-LNG for project opportunities.