Zero Refrigerant Liquefaction
Developments in the ZR-LNG Technology

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Abstract

Increasing LNG plant complexity and the high capital costs associated with recent mega-scale LNG developments are being challenged to improve project economics and reduce commercial risk. The patented ZR-LNG process, which requires no external gaseous or liquid hydrocarbon refrigerants, no refrigerant extraction, import system or storage facilities and no ongoing refrigerant make-up provides a simpler and safer low-cost liquefaction solution whilst achieving an energy efficiency close to dual mixed refrigerant schemes. Heavy components and aromatics can be removed within the expander-based ZR-LNG liquefaction unit, without need for a scrub column or stand-alone upstream turbo-expander NGL recovery unit, thus significantly reducing investment cost and footprint of the liquefaction train. This substantial elimination of equipment not only reduces capital cost but together with the absence of liquid hydrocarbon refrigerants makes the process particularly well suited to FLNG where weight and space constraints and emphasis on safety are key design drivers.

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1. Introduction

Gasconsult Limited has developed and patented a mid-scale Liquefied Natural Gas (LNG) liquefaction technology termed ZR-LNG (Zero Refrigerant 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. The resulting design provides high energy efficiency, low equipment count and a small footprint.

The benefits of ZR-LNG are significantly amplified on Floating Liquified Natural Gas (FLNG) schemes. The recent award of a grant from the UK Government's Innovate fund has now allowed design development of the process to quantify the benefits of the system. This design development work was undertaken by CB&I (now McDermott) for a standardised FLNG liquefaction module based on process simulations provided by Gasconsult and conditioned by CB&I.

CB&I's work was confined to the liquefaction unit. No development of the processing units upstream or downstream of liquefaction were considered unless it had an impact on the design and operation of the liquefaction module itself.

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 below. The actual LNG output delivered by the module in a particular project 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 the 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 installed power available from the gas turbines under the BoD conditions limited the LNG production to around 1.4 Mtpa, but 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 original decision to size the standardised module for 1.5 Mtpa.

The design development envisaged that two 1.5 Mtpa modules would be installed on a custom-built hull, though this configuration is not prescriptive and retrofit of the modules to modified LNG carriers may also be of interest.

The objectives of CB&I's work were to develop the ZR-LNG liquefaction technology to a level of engineering development that confirms the integrity of the original ZR-LNG design concepts and the mechanical practicality of the design, and to provide a functional preliminary layout and an independent realistic cost estimate for a modularised liquefaction unit.

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 approach include a reduction in ongoing engineering costs and reduction in project schedules.

2. Basis of Design

To provide a reference point for the data presented in this paper the BoD is provided as Tables 1 and 2. It includes the key assumptions necessary for development of a liquefaction module on an FLNG vessel for a broad range of possible locations and characteristics. The basis includes the specific inputs to the liquefaction module design (such as feed gas conditions and prevailing ambient conditions) 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 a reasonably warm ambient temperature and seawater temperature. The output of the standard liquefaction modules will be higher than 1.5 Mtpa in case of relocation to an environment with lower 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 KEY PROCESS CONDITIONS		
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]	m^3	210,000
Condensate Storage Capacity	m^3	50,000
Seawater Temperature	°C	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

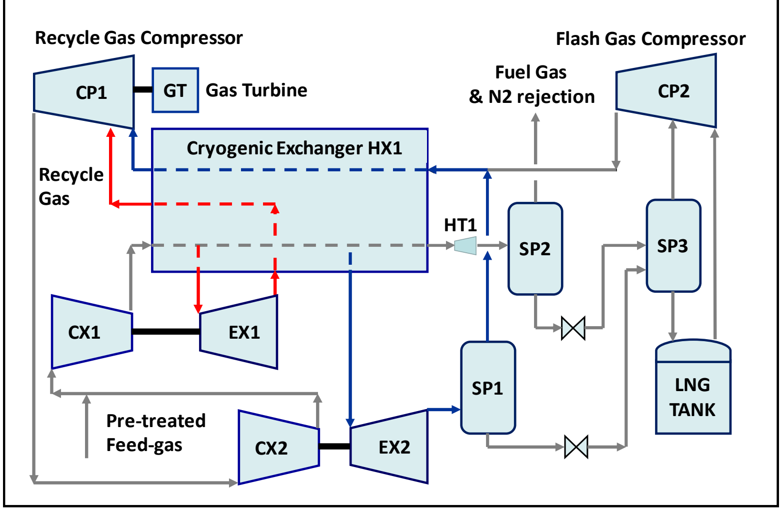
2 Membrane type storage containment

3. The ZR-LNG Process

3.1 Process Configuration

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.

Fig 1 Basic ZR-LNG Flow-scheme



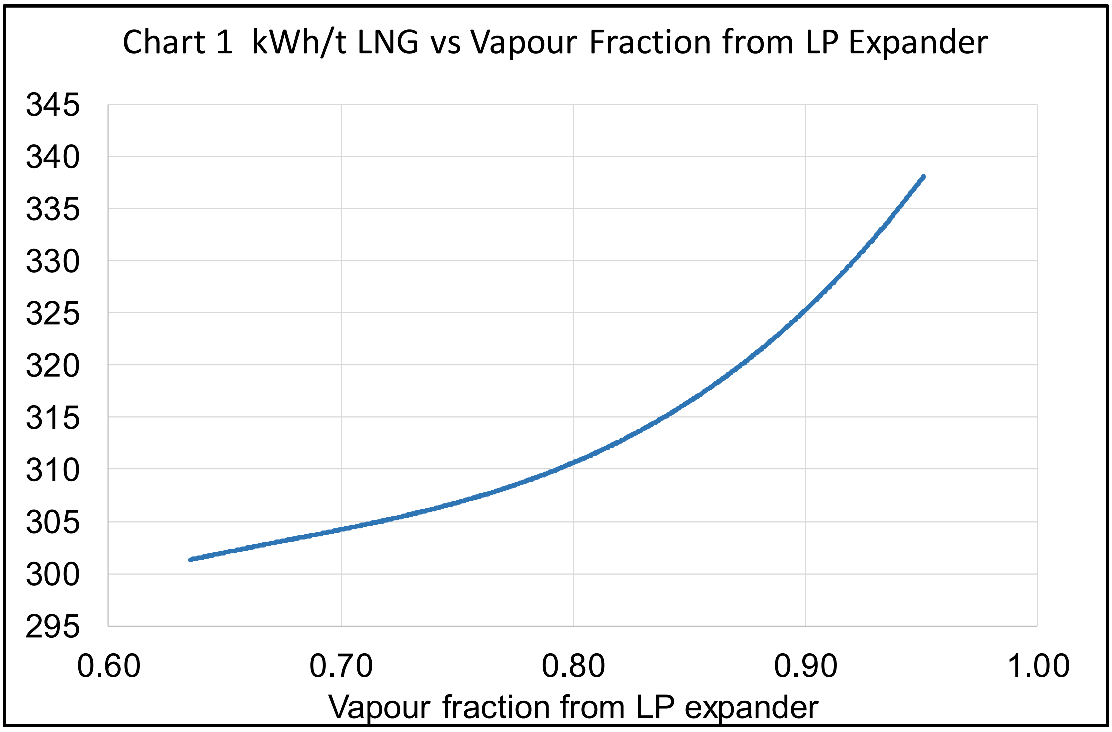
The High Pressure (HP) expander EX1 provides a warmer level of cooling of the feed gas, with the expander outlet stream reheated and returned to the suction of the recycle compressor. The shaft power produced by EX1 is typically used in an expander-driven compressor CX1 to compress the feed gas to a higher pressure than the feed gas to improve 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 deg C and is then let down to an intermediate pressure across a hydraulic turbine HT1 (or optionally, across a Joule-Thompson (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 shows 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 deg C typical of conventional LNG liquefaction practice.

ZR-LNG is similar in operating principle to nitrogen expander schemes. However, it enjoys certain advantages over nitrogen as 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 above features, together with the optimised distribution of flows, temperatures and pressures in the expander circuits makes for a highly efficient system, with a simulated specific power of 313 kWh/tonne under the BoD conditions. Table 3 provides the key process parameters for the BoD specified in Table 1. No reliquefaction of boil-off gas from the LNG storage has been allowed for.

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	-0.6

3.3 Process Performance Discussion

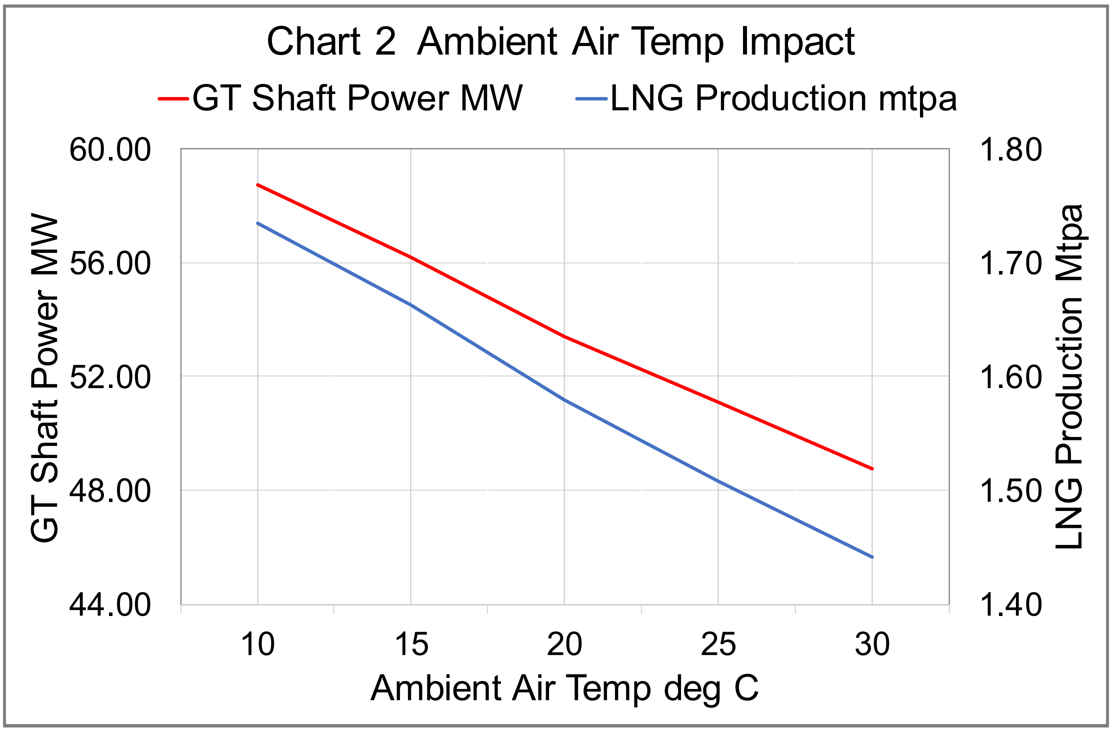
The above data is based on the prevailing conditions described in the BoD, but in commercial operations the module may operate with different feed gas compositions, ambient air temperatures and cooling water temperatures.

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 the refrigerant composition and to adjust it for variation in feed composition – a feature of Mixed Refrigerant (MR) processes - is eliminated, a significant operational simplification. LNG production in actual operation can be maximised by minor adjustments in the flow ratio between the expanders.

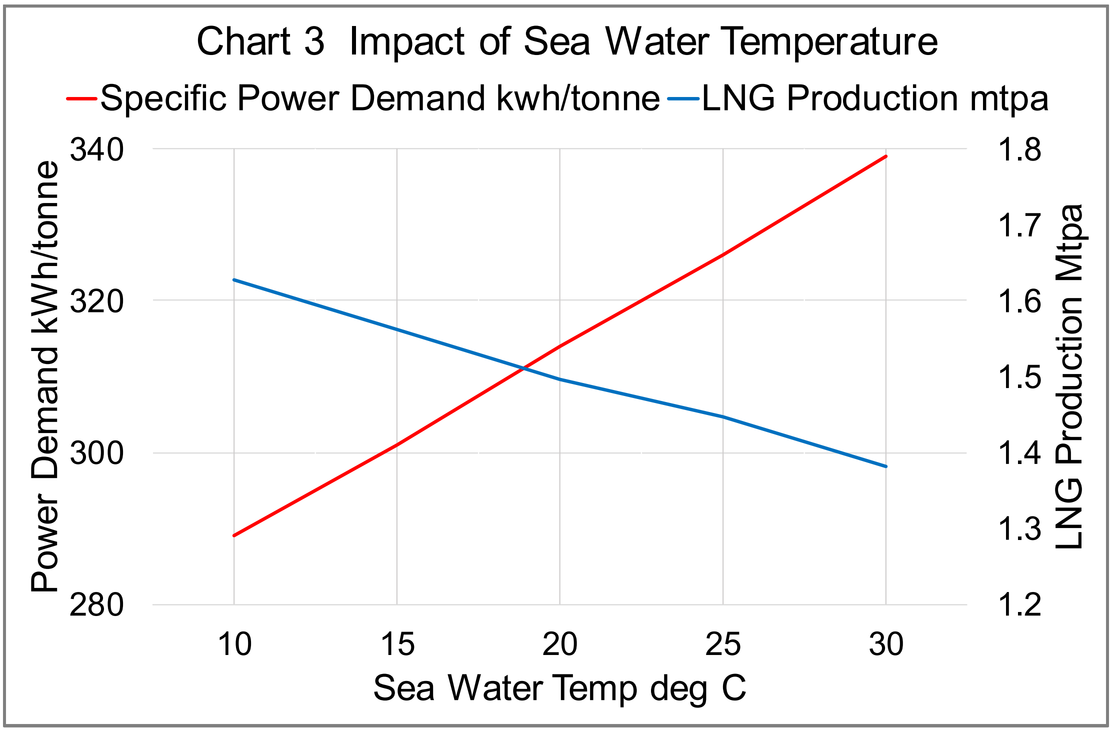
An increase in the C2+ content of the feed gas can be expected to reduce the compression power within the same equipment due to the higher overall condensing temperature. The required gas turbine power demand will therefore be reduced, and, as this is the limiting equipment item in the 1.5 Mtpa standard 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 % N_2 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.

The impact of ambient air temperature is similar to that on other gas turbine driven 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 the maximum of the standardised equipment capacity of 1.5 Mtpa. The impact of ambient temperature is shown in Chart 2.



Similarly, 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 liquefaction efficiency is shown in Chart 3.



3.4 Operability

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
- Module 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 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.

3.5 Reliability

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% (so a 100% reduction in production); 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 availability for both scheduled and unscheduled outages. The predicted plant availability is 96% in terms of total LNG production for the base case (when instantaneous production rate may be between 0% and 100% depending on which failure occurs), so the overall unavailability is 4%.

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 so cumulatively account for about 37%.

The predicted plant production availability is summarised in table 4.

TABLE 4 AVAILABILITY ANALYSIS		
Liquefaction & Compression Reliability	96.7	%
Liquefaction & Compression Availability	96.0	%
Liquefaction & Compression Unit Unavailability	4.0	%
Unscheduled unavailability	3.3	%
Scheduled unavailability	0.7	%

3.6 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 so minimising hydrocarbon loss to flare and consequently reducing the lifetime emissions of CO_2 per tonne of LNG as compared to other liquefaction technologies.

4. Alternative Process Configurations

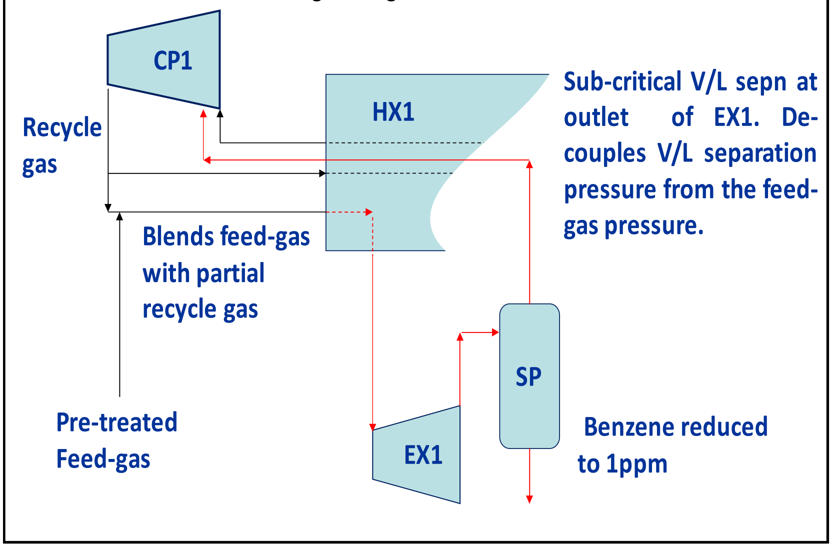
As an open methane cycle process ZR-LNG lends itself to two interesting process configurations not possible with MR or nitrogen expander schemes.

4.1 Integrated Heavies Removal (IHR)

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.

With the ZR-LNG process heavy components can be removed by passing the feed gas plus 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

Fig 2 Integrated Heavies Removal

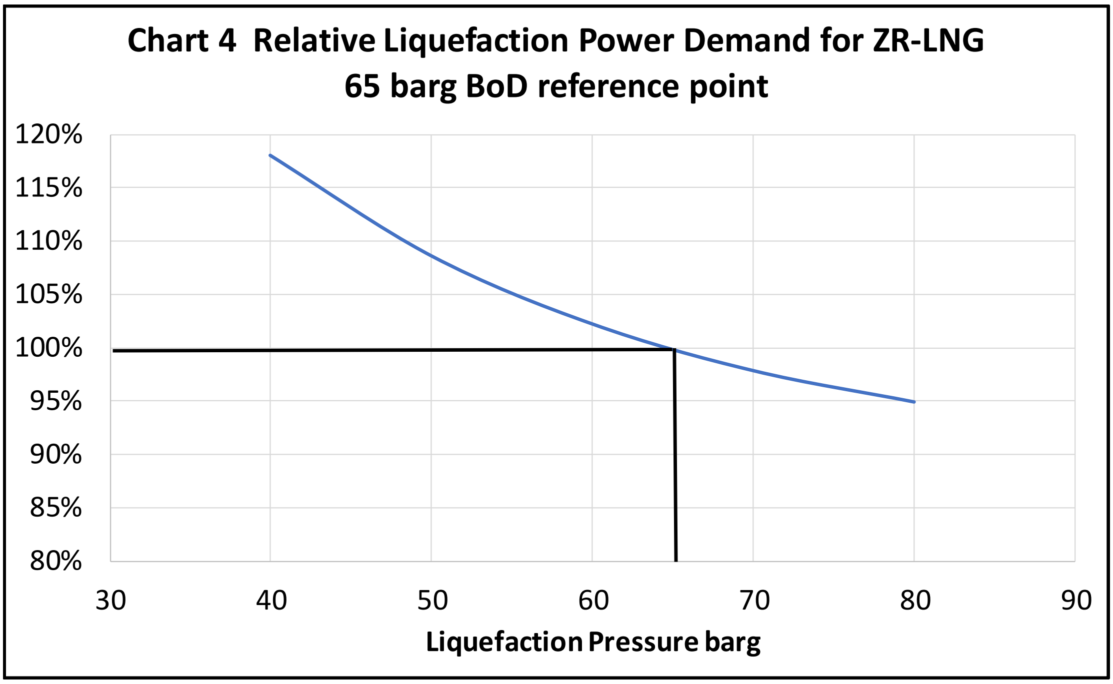


configuration. In addition to cost, the weight and footprint reduction is particularly relevant to FLNG applications.

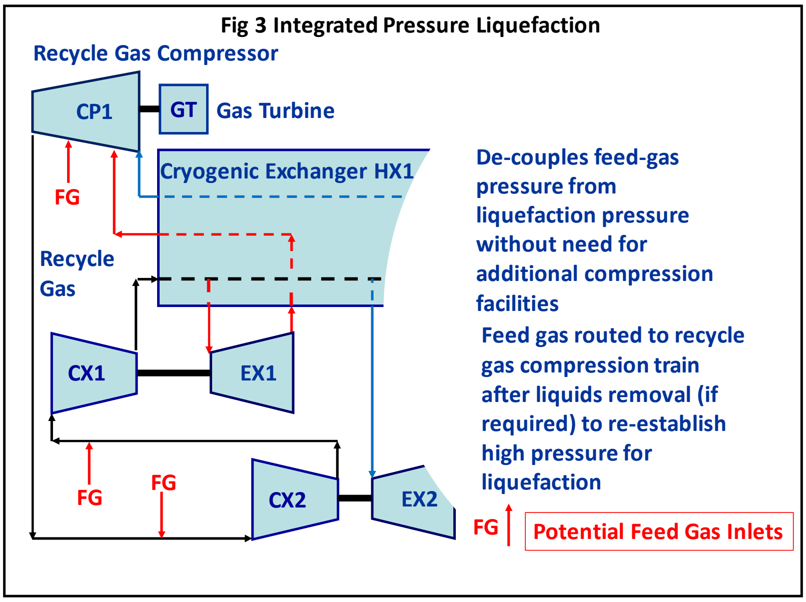
Simulations performed in the CB&I study indicated that benzene concentrations up to 500 vppm can the reduced to 1ppm in the LNG product when using IHR with use of a simple vapour/liquid separator (without need for a column).

4.2 Integrated Pressure Liquefaction

All liquefaction technologies consume more power at lower feed gas pressures. Chart 4 details the impact on ZR-LNG power demand against the BoD reference feed gas pressure of 65 barg.



ZR-LNG provides an elegant solution for lower pressure feed gases which can be routed after liquids separation back to an inter-stage suction point of 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.



5. 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.

5.1 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. The Siemens SGT-A65 gas turbine was used as the basis for the module design, although the BHGE LM6000PF+ is equally suitable. It should also be noted that the module design would also accommodate electric motor drive as an alternative to gas turbines.

5.2 Expander-Compressors (Companders)

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.

5.3 Main Cryogenic Heat Exchanger (Cold Box)

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 (USA) per Table 5.

TABLE 5 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 lighter 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 in Table 6, mostly for use in ethylene purification and natural gas processing facilities, the biggest 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.

6. 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 4,422 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 6.

TABLE 6 ESTIMATED WEIGHTS	Equipment Gross Dry Weight (tonne)	Bulks Gross Dry Weight (tonne)	Structural Gross Dry Weight (tonne)	Total Dry Weight (tonne)
Module Total	1207	1043	2172	4422

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.

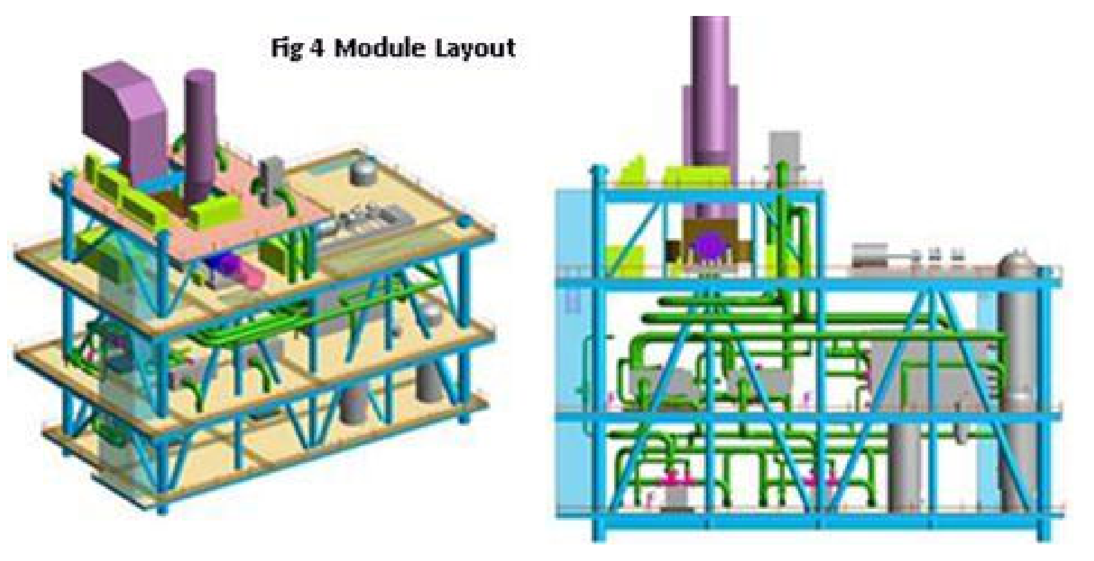


Fig 4 Module Layout

One key factor considered in depth was the best 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 4) 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.

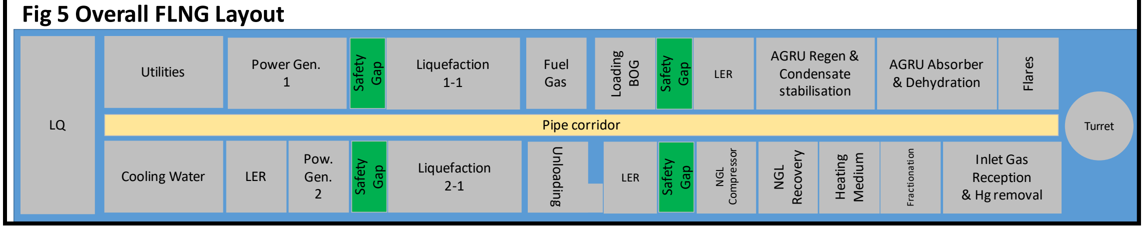
7. FLNG Vessel Layout

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 380 m and breadth of 65 m 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 5

Fig 5 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
- Mooring turret near the bow.
- 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 piperack.

8. 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 7.

TABLE 7 COST ESTIMATE BREAKDOWN	
ITEM	US$ (000s)
Home Office	26,642
Mechanical Equipment	76,953
Bulk Material	31,710
Shop Fabrication/Freight/Spares	59,695
TOTAL	195,000

The following methodology was applied to develop the cost estimate. Where appropriate reference was made to CB&I's extensive cost database:

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. The cost is based on London based execution with support from India (in a 50:50 split).

Mechanical Equipment

A costed equipment list was developed for the estimate. The majority of equipment items have been 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 is 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. Bulk material prices were taken from CB&I's database applied against the estimated material weights.

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

9. Summary

The foregoing details assessment data which is now available to support evaluation of ZR-LNG technology during the early phases of projects. The authors provide below their perspectives of how this may be a beneficial fit with factors impacting plant operations and project financial returns.

9.1 General Perspective

FLNG schemes will by their nature be lower capacity than current base load plants as they are deck space constrained. Economies of scale are therefore challenging. Special design considerations apply – there is a need for compact layouts, lower weight and smaller footprint to minimise the size and cost of the host hull. Safety issues are paramount considering the high equipment density and limited and difficult personnel exit opportunities available in the event of a fire or explosion.

From a general perspective the methane expander based ZR-LNG process is advantageous for FLNG on the issues of safety, operational logistics and capital cost.

With regard to safety 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.

Operationally there are no refrigerant make-up costs. Also, there is no need for ongoing refrigerant tuning or import of refrigerant components such as ethylene or isopentane required to optimise the refrigerant composition and ensure maximum liquefaction efficiency. The methane refrigerant is also always in a single-phase providing advantages over MR schemes on floating facilities subject to motion.

Regarding capital cost ZR-LNG eliminates all the refrigerant infrastructure associated with MR schemes, saving cost, weight and footprint. This can be very significant and is not typically appreciated. Analysis of published information indicates the space requirement of refrigerant infrastructure for SMR schemes can add up to 30% to the footprint of the refrigeration and liquefaction plot area for a single train plant[1]. CB&I's work also projected that SMR schemes had a 28 Outside Battery Limit (OBL) equipment count versus 9 for ZR-LNG.

9.2 Economic Perspective

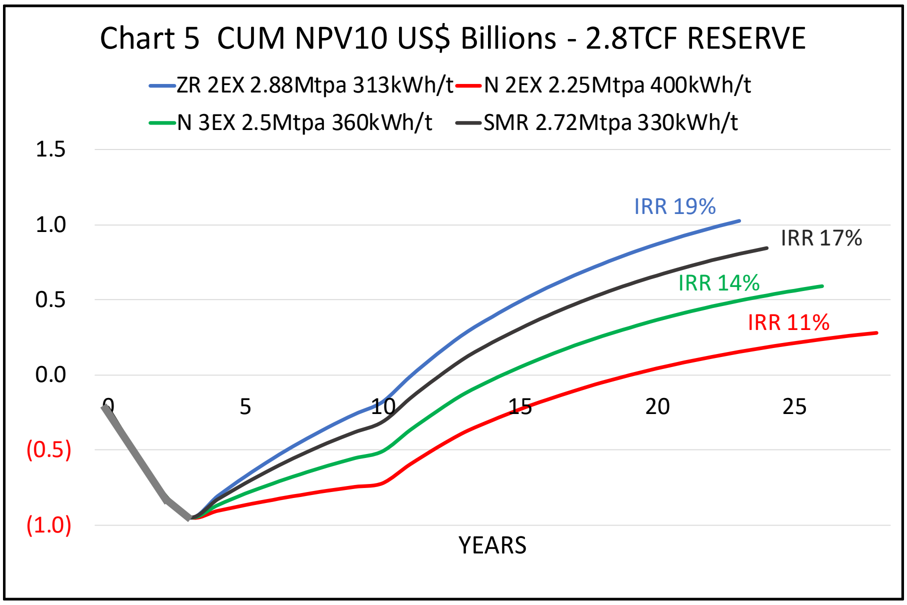
A key driver impacting LNG project returns is the need to maximise LNG production through enhanced liquefaction cycle efficiency. Most mid-scale to large LNG plants are built by assembling a matched set of ancillary equipment around a selected refrigerant compressor driver and maximising production up to the available LNG capacity of that driver. Maximum production is achieved by the liquefaction cycle with the highest efficiency. This factor has been behind the ever-increasing complexity of large base load schemes which for this purpose have mainly deployed C3MR (Propane Mixed Refrigerant) or DMR technologies. C3MR and DMR will likely be precluded from mid-scale plants because of their poor scalability to smaller schemes and the need for mega-scale gas reserves to recover their high capital cost.

Outside the larger capacity Prelude project which deploys Dual Mixed Refrigerant (DMR) technology and is supported by high levels of co-liquids production (capacities of 3.6 Mtpa LNG, 1.3 Mtpa condensate, 0.4 Mtpa LPG) current processes deployed on mid-scale FLNG facilities include Single Mixed Refrigerant (SMR) and nitrogen expander schemes.

CB&I's work demonstrated that ZR-LNG had a power demand equivalent or better than SMR schemes and very significantly below nitrogen expander processes. To provide a quantification of the impact of these different process efficiencies a financial model was developed based on parameters indicated in Table 8.

TABLE 8			
Capital Cost (FLNG + Field Dev)	$3 billion	Gas Sell Price	$10/mil BTU
Debt : Equity	60:40	Gas Cost	$3/mil BTU
Discount Rate	10%	Other Costs	$1.1-1.4/mil/BTU
Loan Repayment	7 years	Shipping	$2/mil BTU
Depreciation	10 years	Loan Interest Rate	8%
Tax holiday	7 years	Tax Rate	20%

Chart 5 plots the cumulative Net Present Value (NPV) of ZR-LNG, SMR and triple and dual nitrogen expander processes for a nominal 3 Mtpa plant processing a 2.8 TCF field. The capex of $3 billion, which covers both the FLNG and the gas field development, was kept the same for all technologies as differentials in the liquefaction section would represent only a small percentage of total capex. Because its better efficiency leads to higher production capacity ZR achieves higher returns, and it also achieves this in a shorter time period – 5 years earlier than the dual nitrogen scheme.



In an era of depressed energy prices there are no “shoo-in” stranded gas FLNG projects. Whilst FLNG schemes avoid regulatory costs associated with land-based plants, pipeline costs to land and enjoy the benefits of efficient fabrication in specialised yards, they are penalised by relative lack of scale. As can be seen from Chart 5 the authors project Internal Rates of Return (IRR) from 11 to 19% even after allowance for debt financing and a tax holiday of 7 years. Elimination of the tax holiday drops the ZR-LNG IRR to 14% which is a utility type return for what is arguably a high-risk project.

Chart 5 provides an explanation for the current focus on the US for LNG projects based on an existing pipeline gas supply and avoiding the cost of stranded field development. The reduced capital cost under such a scenario would raise the ZR-LNG IRR to 30%.

Chart 5 additionally demonstrates the benefit of looking at new technology to improve project returns

For the purposes of further comparison Gasconsult also assembled some industry data using CB&I material, other published data[2] and conditioned this using internal resources to produce industry metrics for FLNG of Mtpa/hectare of deck space and US$/Mtpa capacity. This is shown in Table 9. ZR-LNG compares favourably on these metrics against existing mid-scale technologies, particularly when consideration is given to the operational benefits reflected under 9.1

TABLE 9								
Project	**Capex $bn**	**Mtpa**	**Storage m3**	**Deck Area m**	**Process**	**kWh/t**	**Mtpa/ha**	**$/Mtpa**
Hilli Episeyo[1]	1.44	2.4	125000	294x62.6	SMR	350	1.05	600
				210x10.5[2]				
				210x10.5[2]				
Shell Prelude[3]	7.2	3.6	232000	488x74	DMR	280	1.0	2000
Petronas FLNG1	1.16	1.2	177000	365x60	N2 3EX	360	0.54	967
ZR-LNG	1.6	2.88	210000	380x65	CH4 2EX	313	1.21	530

[1] Retrofit of 1975 Moss LNG Carrier
[2] Sponsons added to support process equipment and provide buoyancy
[3] Additional returns from co-produced liquids

10. Conclusion

Methane expander liquefaction processes offer some fundamental advantages in project returns, operability, logistics, safety and reduction in plant complexity. The level of engineering performed during the CB&I development has now demonstrated the commercial readiness of the ZR process. Quality data is now available to allow detailed assessment of ZR-LNG for project opportunities.

REFERENCES

[1] Lessons Learnt of China LNG Projects. Habibie Razak Black & Veatch April 2013
[2] Songhurst Floating Liquefaction Oxford Institute for Energy Studies Nov 2016