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Title: Dual Expander Methane Cycle Liquefaction Technology Applied to FLNG

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Abstract: The Gasconsult ZR-LNG™ LNG liquefaction technology, deploying a patented dual methane expander refrigeration configuration, provides an improvement in project returns and safety for single train natural gas liquefaction capacities in the range 0.2 – 2.0 million tonnes/y of LNG.

The ZR-LNG™ process is characterised by a simple flowscheme, low equipment count, low energy requirement, and absence of liquid hydrocarbon refrigerants. It has special relevance for FLNG applications.

Capital cost savings and enhanced production capacity are expected against the dual expander nitrogen and single mixed refrigerant systems. The process has a power requirement of typically 270 – 330 kWh/tonne of LNG - significantly lower than alternative mid-scale processes, and only marginally inferior to large-scale base load plants. The technology achieves this without enhancements such as feed pre-cooling and other process nuances often used with alternative technologies as a means of improving energy performance.

Dual Expander Methane Cycle Liquefaction Technology Applied to FLNG

1 Introduction

Gasconsult Limited has developed and patented a new LNG liquefaction technology termed ZR-LNG™ (Zero Refrigerant LNG). The technology uses a dual methane expander refrigeration configuration which provides high energy efficiency, low carbon emissions and low capital cost. It is an advance on existing methane expander cycles deployed on numerous US LNG peaking plants and the various nitrogen cycle and single mixed refrigerant (SMR) processes proposed for mid-scale applications.

The process was originally conceived in the mid 2000s with the key objectives of developing a simple, low cost and energy efficient liquefaction cycle suited to mid-scale operation. Extensive engineering development was completed on early versions of the technology for a 1 million tonnes/y modular train for floating LNG (FLNG) application. Design development has subsequently seen a reduction in complexity, total elimination of liquid hydrocarbon refrigerants and a reduction in capital cost. A compressor power demand of 300kWh/tonne with 20°C cooled temperature is achieved at a liquefaction unit capital cost (excluding gas pre-treatment) in the range $130-150 per annual tonne of capacity for modularised units in FLNG application. The low power demand is achieved without the complexity of feed gas pre-cooling or other process nuances; providing an intrinsic simplicity to the system. It permits greater LNG production from a given gas turbine driver, substantially enhancing project returns.

2 Scale and Design Perspectives for LNG Liquefaction Technologies

Base load LNG production is taking place in ever larger capacity plants. Single train LNG outputs of 7.8 million tonnes/y have been installed in Qatar. These large plants are characterized by a high degree of complexity to maximise energy efficiency, enhance co-product value realisation and improve on-line availability. They carry the knock-on burdens of limited vendor competition for large high value equipment components, high capital cost and extended project schedules. A further factor impacting the application of these mega-scale trains is the requirement for a world class gas reserve, possibly in excess of 20 trillion cubic feet (TCF); required to sustain multiple train plants for up to 25 years.

So-called mid-scale LNG for exploitation of the numerous smaller discovered gas fields with reserves of around 1 TCF has been a discussion point for a decade or more. Of necessity these smaller gas prospects require lower capacity and lower capital cost plants than current base load schemes if they are to be monetised. Despite initial interest in the mid-scale sector little materialised, particularly in respect of FLNG. Strong interest is only now resurfacing.

A feature of FLNG designs is a marked preference by certain operators for elimination of liquid hydrocarbon refrigerants. Higher molecular weight hydrocarbons, particularly propane, are extremely hazardous and represent an explosion/fire risk when accumulating in confined spaces. For safety reasons a level of support has thus developed for nitrogen expander processes for FLNG applications.

Power consumption for nitrogen cycles is typically 30-50% higher than for mixed refrigerant processes, and the inherent large gas recirculation rates also lead to large line sizes and heavy plant. These factors disadvantage nitrogen cycle schemes particularly for higher plant capacities. Arguments have been made that the low energy efficiency is affordable with a low cost energy source like stranded gas[1]. However there are compelling arguments for pursuing high process efficiency, particularly if an intrinsically simple configuration can be maintained. Lower power consumption increases plant capacity and project NPV from equivalently powered compression equipment and reduces associated CO_2 emissions per unit of LNG production.

3 ZR-LNG™ Technology

The need to reduce the power demand for an expander based process while preserving the safety and simplicity of the nitrogen cycle led to the development of the ZR-LNG™ process.

3.1 Process Scheme

In this process the refrigerant is methane derived from the feed natural gas. A net liquefaction unit drive power of 300 kWh/tonne of LNG with 20°C cooled temperature is achieved; depending on the feedstock composition, pressure and ambient conditions. This low power demand is achieved without the complexity and cost arising from feed gas pre-cooling. A schematic of the process is shown in Fig 1.

Liquefaction is achieved through the use of two separate expander refrigeration circuits indicated in red and blue. Typically 35% of the compression power requirement to operate the process is recovered through the gas phase expanders. A further reduction in power demand is effected by a turbine on the liquid product run down to storage.

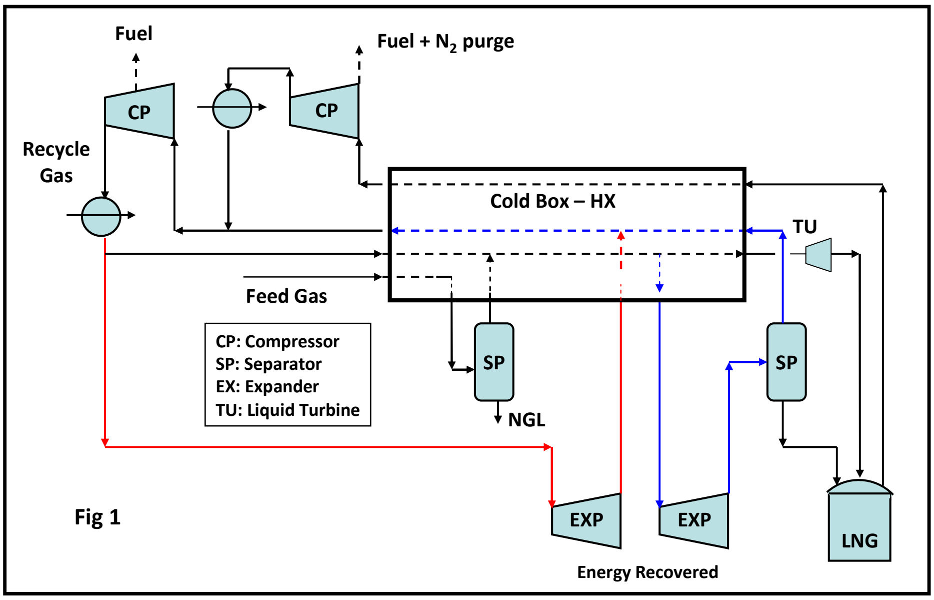

Fig 1

With its low energy consumption and low capital cost, the process is suitable for both onshore and offshore application up to a capacity of 2 million tonnes/y per train and can operate on a full range of hydrocarbon gases.

The technology encapsulates simplicity; a 1 million tonnes/y plant comprises only 2 compressor packages plus 8 major equipment items. The cold box needs only three passages (or four when pre-condensation of NGLs is necessary); and all passages in the heat exchange cores have vapour phase feeds. As the process has no external cryogenic refrigerant cycle and no liquid or nitrogen top-up system, equipment items are eliminated, together with associated bulk materials, fabrication and construction. The focus on simplicity achieves a significant reduction in capital cost relative to SMR cycles – in the order of 30%.

Further all major equipment in this mid-scale size range including drivers, compressors, expanders and the plate fin heat exchanger can be competitively bid and sourced from multiple vendors, avoiding a procurement issue faced by certain large base load technologies. This reduces capital cost and schedule.

Two main factors contribute to ZR-LNG™'s other key attribute; its significantly lower power requirement relative to nitrogen cycles. The main contributing factor is the higher molar specific heat and lower molar compression power requirement of methane. This yields lower recycle flow rates and attendant lower power demand. A second factor is that liquefaction of part of the feed gas occurs in the liquefying expander, converting latent heat directly into mechanical work.

Gasconsult has quantified the benefits of the above factors. Typical dual expander nitrogen cycle configurations were evaluated on the same basis as ZR-LNG™ with respect to ambient conditions, machine efficiencies, loop pressure drops, heat exchanger temperature approaches and heat in-leakage. HYSYS simulations indicate the ZR-LNG™ process has up to 30% lower suction compressor volumes and over 20% lower aggregate machine kW than the dual nitrogen expander schemes.

3.2 Process Flexibility

Simulation work using HYSYS has been carried out on both lean gas feeds and feeds containing over 7.5% C_2+. The impact of varying gas compositions on process efficiency was found to be limited.

Consideration has also been given to the impact of nitrogen in the feed gas because of its potential to build up in the recirculating flows, causing a potential increase in power consumption. Most natural gas feeds contain less than 2% nitrogen. Simulations with up to 5% nitrogen in the feed resulted in an increase in specific power demand of approximately 10%.

Given early work was centred on FLNG application of the technology in the North Sea design excursions have also been run to reflect the impact of higher cooling water temperatures as might be experienced in the Middle East and Asia. The impact of varying 'cooled to' temperatures is reflected in Fig 2. This shows little difference in impact of this parameter between ZR-LNG™ and SMR or nitrogen cycle schemes.

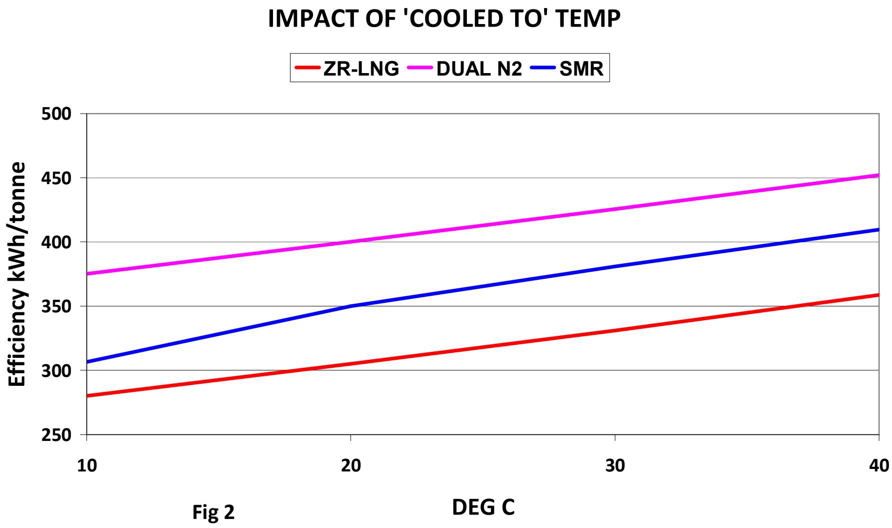

Fig 2

3.3 Applicability to FLNG Projects

FLNG schemes draw experience and expertise from conventional onshore LNG plants, LNG shipping/marine facilities and floating production storage and offloading (FPSO) operations, the latter a well established technology for offshore oil recovery. There are many technical challenges in establishing a safe, high availability and viable design for offshore liquefaction, product storage and transfer. A consensus exists that FLNG is technically more challenging than FPSO.

The technical issues include:

- Product containment system and impact of sloshing
- Equipment spacing, plant layout and location of living quarters
- Selection of liquefaction process and extent of liquid hydrocarbon refrigerant
- Tandem or side by side product transfer
- Impact of ships motion on processing operations

It is beyond the scope of this paper to discuss all these issues. However it is well recorded that nitrogen cycle plants have specific advantages in addressing certain safety and operability issues. Firstly the nitrogen process does not use a liquid hydrocarbon as the refrigerant medium. There is therefore no additional inventory of high molecular weight liquid hydrocarbons with attendant risk of fire/explosion in the event of leakage. On a floating facility with constrained escape options this is deemed by many operators to be a decisive factor in selecting the liquefaction technology. A second factor is that the nitrogen cycle is a single phase process and is unaffected by vessel motions. By contrast, in SMR processes, the refrigerant undergoes evaporation in the system heat exchanger, creating a two phase flow which may be motion sensitive.

The ZR-LNG™ process enjoys the same safety and operational benefits as the nitrogen system. Further it has a superior energy efficiency to both the nitrogen and SMR processes without the cost and complexity of feed gas pre-cooling; reducing weight and required deck space. These attributes make the technology particularly well suited to FLNG applications.

4 Assessment Data

Fig 1 foregoing provides the basic flow scheme applicable to a nominal 1 million tonnes/y FLNG train.

4.1 One Million tonnes/y FLNG Modular Train

The Basis of Design applicable to the presented assessment data is recorded in Table 1.

TABLE 1	**BASIS OF DESIGN**
Gas Composition Mol %:	CH_4 95%; C_2H_6 4%; C_3H_8 1%
Gas Pressure at liquefaction inlet	60 bar g
Sea Water Temperature	13 deg C
Indirect cooling - Sea Water/Circ Water	3°C approach
Process Streams cooled to	20 deg C
Heat Leak to Cold Box	0.50%
Minimum cryogenic approach temp	3 deg C
Recycle gas compressor polytropic η	85%
Expander adiabatic η	87%

The related power demands are recorded in Table 2. The power consumption of 304 kWh/tonne is achieved by the process in its basic form; and with no feed gas pre-cooling. Compressor and expander efficiency data was sourced from proven vendors against detailed equipment specifications.

An associated gas stream containing >7.5% C_2+ was also modeled and produced a virtually identical outcome in terms of process efficiency.

TABLE 2	**BASIC OPERATING PARAMETERS**
On line factor	345 days per year
Flow rate	121 tonnes per hour
Main recycle compressor power demand	54.7MWe
Flash gas compressor power demand	3.4MWe
Total Power	58.1MWe
Expander Power Recovered to process	21.4MWe
Net Power	36.7MWe
kWh/tonne of product	304

The cost estimate using pre-fabricated liquefaction modules for FLNG application is provided in Table 3. This estimate, based on vendor quotations against fully detailed equipment specifications, covers an EPIC work scope and is provided on a 2013 instant execution basis. It relates to the liquefaction unit only and excludes the vessel, feed gas purification, NGL fractionation, utilities, LNG/NGL storage, flare and owners costs.

TABLE 3 – 1 million tonnes/y train	**CAPEX ESTIMATE 2013 US$ Mil**
Equipment Supply + Spares	62.8
Bulks Supply	14.8
Installation/Construction/Fabrication	18.9
Transportation	1.9
PLANT TOTAL	**98.4**
Licence Fee/Insurance/Certification	6.0
Project Management/Engineering/Commissioning	28.1
TOTAL ENGINEERING + FEES	**34.1**
CONTINGENCY	**19.9**
TOTAL	**152.4**

Having completed work on the nominal 1 million tonnes/y scheme discussions were held with a number of industry players. A regular, though not unanimous feedback, was that project viability was greatly enhanced at higher plant capacities; some suggesting that 4 million tonnes/y was a minimum plant size required to secure acceptable project returns. Gasconsult thus entered further discussions with vendors and with their support configured a nominal 2 million tonnes/y train. The cost estimate for this is provided in Table 4. The Basis of Design and Scope of Work was prepared on the same basis as above.

TABLE 4 - 2 Million tonnes/y train	CAPEX ESTIMATE 2013 US$ Mil
Equipment Supply + Spares	107.3
Bulks Supply	25.3
Installation/Construction/Fabrication	32.2
Transportation	3.2
PLANT TOTAL	**168.0**
Licence Fee/Insurance/Certification	11.5
Project Management/Engineering/Commissioning	48.1
TOTAL ENGINEERING + FEES	**59.6**
CONTINGENCY	**34.1**
TOTAL	**261.7**

4.2 Comparison with other Mid-Scale Technologies

ZR-LNG™ was never envisaged to compete with large land based base load plants of the type constructed in Qatar, Oman, SE Asia and Australia. The bench mark technologies were always considered the generic SMR and dual nitrogen expander processes and their several commercially promoted variants. On a like for like plant capacity and Basis of Design (Table 1), Table 5 details the relative capital costs and power consumptions for the liquefaction units only. The SMR and dual expander nitrogen process data has been secured from literature searches and reports the most competitive data from the range found.

TABLE 5 - SYSTEM	LICENSOR/OWNER	ENERGY USE kWhr/TONNE	RELATIVE CAPEX	RELATIVE CO_2 EMISSIONS
ZR-LNG™	Gasconsult	304	100	0.16kg/kg LNG
Nitrogen Expander	Numerous	400[3]	115	0.21kg/kg LNG
SMR	Numerous	350[4]	150	0.18kg/kg LNG

5 Process Selection and Impact on Project Returns

Specific power consumption is an important consideration in liquefaction technology evaluation, resulting in an increase in overall gas consumption (fuel + feedstock) of 2-3% at the lower end of the efficiency spectrum. In a stranded gas cost environment differences in process efficiency as measured by fuel cost may be of marginal overall significance. High efficiency is more significant in a high gas cost environment; or for financially challenged projects requiring a low cost development strategy i.e. utilising the efficiency advantage to enable installation of smaller, lower capital cost compression/driver equipment and its reduced quantum of associated bulk materials and fabrication.

More relevantly however LNG projects bear high costs from the overall system. In the case of FLNG this includes the cost of other topsides including gas processing and utility modules plus a hull and product storage. From a project return and capital efficiency perspective there is considerable benefit in securing maximum output from the compressor driver, the normal capacity limiting equipment item for liquefaction configurations. It is in this area, arising from its high energy efficiency, that ZR-LNG™ demonstrates its most compelling commercial advantage.

All things being equal (e.g. compressor/driver efficiency and an overall economically matched process equipment configuration) the capacity output from a ZR-LNG™ scheme will realise a higher plant capacity for an equivalent installed compression power than either SMR or dual expander nitrogen schemes. This higher throughput translates into higher cash flows which are particularly beneficial in the early years of a project to its lifetime returns as measured by NPV or IRR.

Assuming, for example, an output of 35.5MW from a GE LM6000 turbine at 20°C, (after allowing for inlet/outlet losses, compressor fouling, turbine aging and 4% API guarantee margin)[2] Table 6 depicts the LNG production from the candidate technologies for a 2 million tonnes/y plant comprising 2 x nominal 1 million tonnes/y liquefaction trains with a common nominal 2 million tonnes/y gas processing system. The assumption was a fully integrated project including the upstream gas field development. The following values were conditioned to reflect differences between the technologies as presented in Table 6:

a) Adjustments (reductions) to the capital costs of the SMR and nitrogen expander schemes to reflect their lower gas processing capacities
b) Adjustments (increase in cost) to reflect the additional complexity and higher equipment count of the SMR liquefaction scheme
c) Adjustments to reflect the higher on-line availability of expander based processes based on their lack of complexity and faster start-up (expected 6 vs 24 hours for SMR).

It is recognised that the adjustments per a) and b) are minor in the context of the overall estimate of cost. They reflect small but real differences between large numbers in the overall estimate, which given the relative lack of history on FLNG projects may in themselves contain a considerable measure of uncertainty. For the purposes of comparing the liquefaction technologies however the adjustments provide a level playing field.

TABLE 6 - 2 x Nominal 1 million tonnes/y FLNG	ZR-LNG™	SMR	Dual Nitrogen Exp
Field Development $ millions	500	500	500
Hull + Topsides $ millions	1306	1391	1306
Base Capex $ millions	1806	1891	1806
Gas Processing delta $ millions	0	-7	-20
Net Capex $ millions	1806	1884	1786
Nominal kWh/tonne	304	350[4]	400[3]
Output tonnes/y from 2 x LM6000 at 35.5MW	1,934,000	1,655,000	1,470,000
Field Life - Years	20	24	27
On-line availability - days/year	345	340	345

Based on the above, project NPVs were calculated for a 2 TCF field. The calculations assume exhaustion of the gas reserve on a constant output basis throughout its life, probably an unlikely occurrence unless later phase inlet compression equipment is installed. However in respect of process comparison the assumption provides a like for like scenario.

Calculations were based on the following parameters:

- a debt:equity ratio of 70:30
- loan interest rate of 8%
- discount rate 15%
- loan repayment period 7 years
- depreciation rate 5%
- tax rate 30%
- gas sales price of $10/million BTU (EU basis)
- shipping cost to market $2/million BTU
- interest during construction capitalised
- O&M costs reflecting western norms

The outcome, showing cumulative NPV15 is shown in Figure 3. It is clear that the major impact on project returns is the relative process efficiencies of the liquefaction technologies. For a given installed compression power the more efficient the process the greater the plant capacity and the greater the early phase revenues which enhance the project NPV and IRR. Further, the higher capacity ZR-LNG^{TM} scheme earns its full project return as measured by NPV in a shorter time period. For FLNG applications financial returns would be further advantaged by earlier re-deployment of the floating facility to another stranded gas opportunity.

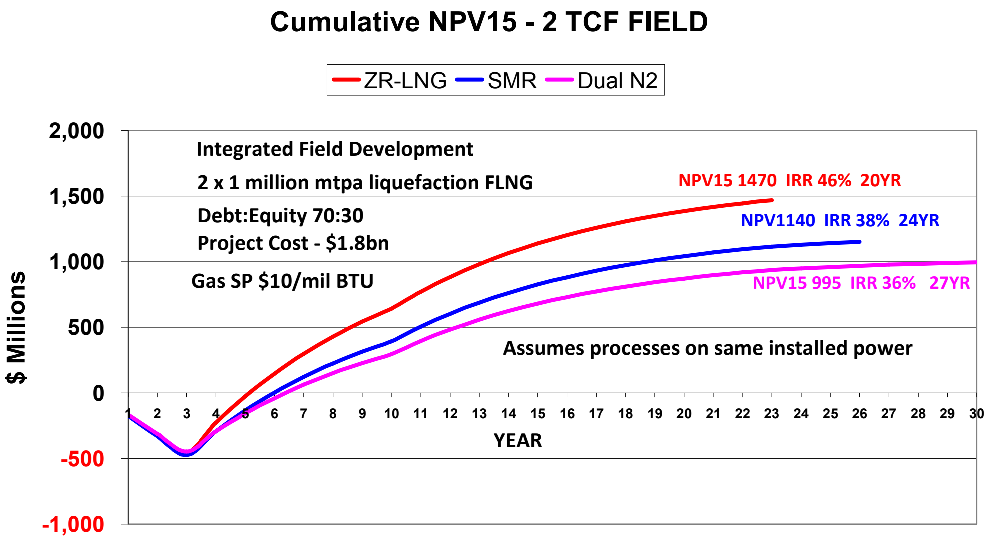

Fig 3

It is clear that process efficiency can be increased at the cost of additional complexity and increased capital (feed gas pre-cooling, use of cold deep seawater cooling etc). Some argue[5] that plant capacity, which drives the returns, is a capital cost issue and could be increased by selecting multiple drivers or a driver with more power output (e.g. a Rolls-Royce Trent instead of an LM6000). Such possibilities would clearly be evaluated at a project's feasibility phase, along with overall system efficiency. They are beyond the scope of this paper, whose purpose is to evaluate the liquefaction technologies on a level playing field. In regard to improved efficiency or increased capacity however, these process options are available to the benefit of all the reference technologies and the intrinsically higher efficiency process would always retain its inherent advantage in terms of project financial returns. Further in the case of FLNG applications in particular, physical constraints arising from available deck space may be an inhibiting factor in respect of chasing incremental efficiency or capacity through the use of larger/multiple equipment items or more complex configurations.

6 Conclusions

The ZR-LNG™ process is positioned as a simpler, lower capital cost and more energy efficient process than both nitrogen expander cycles and SMR schemes in the mid-scale single train capacity range up to 2 million tonnes/y. The significant reduction in complexity and cost is achieved with a quite limited sacrifice of energy efficiency compared to existing base load plants. Relative to the SMR and dual expander nitrogen processes ZR-LNG™ represents a step change improvement in project economics when measured on the basis of extracting maximum output from an installed quantum of refrigeration compression power. This technology development also repositions expander technology; widening its application envelope to both larger capacity and higher gas cost schemes.

The ZR-LNG™ economic advantages are secured whilst preserving the well established operational benefits of nitrogen cycles for FLNG applications. These include safety through the elimination of liquid hydrocarbon refrigerants, tolerance to ships motion with its impact on multi-phase flows, rapid start-up and reduced flaring.

The technology is also an excellent fit for expansions at existing LNG production facilities looking for a low cost, small footprint and short schedule project to take advantage of an existing surplus of gas processing capacity.

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