Selecting offshore LNG processes

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The authors consider the crieria for selection of the technology for offshore floating LNG production, and review natural gas liquefaction cycles. The single and dual expander processes, although lower in efficiency than alternatives, appear most suitable because of their greater compactness, ease of operation, and safety.

As LNG production capacity continues to grow and the value of natural gas remains high, the impetus to monetise non-traditional gas resources also grows.

Offshore floating LNG production has generated interest because it offers the potential to avoid flaring or reinjection of associated gas and to monetise smaller or remote fields of non-associated gas.

With the realisation of large floating production, storage, and off-loading (FPSO) facilities for oil production and more recently LPG production, an LNG FPSO project appears to be increasingly more likely in the future.

Offshore natural gas liquefaction has different process requirements to the traditional on-land baseload plants. While thermodynamic efficiency is arguably the most important process selection criteria for large onshore natural gas liquefiers, other factors become more important for offshore projects.

Thermodynamic efficiency is likely to remain critically important. However, for offshore applications criteria such as compactness and process safety become more significant considerations. The high efficiency pre-cooled mixed refrigerant cycles that dominate onshore LNG installations will likely not meet the needs of the future mobile and offshore liquefaction projects.

The authors review natural gas liquefaction cycles in the context of compactness, ease of operation, process safety, and efficiency for offshore liquefaction. Particular attention is paid to the lower-efficiency single and dual expander processes.

These cycles offer several advantages over traditional cascade and mixed refrigerant (MR) liquefiers for offshore, onboard and mobile applications. The authors share their insights gained through their design and operating experience on small-scale N2 cycle LNG plants and marginal field developments.

Global LNG developments

LNG trade in 2004 was approximately 131 million tonnes per annum (MTPA) and is expected to increase by about 50 percent to more than 190MTPA in 2010 [1]. As of October 2005, there were a total of 19 liquefaction facilities in operation worldwide with a total of 69 trains, including three new trains at Atlantic LNG in Trinidad, Egypt LNG and Woodside Petroleum in Australia respectively, and a combined production capacity of more than 150 MTPA.

China's first LNG receiving terminal (3.3 MTPA) in Guangdong is scheduled for completion in 2006/2007. India now has two LNG receiving terminals in operation, at Dahej, and Hazira, with a combined import capacity of 10.0 MTPA, and more are planned [3].

The US is re-emerging as a large LNG importer. With one new offshore receiving terminal opened this year, the US now has five import terminals on the Atlantic and Gulf coasts with a combined capacity of 25 MTPA.

Receiving capacity is expected to increase dramatically in the next five years with four or five (of the over two dozen proposed) new LNG receiving terminals expected to be constructed on the Atlantic and Gulf coasts from 2007 through 2010 to meet LNG imports projected to increase nearly 60 percent during that period [4]. Import terminals are also planned on the West Coast to support high demand in California and along the Mexican boarder.

Traditional onshore liquefaction

The logical starting point for any new LNG production scheme should be the existing industry and processes. The baseload LNG industry now has more than 40 years of history starting with permanent operations of the Camel plant in Algeria in 1964.

The earliest plants consisted of fairly simple liquefaction processes based on either cascaded refrigeration or single mixed refrigerant processes and train capacities were less than 1 MTPA.

In 1972 Brunei Lumut 1 utilised the first two-cycle process using a propane pre-cooled mixed refrigerant (C3MR) developed by Air Products and Chemicals Int. (APCI). This process became the dominant liquefaction process technology by the late 1970s and continues to be the workhorse of the LNG industry today.

During this period APCI and others have made significant improvements on the original C3MR process. Economies of scale, improved process simulation tools, and improved equipment performance (i.e. liquid expanders and gas turbine drivers) have all dramatically decreased installed liquefaction plant costs, improved performance, and increased the capacity of liquefaction trains.

The continued development of traditional LNG plant design can be seen by comparing recently commissioned plants to current and planned facilities.

Less than five years ago Foster Wheeler and Chiyoda Corp. of Japan completed the engineering, procurement and construction (EPC) contract for Oman LNG.

At the time of start-up (February 2000 for Train 2), this plant had the largest trains in operation at 3.3 MTPA and set a benchmark for process efficiency with a reported average specific power of 10.15 kW per tonne per day of LNG [5]. Five years later, installed train capacities are over 5 MTPA with projects in development for 7.8 MTPA.

The liquefaction process typically accounts for 30-40 percent of the capital of the overall plant [6] and has a large impact on utilities and operating costs. Selection of the appropriate cycle is critical to cost-effective LNG projects.

Historically, liquefaction cycle selection was an easy choice to make: the APCI C3MR. Table 1 shows the baseload liquefaction trains currently operating, in various stages of construction, and planned (in the case of AP-X).

The table illustrates two key points: first, the APCI C3MR process dominates the industry; secondly there has been a considerable diversification of liquefaction processes in the last five to seven years. This increased competition has led to increased train capacity, improved driver integration, and decreased capital costs.

Liquefaction Process Nov-04	Licensor	Number of Trains Running	 Constr.	 Planned	Startup Year	% of Market
Propane Precooled MR	**APCI**	**55**	**9**	**?**	**1972**	**77%**
Optimised Cascade	Conoco-Phillips	3	4	?	1999	9%
Single Refrigerant MR	APCI	4	-	-	1970s	5%
Classic Cascade	Marathon/Phillips	1	-	-	1969	1%
Teal Dual Pressure MR		1	-	-		1%
Prico Single Stage MR	Black & Veatch	2	-	-		2%
MR Processes (C3MR & Dual -MR)	Shell	-	3	?	2005	4%
Multifluid Cascade	Linde-Statoil	-	1	?	2006	1%
AP-X Process	APCI	-	-	3 (4)	2007/2008	0%

Note : % of Market based on percentage of total trains running and under construction

Table 1. LNG trains by liquefaction process (References [6], [18], [19])

Four trains of APCI's new AP-X liquefaction process are planned in Qatar for Qatargas II trains 4 and 5 and RasGas II trains 6 and 7.

These planned plants represent the state-of-the-art in land-based liquefaction featuring single train liquefaction capacities of 7.8 MTPA using an N2 expander cycle to affect the sub-cooling of the LNG.

State of development for FPSO

The use of floating production systems within the offshore oil and gas industry is maturing technology with more than 119 currently operating Floating Production Storage and Offloading (FPSOs) and Floating Production Systems (FPSs) , a further 22 under construction or conversion, and 139 prospects were being considered [7].

The offshore market is dominated by FPSO facilities with more FPSO deployments worldwide than all the other floating production systems put together (Spars, Tension Leg Platforms and Semi-Submersibles) [8].

These FPSO production systems range from Aframax-based systems processing - 30,000 barrels per day (BPD) of crude to ULCC (Ultra Large Crude Carrier) based systems processing 200,000 BPD of crude.

The use of FPSOs provides a number of benefits as the production facility also provides storage for the crude. This eliminates the requirement for local infrastructure to transport the crude to shore.

The floating production industry has recently moved to processing gas and condensate as well as crude. Traditionally, associated gas has been re-injected and remote gas reserves were left untapped due to the difficulty in delivering gaseous (low energy density) products to market.

How can we benefit from the associated gas or stranded gas reserves? This challenge has led to the development of LPG FPSOs such as the Sanha for Chevron situated offshore Angola. This project helps to eliminate routine flaring and provides marketable products, but still requires residue gas to be re-injected.

Floating offshore LNG production offers the potential to avoid such re-injection and captures the other benefits associated with crude installations. It eliminates the need for infrastructure and provides storage to enable LNG carriers to be utilised to transfer the product to market.

This concept is now being studied by numerous organisations such as Royal Dutch Shell with their Floating LNG

(FLNG) and Floating Oil and Natural Gas (FONG) concepts for processing gas and associated gas respectively [9]. The floating production concept has not yet been extended to LNG production offshore but Foster Wheeler and others are prepared to engineer such projects [10], [11].

Different floating LNG production process selection criteria have long been recognised with early studies on the topic occurring over 25 years ago [12]. N2 expander cycles for offshore liquefaction were discussed and studied by Foster Wheeler and others in the 1980s [13].

During the 20 years since initial conceptual design, the development of hydrocarbon processing on FPSOs has matured with several production facilities currently operating in a variety of environments and configurations.

Offshore liquefaction process criteria

Offshore liquefaction facilities have different technology selection criteria than their onshore counterparts leading to different optimal processes.

Offshore facilities must be compact, light, and offer high inherent process safety. They must also consider the additional constraints placed on the system in the marine environment such as vessel motion and offer a high degree of modularity, ease of operation, low equipment count, quick start-up, and high availability.

Additionally, because FPSOs will be processing gas from marginal fields they must be tolerant of a variety of process conditions and have a high degree of inherent process robustness. High process efficiency remains an important selection criterion because, even with inexpensive feed gas, poor efficiency must be paid for with increased utilities, compressor capacity, and other major capital expenditure items.

The technology in use on existing FPSOs such as turbines, compressors, towers and separators has already set the groundwork for installing machinery on floating facilities. This development over the past 20 years allows the step to be taken to offshore LNG with a large number of already proven components.

Other factors that must be considered are LNG storage and offloading. The transport in LNG carriers is well established. However partial fill conditions in the LNG FPSO will occur as the LNG is being processed prior to offtake.

This may result in sloshing, which is of particular concern in membrane tanks. The consideration of loss of containment must also be addressed when considering hull fabrication.

The use of concrete for the hull provides benefits in the storage of cryogenic fluids as it retains its structural integrity when in contact with the LNG; however, this must be measured against potential cost reductions if traditional steel ship designs could be utilised.

If offloading is considered with a typical spread-moored configuration such as might be found offshore West Africa, then side-by-side offloading could be considered. This provides the benefit in that typically LNG carriers load at midships - therefore providing more flexibility.

However in less benign seas, weathervaning configurations are often used, possibly with tandem offloading being required. To facilitate this a number of technology suppliers have looked at flexible loading arms for transfer of LNG between the production vessel and the tanker such as the SBM soft yoke mooring and offloading (SYMO) system.

These factors have all been examined in various studies such as Project Azure and the Shell development work on FLNG and FONG [14],[9].

Expander processes

The process criteria outlined in the previous section suggest that gas turbo-expander based processes are well suited for offshore liquefaction. A simple expander refrigeration cycle, the reverse-Brayton, is shown in Figure 1.

While this process has been used to liquefy natural gas it has low efficiency because a gas with uniform flowrate through the cycle cannot closely match the cooling requirements in the process gas.

The working fluid in the refrigeration system, typically N2, is compressed in the main compressor with Stream 1 as its discharge. The heat is rejected from the cycle to the environment as the heat of compression in the after-cooler prior to a second stage of compression in the compressor loading the turbo-expander. The Stream 3 has the highest pressure developed in the cycle. Stream 3 then flows through a second after-cooler to reject additional heat to the environment. Next, Stream 4 enters the recuperative heat exchanger where the refrigerant is cooled to well below ambient temperature. After leaving the heat exchanger, the cooled gas undergoes an isentropic expansion in the turbo-expander, which causes a large temperature drop in the refrigerant and produces shaft work. The lower pressure cold refrigerant in Stream 6 is warmed in the recuperative heat exchanger with simultaneous pre-cooling of the incoming high-pressure N2 refrigerant and removal of the sensible and latent heat in the process stream producing LNG. The warm, low-pressure refrigerant in Stream 7 is then recompressed in the primary compressor to complete the refrigeration cycle.

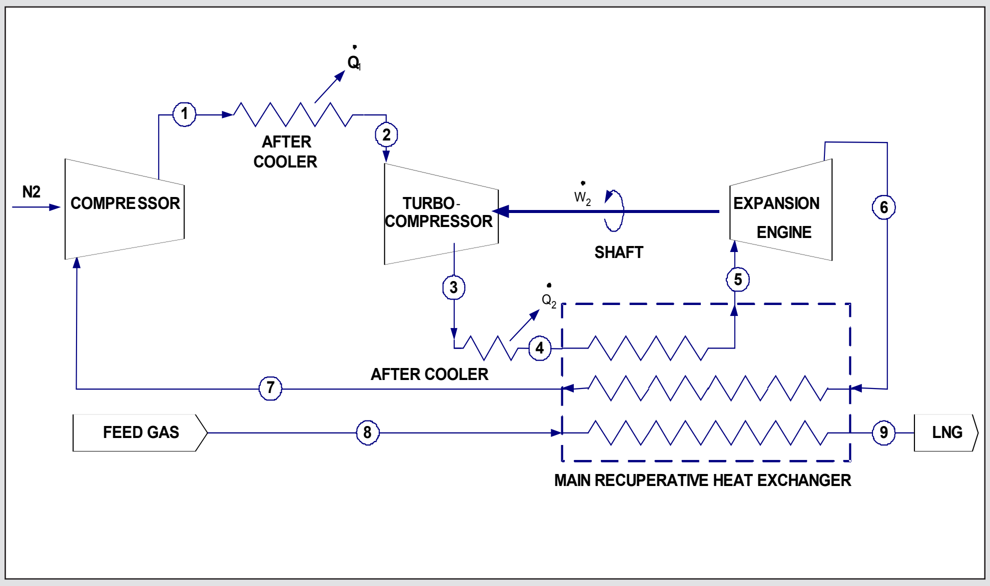

Figure 1. Modified-Brayton cycle refrigerator.

Several variations on a single expander reverse-Brayton cycle may improve efficiency significantly [15]. These variations include using two expanders (with or without the same working fluid), pre-cooling the feed gas with a MR or propane chiller, and expanding a saturated LNG product in controlled stages.

Comparing Conventional to Expander Processes

All large-scale LNG production processes use either an MR or pure component cascaded refrigeration cycle. Expander cycles use all gas (or mostly gas) refrigerants and offer lower efficiency but many benefits for offshore liquefaction. The following compares how each of the offshore process selection criteria is satisfied by traditional baseload and turboexpander liquefaction cycles.

<u>Compact and Light:</u>

The lack of compactness for the MR cycles is potentially their largest disadvantage. MR cycle liquefiers require extensive plot space for refrigerant storage and management.

Two-way, two-phase flow requires specific equipment (heat exchanger) and piping layout. The flammable nature of the refrigerant also places additional constraints on process and piping layout, offset distances, and restricted area classifications to ensure adequate process safety and code compliance.

Using dual mixed refrigerant processes may be acceptable for offshore liquefaction as seen in concepts using either Shell or APCI processes [14].

Expander cycles using N2 as the refrigerant have the potential to be extremely compact because they feature:

- All gas service so there is no large refrigerant storage and management system, decreasing plot requirements and weight
- Decreased offset distances because the refrigerant is non-flammable and places fewer constraints on equipment positioning
- Most of the surface area is dedicated to gas-gas service with flexible orientation. Heat exchanger cores can be arranged as needed. This allows the design of conformal coldboxes and modularized plant layout.

Note that although the refrigerant circulation rate and main heat exchanger duty are significantly decreased in expander cycles, the required heat transfer surface may not decrease because the refrigerant heat transfer coefficient is also much lower.

<u>High inherent safety</u>

The LNG industry has built an excellent safety record that must continue to be aggressively protected as existing plants age and novel processes and production schemes are commercialised.

Transitioning established MR processes to offshore production facilities has an advantage in that their risks and hazards are well understood, documented and mitigated.

MR and Cascade processes have large flammable refrigerant inventories, high refrigerant circulation rates through process lines, and extensive overpressure potential and flare requirements. This makes these processes inherently less safe than expander processes.

Expander processes have higher inherent safety because the refrigerant is inert. Recent studies suggest that although MR liquefaction cycles have significantly increased risk, the effect on overall facility risk may be small.

Risk analysis studies completed for project AZURE suggest that the total process risk for the FPSO is not dramatically increased by the large increase in liquefaction process risk associated with a dual mixed refrigerant process [14].

<u>Marine Environment:</u>

Hydraulic design of the liquefaction process should consider the special constraints created by the marine environment. Previous articles have highlighted the impact of moving floating production on various LNG process equipment items [16],[17}. Appropriate design of the process equipment and plant layout can ensure either expander or MR processes are fit for purpose.

Ease of operation, low equipment count, quick start-up:

Turboexpander-based processes have the advantage in all three of these process selection criteria. Turboexpander processes are extremely easy to operate and control.

The high equipment count and start-up time for MR processes is a function of refrigerant management and the inherent properties of the process. The number of storage tanks, separators, valve manifolds, and instruments and controls required to adjust and control the refrigerant charge and composition in the MR processes is high.

Cold production in a turboexpander process is largely independent of the process gas. MR processes are more complicated because refrigerant composition, process pressures and temperatures, and the feed gas conditions are all coupled.

Start-up times may be limited by either thermal shock and equipment cool down times or by non-mechanical issues.

Heat exchangers and piping must be cooled down in a controlled fashion to ensure thermal stresses associated with the change in temperature do not damage the equipment. Non-mechanical issues relate to refrigerant charging and tuning in both processes.

High Efficiency:
There are only incremental improvements to be made in the existing MR cycle liquefiers. They were initially chosen because they offered the highest efficiency and have been refined for the past 30 years. The high efficiency on Oman LNG and other recent plants are a testament to this.

Expander-based processes on the other hand have been steadily improving with advances in plate fin heat exchangers, turbomachinery, and process configuration. Expander cycles shift the key efficiency-determining element of the process from the LNG heat exchanger to the expander.

Expander efficiency is critical to efficient operation as is compressor efficiency and process configuration. Dual-expander processes for LNG liquefaction may be either open art or proprietary and offer the potential to greatly increase efficiency by better matching the natural gas cooling curves. The efficiency of several expander plants is shown in Table 2.

Data from the tables comes from a variety of sources. The Wildwood liquefaction plant is a distributed-scale LNG facility operating near Stockton, California on a single N2 expander cycle.

The plant processes a low-BTU non-associated gas containing about 20% N2 at a feed pressure of 280 psig (19 bar) and produces a 97%+ C1 LNG stream.

A variety of features contribute to the apparent low efficiency. First, the work associated with lower pressure liquefaction and N2 rejection is included in the provided value. Second, initial CAPEX for the project was a key factor.

This supported the choice of an expander process and other decisions that further decreased efficiency, including the use of modular stainless steel heat exchangers. Third, the plant has a small production rate and some equipment is inherently less efficient.

The second N2 expander plant is onboard the LNG Jamal, an LNG carrier built for the Oman LNG project. Kryopak provides details for a "typical", actually operating, single expander plant using the process gas as the working fluid at a capacity of 125 tonnes of LNG per day.

The final two values from an ABB reference are simulated for a dual-expander process using both N2 and flammable refrigerants in separate circuits without and with propane pre-cooling respectively.

Plant	Liquefaction Process	Status	Licensor	Efficiency kW*day/ton	Relative Power
OMAN LNG, Trains 1,2 (*1*)	**C3 Precooled MR**	**Operational**	**APCI**	**12.2**	**100%**
Wildwood LNG Plant (*2*)	Single N_2 expander, closed	Operational	CFS	40.5	332%
LNG Jamal BOG Reliquefier (*3*)	Single Expander, N_2	Built, des. Cap.	-	37.8	310%
Kryopak EXP-Typical (*4*)	Single expander, process fluid	Operational??	KryoPak, Inc.	20.4	167%
Predicted / Patented (*5*)	Dual Expander C1 / N_2	Simulated	ABB	16.5	135%
Predicted / Patented (*5*)	C3 - Dual Expander C1 / N_2	Simulated	ABB	**13.5**	**111%**

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Table 2. Expander plant performance relative to Oman LNG

Table 2 shows a wide range of performance for commercial expander natural gas liquefiers. As in all such comparisons, scrutiny should be paid to what exactly is being measured and how data is reported as they come from various sources. From the table it is fair to say that:

- All expander cycle plants are less efficient than the C3MR benchmark
- Dual-expander processes offer higher efficiency than single expander processes
- Propane pre-cooled dual expander processes may be approaching the efficiencies of state-of-the-art C3MR cycles but have surrendered their inherent advantages of low flammable refrigerant inventory, low equipment count, and simplicity

Regardless of reporting and site specific differences, it is clear that some small expander-based processes have been selected even though they were considerably less efficient than competing technologies.

This is a testament that factors other than efficiency, notably project economics, are ultimately the drivers in project progression. While these projects undertaken to date are relatively specialized, it is apparent that some expander-based processes offer potential for the more general offshore market.

Based on the efficiencies reported by ABB and Kryopak, expander processes may offer adequate efficiency for offshore liquefaction on FPSOs in either single or double expander configurations depending on process specific details.

Conclusions

Consideration of many relevant process selection criteria for onshore and offshore natural gas liquefaction would suggest that expander cycles are better suited to offshore liquefaction on FPSOs than traditional liquid refrigerant processes.

The expander cycle's primary disadvantage remains that it has an inherently lower efficiency than common onshore processes such as C3MR and Cascade processes.

When considering marginal field developments, either onshore or offshore, the use of non-proprietary turbo-expander based processes should be considered because they offer the potential for a compact plant, simple robust operation, lower initial CAPEX, and a high degree of process safety.

Higher operating costs must be considered with other costs for the shorter, less defined marginal project life. The ultimate choice of which process to select will remain dependent on project specific variables and potential development state of novel processes. ■

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