LNG FPSOs - Competing Technologies are Making Progress

David Wood

2nd June 2009

Breakfast Presentation
at Energy Institute, London

Companies Offering Natural Gas Liquefaction Technologies Focused on the LNG FPSO

There are a number of companies offering gas liquefaction technologies, some of these are focused on small-scale boil-off gas and onshore peak shaving plants. Several though have announced developments recently that target deployment on LNG FPSOs. These are:

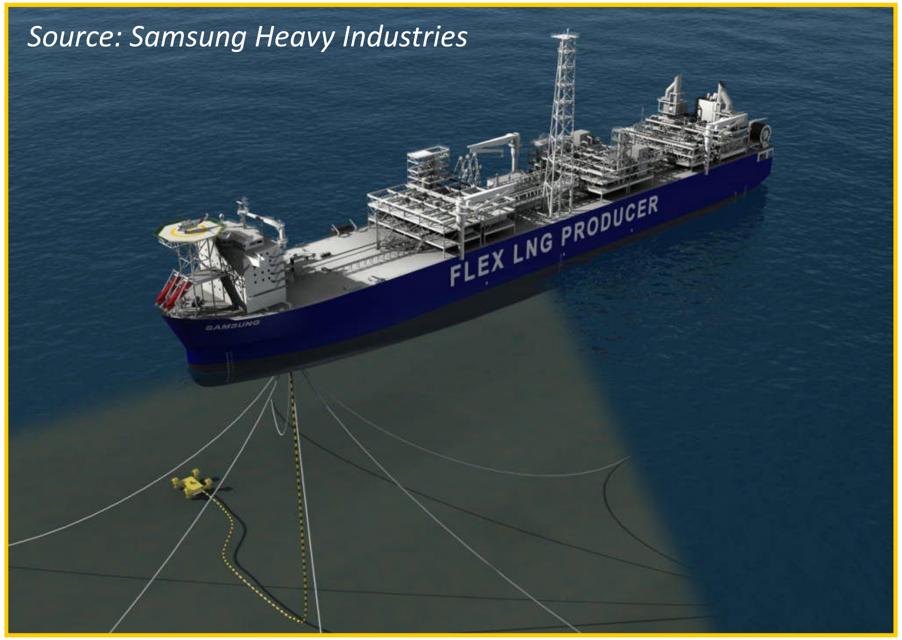
- APCI (Air Products Chemical Industries)
- Black & Veatch
- CB&I (Chicago Bridge & Iron) / Lummus
- Kanfa Aragon
- Linde
- Mustang Engineering

Such technologies developments reflect the interest expressed by several major IOCs, NOCs and independent oil and gas producing companies to deploy LNG FPSOs to develop stranded gas fields around the world.

Floating Gas Liquefaction Plants

FLEX LNG Producer

Four “LNG Producer” hulls, each with a 170,000 m^3 capacity, are on order at Samsung Heavy Industries (SHI) in Korea. These orders were placed from March 2007 to April 2008 for deliveries initially set for Dec 2010 to Mar 2012. To be deployed offshore Nigeria and Papua New Guinea.



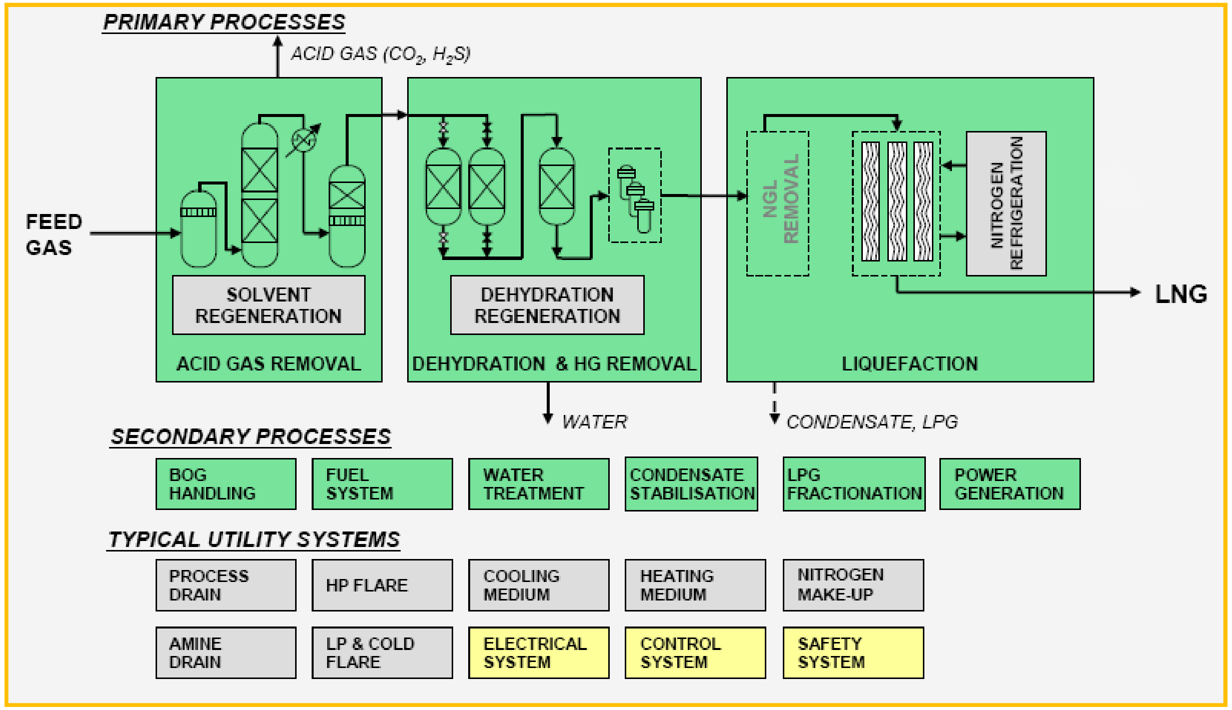
Delivery dates were pushed back 6 to 7 months in January 2009.

pre-FEED and FEED work for field-specific modules applicable to multiple locations is ongoing.

Samsung Heavy Industries Co. Ltd. let a US$200 million contract to Kanfa Aragon AS to develop the LNG topsides in January 2009.

LNG FPSO – Topsides Process Requirements

The natural gas liquefaction process is only a small part of what is required to deliver an FPSO.



Source: Kanfa Aragon, March 2009

Criteria Impacting LNG FPSO Design Agenda: Liquefaction Process Technology Issues

Choice of the liquefaction technology is likely to have implications for the following issues:

- Simplicity of operation (high uptime)
- Systems that would minimize weather-related downtime
- Quick start and shutdown capability
- Process efficiency (over a range of ambient temperature conditions)
- High energy efficiency
- Production rate flexibility
- Capable of handling a wide range of feed gas compositions
- Processing options to recover LPG and NGLs
- Low requirements for handling potentially hazardous refrigerants

David Wood, E&P Magazine (Hart) May 2009

Criteria Impacting LNG FPSO Design Agenda: Marine / Project Engineering Issues

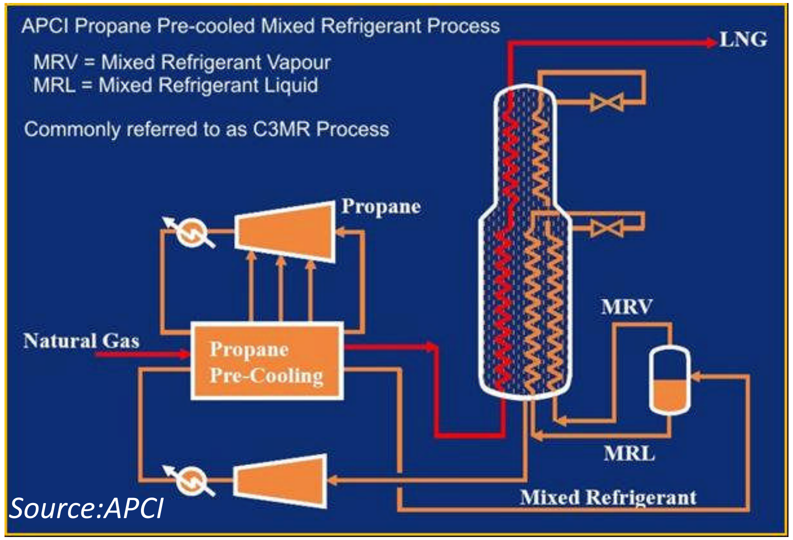
The capacity of an LNG FPSO, in addition to process technology, needs to incorporate the requirements for:

- Process, storage, and offloading safety
- Low weight
- Compactness (to minimize deck area and overall vessel size)
- Low equipment count
- Small operating crew
- Modular design
- Stable decks (robust to vessel motions)
- LNG storage tanks that are unaffected by cargo sloshing impacts
- Facility security

David Wood, E&P Magazine (Hart) May 2009

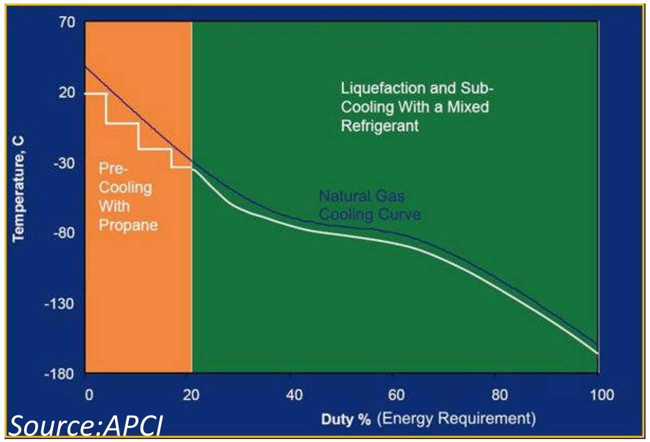
Work-horse of Onshore Liquefaction: Propane Pre-cooled Mixed Refrigerant (C3MR) Process

The pre-cooling cycle uses propane at three or four pressure levels and can cool the process gas down to -40°C. In the mixed-refrigerant cycle, the partially liquefied refrigerant is separated into vapour and liquid streams, which are used to liquefy and sub-cool the process stream cooling from typically -35°C to between -150°C and -160°C.



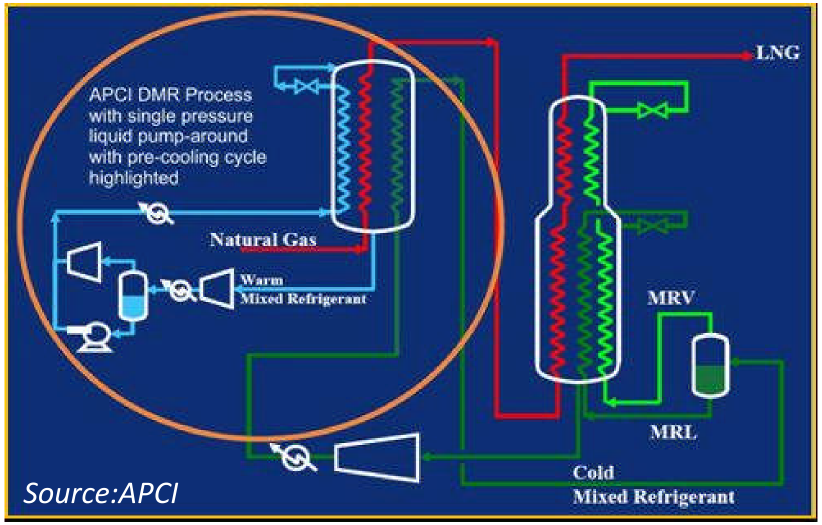
Mark Roberts, APCI Feb 2009

C3MR mixed refrigerant natural gas and refrigerant cooling curves



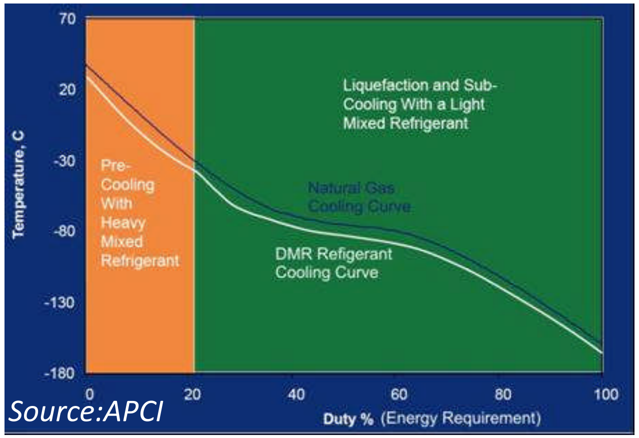
Dual Mixed Refrigerant (DMR) Process

APCI favour their dual mixed refrigerant (DMR) process for offshore deployment , which provides the highest thermal efficiency, but also the greatest equipment count, complexity and multiple refrigerant handling. APCI are also developing new designs which use non-flammable environmentally acceptable refrigerants such as HFC compounds to replace flammable hydrocarbon gases.



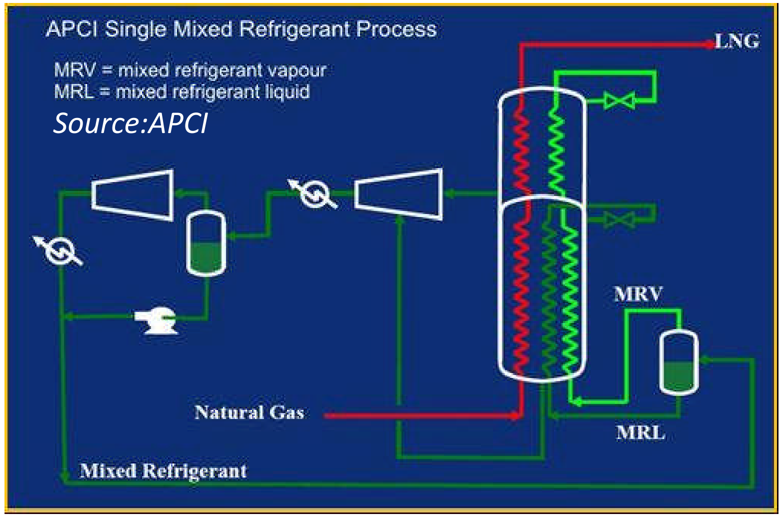
Mark Roberts, APCI Feb 2009

Dual mixed refrigerant (DMR) natural gas and refrigerant cooling curves



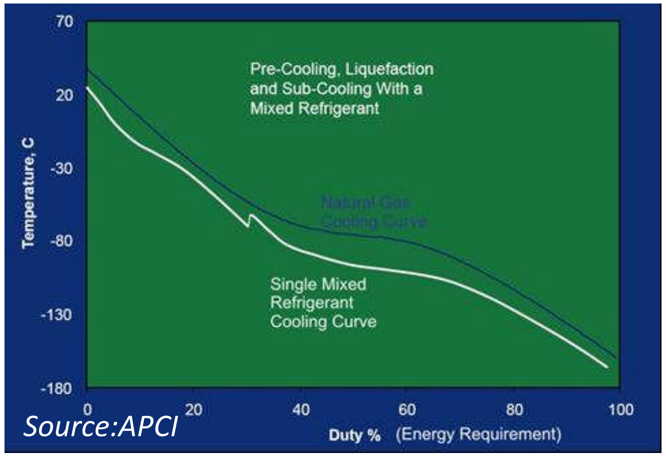
Single Mixed Refrigerant (SMR) Gas Liquefaction Process

Single mixed refrigerant processes are less efficient over the entire cooling range than dual mixed refrigerant (DMR) or C3MR processes. This means that they require more energy and gas feed to achieve liquefaction, but require less plant items, space and refrigerants, which should in many gas projects lead to lower operating costs and manpower.



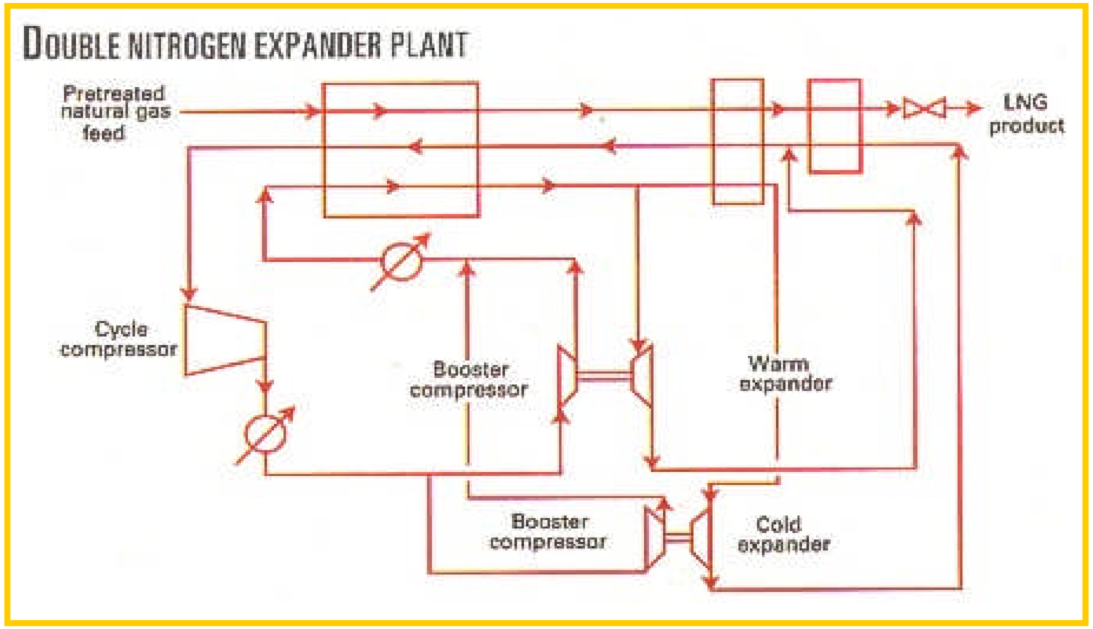
Mark Roberts, APCI Feb 2009

C3MR mixed refrigerant natural gas and refrigerant cooling curves



Nitrogen-expander Liquefaction Process: Proposed for LNG FPSO Deployment

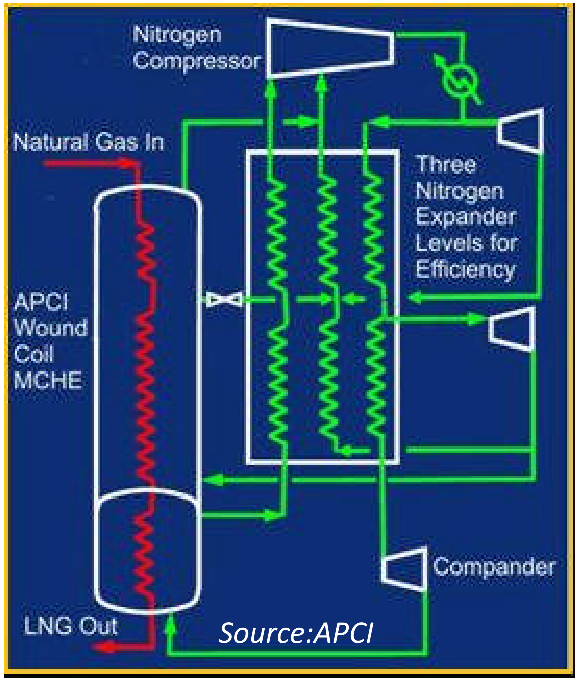
The first reported work on floating gas liquefaction in 1981 recommended the nitrogen-expander refrigeration cycle with aluminium plate-fin heat exchangers, as used extensively in small-scale, low-cost LNG peak-shaving applications. This has been further developed by adding expander cycles.



Reverse-Brayton gas expander cycle

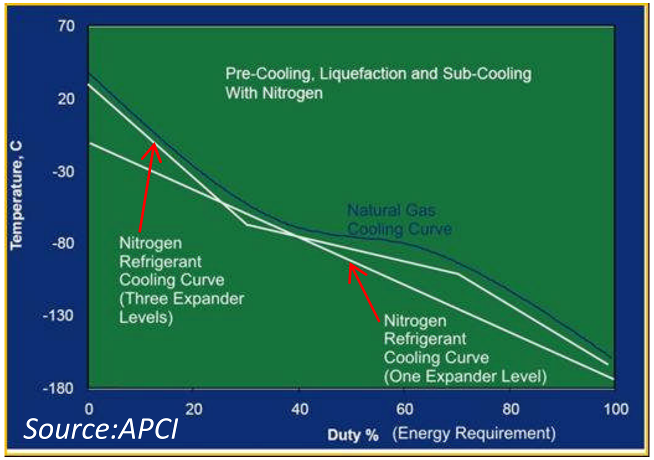
Nitrogen Recycle Expander Process

APCI have worked to develop the sub-cooling nitrogen refrigeration cycle at the back end of their AP-X process to work as a standalone nitrogen recycle expander process for offshore deployment.



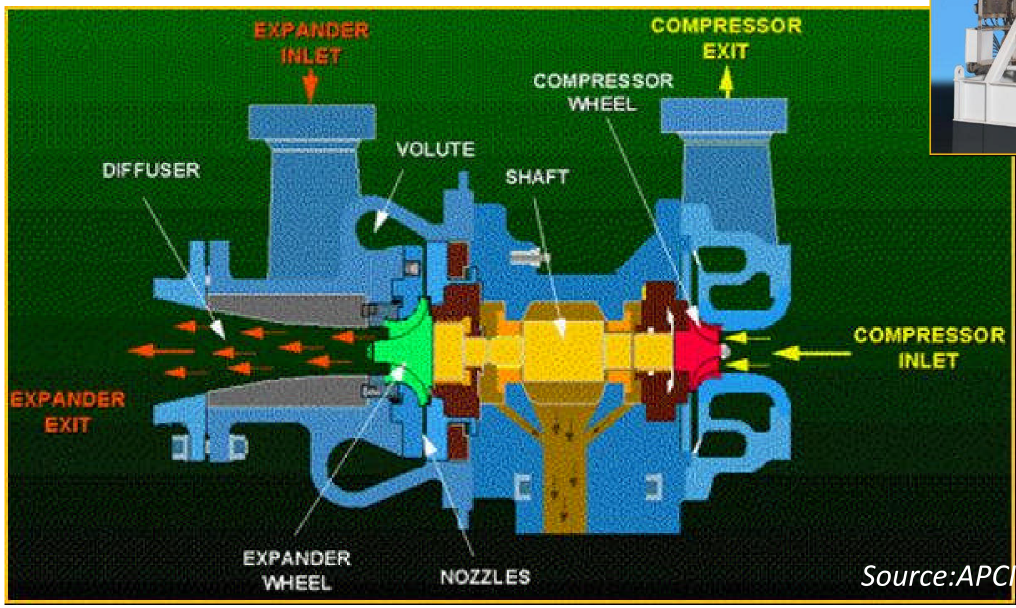
Mark Roberts, APCI Feb 2009

Better thermal efficiency can be achieved by adding two and three separate expander levels and combining these with a spool wound MCHE to optimise LNG stability and handling. This adds to cost, weight and space requirements.



Single-shaft Expander/Process Compressor (Compander) Units

Recycle companders, where the work generated by the expanding fluid is recovered by compressing a process fluid in a compressor wheel mounted on the same shaft with the expander wheel, are used in nitrogen recycle liquefaction processes.

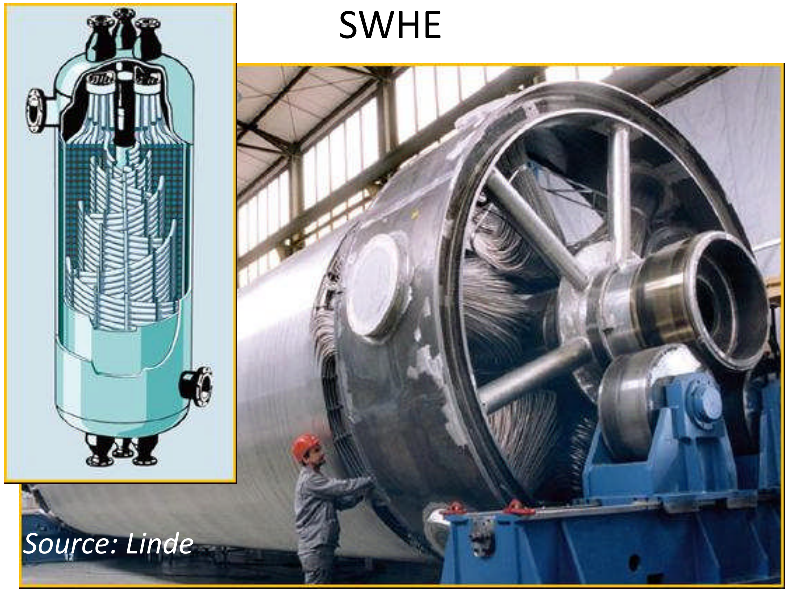


APCI High Capacity Nitrogen Compander as installed on Qatargas Trains 4-5-6-7 and RasGas Trains 6-7 base load AP-X liquefaction plants. Up to 92% efficiency claimed.

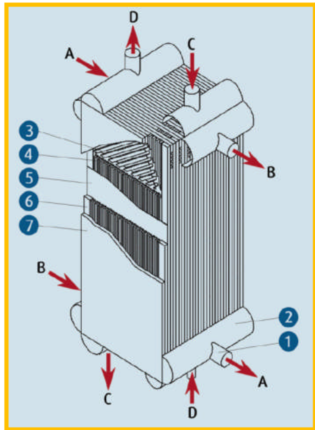
Heat Exchanger Alternatives

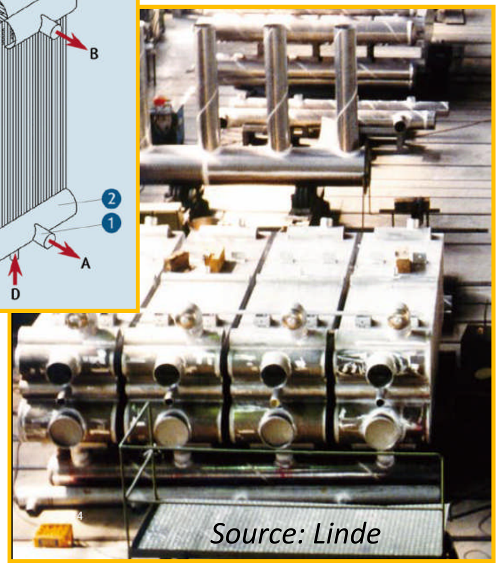
Spool (or Coil) Wound Heat Exchangers (SWHE) are offered by APCI and Linde. The vacuum brazed aluminium plate-fin heat exchangers (BAHX or PFHE) are key components in many cryogenic process plants. They are the preferred heat exchangers in small LNG plants.

SWHE



BAHX





Heat Exchanger Trade Offs: SWHE versus BAHX

Spool-wound heat exchangers - advantages:
Efficient -providing a large cooling surface area per shell
Tolerant against thermal shocks due to its robustness
Reliable in large capacity plants
Spool-wound heat exchangers -disadvantages:
High cost and limited suppliers
Size and weight
Limited flexibility with respect to variable composition feed gas streams

Plate-fin heat exchangers - advantages:
Compactness, which saves installation space and cost
Many process streams can be treated in only one unit
Low equipment weight
Plate-fin heat exchangers - disadvantages:
Vulnerable to thermal shocks, motion and varying operating conditions
Potentially higher maintenance
Slightly lower efficiency

MCR Cryogenic Heat Exchanger
APCI Development for an LNG FPSO

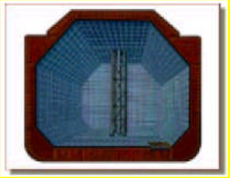
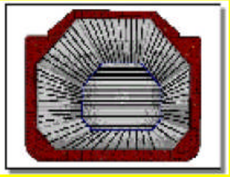
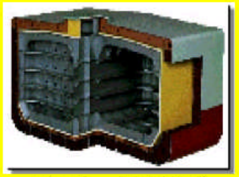
APCI claim that their DMR process offers flexibility in exchanger and compressor design, and the process can be configured to minimize hydrocarbon inventories or eliminate specific components from the multi-component refrigerant (MCR) mix using HFCs.

- APCI conducted (2000) detailed studies of the structural integrity of their coil-wound heat exchanger shell and internal structures (Heriot-Watt University, Scotland). The tests were successful from both mechanical and process design standpoints under simulated North Sea 100-year storm conditions.

- APCI claim that these developments of their DMR liquefaction processes and heat exchanger applications should result in LNG FPSO plants with high thermodynamic cycle efficiency involving low cost, simple construction, easy operation, and low maintenance.

LNG Storage Tank Options

There are four distinct storage tank (containment) system designs for LNG in marine vessels. Containment poses a problem for the FPSO because it is important to have tanks that facilitate a flat deck for the topsides modules.

	Membrane Type		Independent Type	
	GTT Mark III	GTT No.96	Moss	IHI-SPB
Tank Shape				
Tank Wall Thickness	SUS 304L 1.2 mm	Invar (36% Ni) 0.7 mm	Al Alloy (A5083) 50 mm	Al Alloy (A5083) Ni 9% Steel SUS304 10~25 mm
Insulation Thickness	Reinforced Polyurethane Foam 270 mm	Plywood Box + Perlite 530 mm	Polyurethane Foam 250 mm	Polyurethane Foam 250 mm
Gross Ton (138K)	92,900 (100%)	95,500 (102%)	110,000 (118%)	103,000 (110%)*

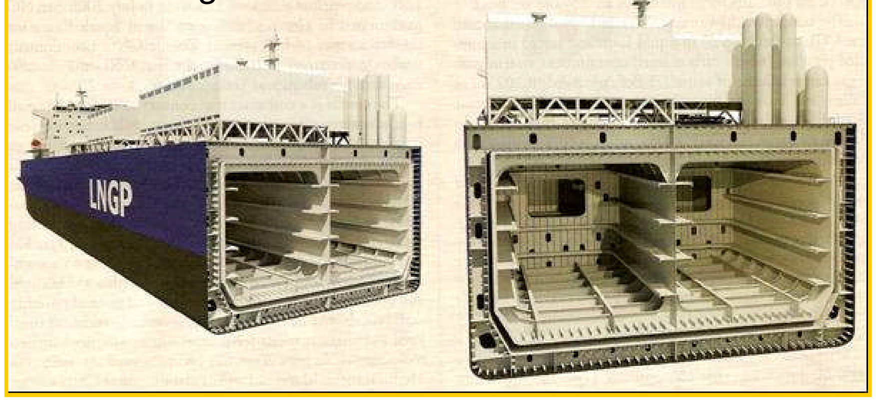
Source: Leo Festen CB&I Lummus Presentation, October 2008

Potential damaged by sloshing when partially filled and subjected to marine turbulence rules out membrane systems without substantial reinforcement.

IHI-SPB designs are being favoured.

SPB tank technology is planned for the *LNG Producer* because it offers a sloshing resistant containment system and maximizes flat deck space for topside equipment.

www.flexlng.com



Wood & Mokhatab World Oil, October 2008

Vessel is a self-propelled FPSO combining proven existing technologies:

- sloshing resistant SPB containment systems retaining maximum deck space.
- dual nitrogen turbo-expander liquefaction technology.
- proven LNG transfer technology – marine loading arms.
- proven ship-to-ship mooring system.

[SPB = self-supporting, prismatic IMO type B tank]

SBM / Linde LNG FPSO
SMR Large Single Train Concept

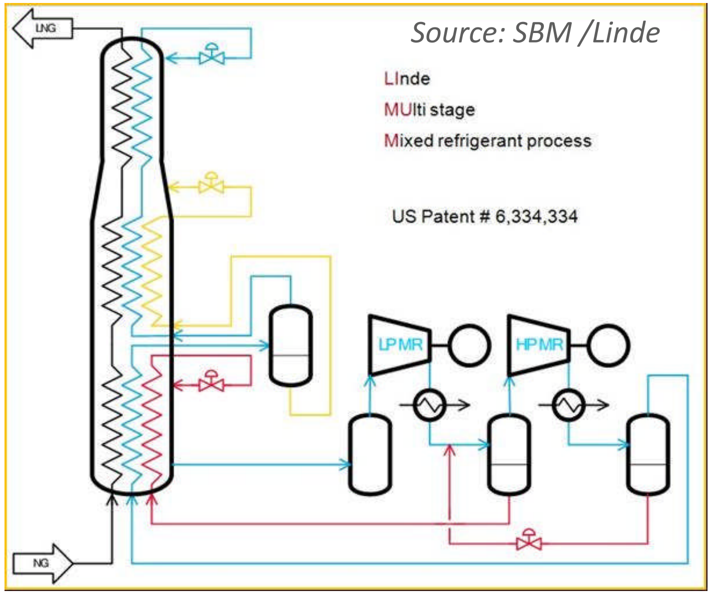
Secured an option with Samsung heavy Industries (SHI -South Korea) to build its first hull (to be confirmed in 2010 for a 2013 delivery date). SHI valued the work at $660 million for design specifications including a 2.5 mtpa capacity vessel with storage space of about 180,000 m^3 for LNG and a further 50,000 m^3 storage to be allocated to LPG, condensate or LNG depending upon the feed gas composition. FEED study planned for 2009.

Source: SBM /Linde LNG FPSO Brochure, 2008

SBM / Linde claim that their SMR process is some 15% more efficient than a dual-cycle nitrogen expander plants and 25% more efficient than a single-cycle nitrogen expander plant. On the other hand they concede that their SMR process is up to 5% less efficient than dual-cycle mixed-refrigerant plants.

SBM / Linde SMR Liquefaction Process LIMUM

The design can include two heat exchangers operating in sequence for the large capacity plants and compressor power drivers for the low pressure (LP) and high pressure (HP) mixed refrigerant cycles. The process involves gaseous and liquid refrigerant components at various stages in the cycle.



Each heat exchanger has five separate refrigerant entry points and five separate refrigerant exit points.

Each cycle involves different phases and different temperatures and pressures.

Robust SWHE claimed to have a higher tolerance against thermal stress than BAHX designs.

Linde Process Energy / Fuel Consumption Comparisons for Three Processes

Linde's comparisons highlight that SMR is substantially more efficient than their single nitrogen cycle process, but less efficient than their DMR process. Exact SMR energy consumption depends on compressor configuration.

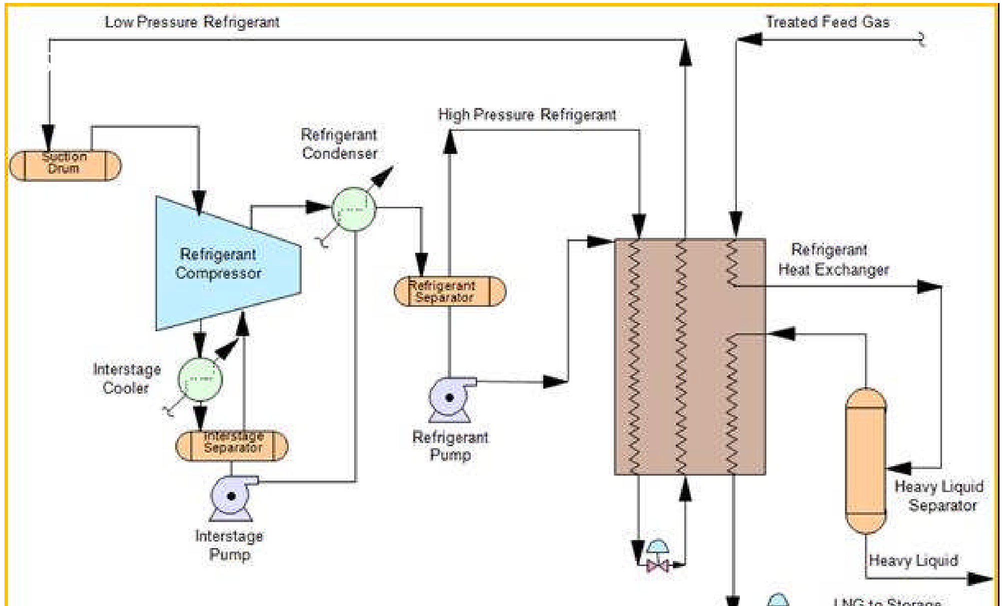
Source: SBM /Linde	CO_2 pre-cooled N_2 expander (cLNG)	SMR process LIMUM®	DMR process
Specific energy consumption (kWh/t_{LNG})	430	300	270
Total energy consumption (MW) @ 300 t_{LNG}/h	129	90	81
Fuel consumption (MMBTU/h) @ 35% efficiency	1,258	877	790
Fuel cost per year (MMUS$) @ 1.00 US$ per MMBTU	10.6	7.4	6.6

Control of one SMR refrigeration cycle involves 2 rotating machines.

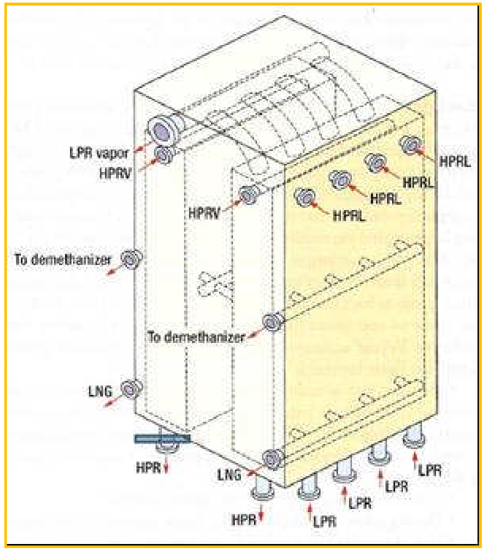
SBM / Linde point out that for a comparable capacity a dual nitrogen cycle would likely involve 2 trains with 6 to 8 rotating machines (2 or 4 compressors plus 4 expander / booster units.

Black & Veatch:
PRICO SMR Gas Liquefaction Process

This SMR system uses a plate-fin main heat exchanger in a cold box configuration for a maximum 1 mtpa LNG capacity in a single-train plant (~130 mmscf/d). Main application to date has been for small-scale onshore peak shaving plants.



Source: Black & Veatch

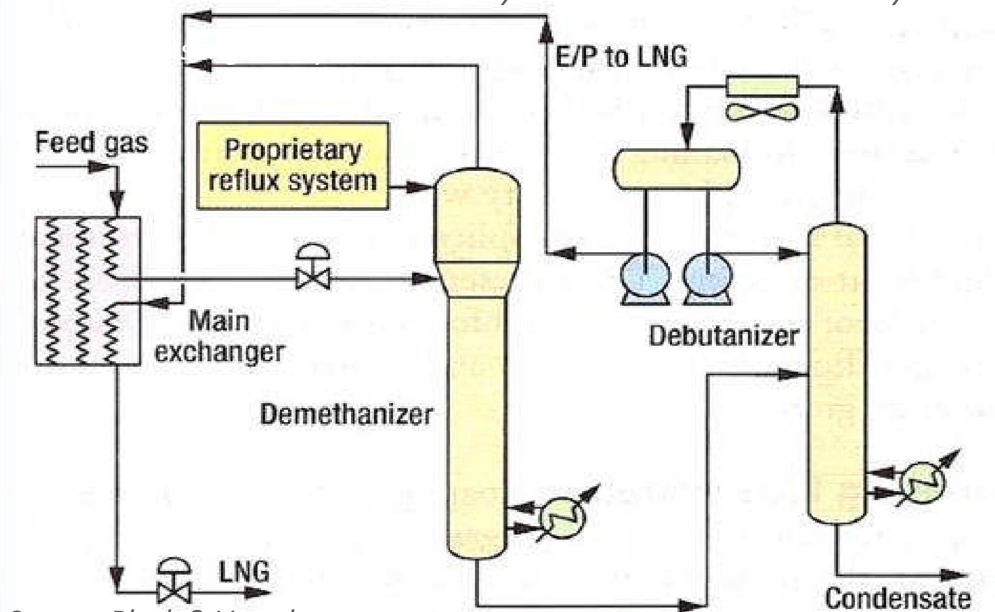


Source: Price et al, Hydrocarbon Processing, July 2008

Natural Gas Liquid (NGL) and Heavy Hydrocarbon (C5+) Recovery

Depending on the composition of the feed gas to be liquefied, heavy hydrocarbons are likely to need removing prior to gas liquefaction to prevent plugging due to solidification at low temperature.

NGL Recovery with Black & Veatch's Prico System



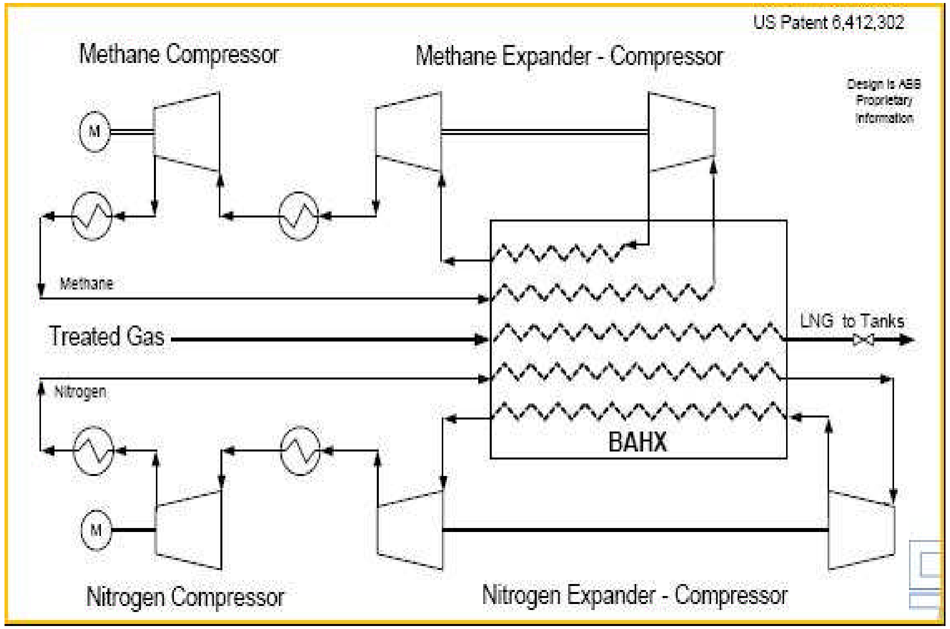
Source: Black & Veatch

If the heavy liquid is of sufficient quantity, fractionation of these NGLs into products such as ethane, LPG (propane and butane), and gasoline may be economically attractive. A single C5+ condensate product may be the only liquid product that is commercially viable in small quantities.

Source: Price et al, Hydrocarbon Processing, July 2008

CB&I Lummus with Höegh and Co: Niche LNG FPSO

Gas is liquefied in two independent cycles, using methane-rich feed-gas as refrigerant for the first stage, and then moving to nitrogen, with both cycles utilizing turbo-expanders. Refrigerants are always in the gaseous phase.

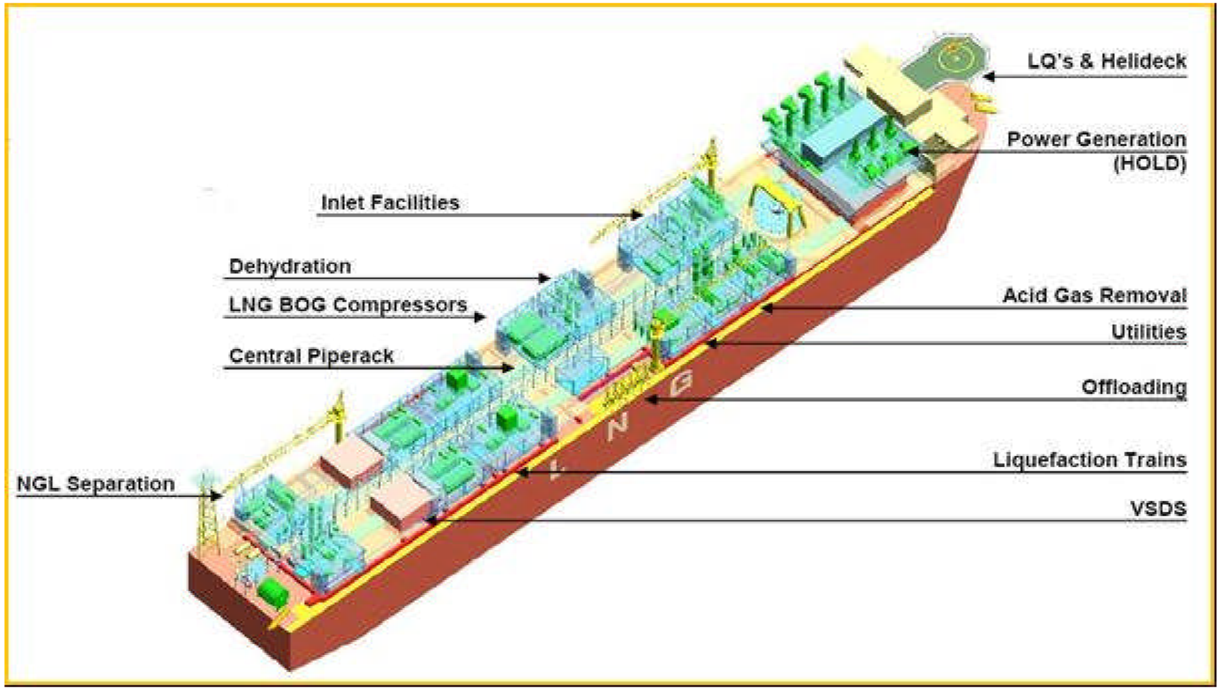


Höegh LNG FPSO design caters for ~3.0 bcma (2 trains~1.6 to 2.0 mtpa of LNG plus ~0.4 mtpa of LPG/condensate). It can be expanded to 2.4 mtpa of LNG or reduced to 1.0 mtpa. The LNG FPSO is designed to have storage capacity of 190,000 m^3 of LNG and 30,000 m^3 LPG/condensate. The first delivery of a vessel is planned with Daewoo for ~2012. Up to 2 mtpa can fit on a Q-flex-sized ship.

Source: Leo Festen CB&I Lummus Presentation, October 2008

Höegh LNG FPSO – Design Incorporates Niche LNG Liquefaction Technology

3000 tonnes maximum with base case of 14 modules distributed with safety gaps. Power generation drivers are placed in a hold below deck. LNG offloading requires a side-by-side system.

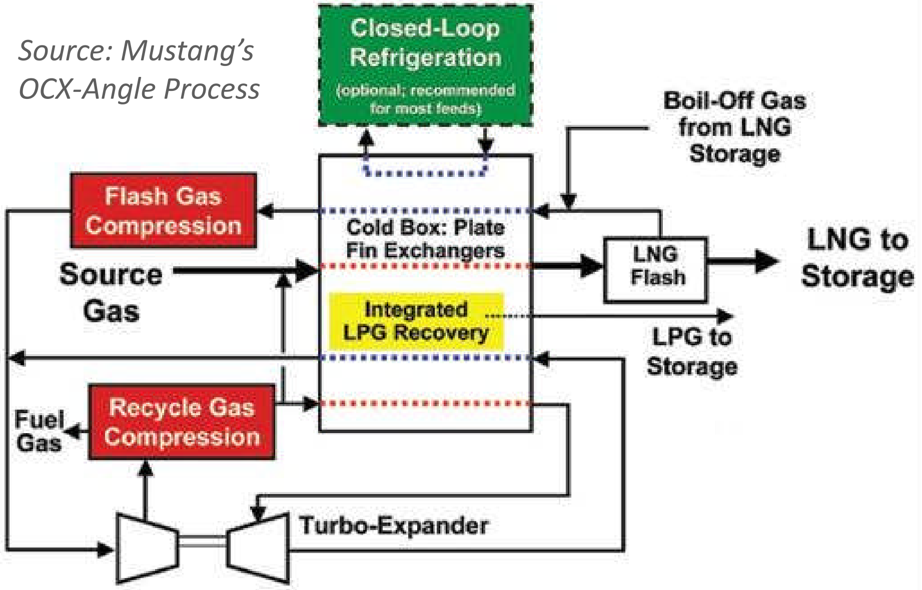


Source: Leo Festen CB&I Lummus Presentation, October 2008

Mustang Engineering: "Smart" Suite of Liquefaction Processes Proposed

Mustang (part of UK's Wood Group) has developed a suite of proprietary turbo expander-based LNG liquefaction processes that are suited for use on LNG FPSOs with capacities of 0.5 to more than 2.0 mtpa with a range of feed gas specifications.

Source: Mustang's OCX-Angle Process



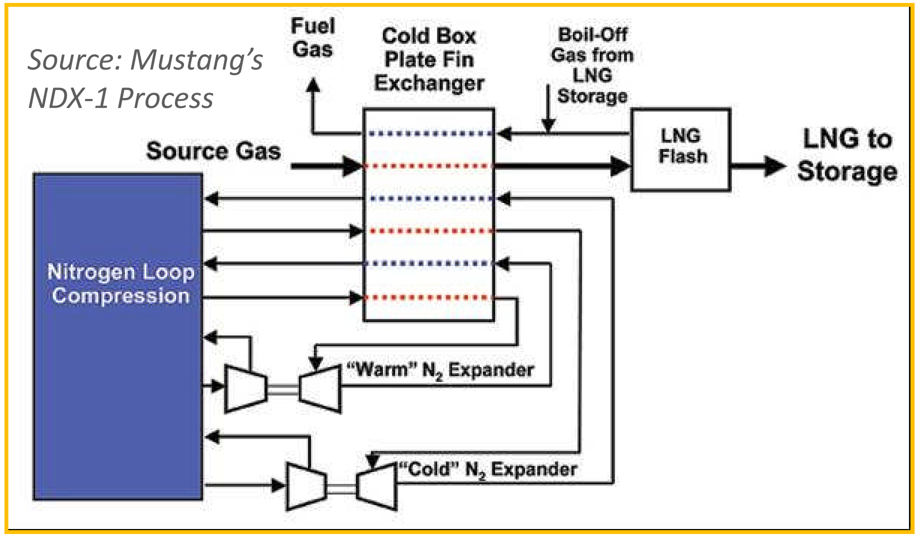
Several open-cycle (i.e. feed gas used as refrigerant) processes are combined with propane pre-cooling, LPG recovery and boil-off gas recovery modules.

More recently developed into the dual nitrogen expander process NDX-1.

Source: Susan Walther et al. LNG Industry, Winter 2008

Mustang Engineering: NDX-1 Process

Mustang claim that their NDX-1 dual expander nitrogen process is simple, compact, energy-efficient, and flexible over a wide range of feed gas compositions, offering a thermal efficiency of between 91% and 93% (or higher in optimal conditions).



Two streams of nitrogen at high pressure and ambient temperature are cooled in the main plate fin heat exchanger.

The first stream is cooled to an intermediate temperature and is then dropped in pressure and temperature across the expander side of an expander compressor.

Source: Susan Walther et al. LNG Industry, Winter 2008

Mustang Engineering: Process Efficiency Comparisons – Optimized NDX-1

A single NDX-1 liquefaction processing train can be sized up to about 0.75 mtpa. For a plant of 1.5 to 2 mtpa it is likely that three trains would be required, meaning a significant rotating equipment count. The optimized design uses the LM2500 gas turbine driver rather than the LM6000, which is attractive but has never been used to drive compression offshore.

Source: Mustang	Mustang LNG Smart® liquefaction processes			
	NDX-1	OCX-2	OCX-R	OCX-Angle
Refrigerant	Nitrogen gas	Source gas	Source gas and closed loop refrigerant	Source gas and closed loop refrigerant
Thermal efficiency*	93%	92%	93%	93%
Specific power kW-h/kg product	0.41	0.46	0.40	0.41
Total power for 150 million ft³/d feed gas, kW	50 800	56 300	49 300	50 580

**Thermal efficiency calculated as the ratio of the higher heating value of the products to that of the feed gas.*

Source: Susan Walther et al. LNG Industry, Winter 2008

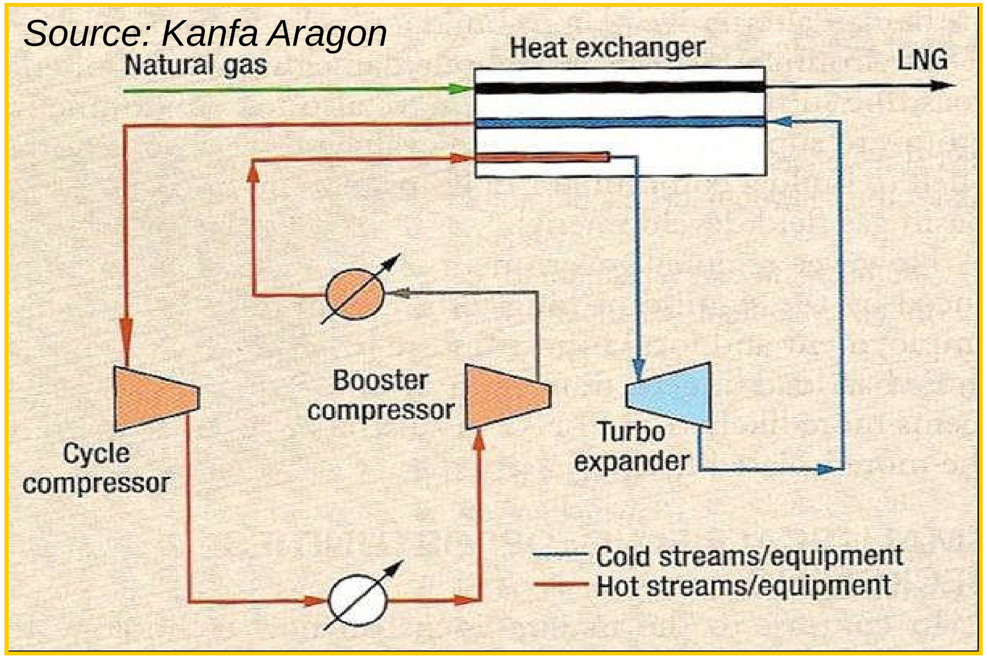
Mustang Engineering:
LNG FPSO Alliances Announced in 2009

February 2009 Gasol (AIM listed oil and gas company) announced that with the assistance of Teekay Corporation ("Teekay") it had developed the concept of a Near-Shore LNG Production System ("NSPS™") with a view to applying this concept to gas monetization projects in Nigeria and elsewhere in the Gulf of Guinea region. The NSPS concept will be used on using floating modules on barges that are berthed and moored to a fixed and protected jetty in benign waters in close proximity to the shore, to produce LNG, LPG, condensates and power.

May 2009 Petronas (60%), MISC (30%) and Mustang (10%) formed a Kuala Lumpur – based joint-venture company to provide floating liquefied natural gas (LNG) engineering solutions and services worldwide. Initially the new joint-venture will focus on accomplishing a FEED study for a project in Malaysia. The project has already progressed to achieve first gas production from a floating LNG facility in late 2013.

Flex LNG – Dual Nitrogen Turbo Expansion Refrigeration Cycle

The nitrogen turbo expansion refrigeration cycle for the Flex LNG concept provides refrigeration by compression and expansion of a refrigerant that is kept in the gas phase throughout the entire system.



Wood & Mokhatab World Oil, October 2008

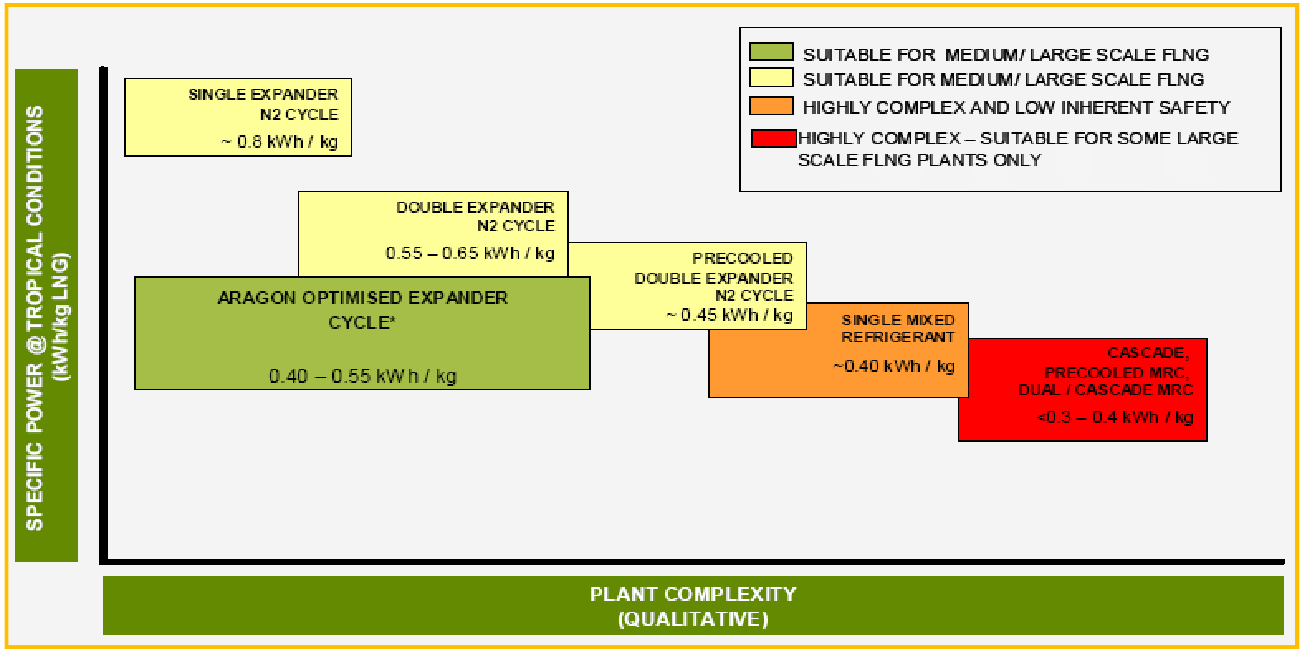
The cycled refrigeration gas is first pre-cooled in the main heat exchanger with the returning cold gas.

This temperature exchange takes place in the same heat exchanger that cools the process gas.

Exactly how Kanfa Aragon plans to optimize its dual cycle process is not yet revealed.

LNG Process Power Requirements in Tropical Conditions

Apart from APCI in Qatar no technology provider has yet built large scale nitrogen expander cycles so power requirements and efficiency remains uncertain. Costain is the process engineer involved in Kanfa Aragon design.



Source: Kanfa Aragon, March 2009

Number of Trains is Critical for Capacity, Weight and Rotating Equipment Count

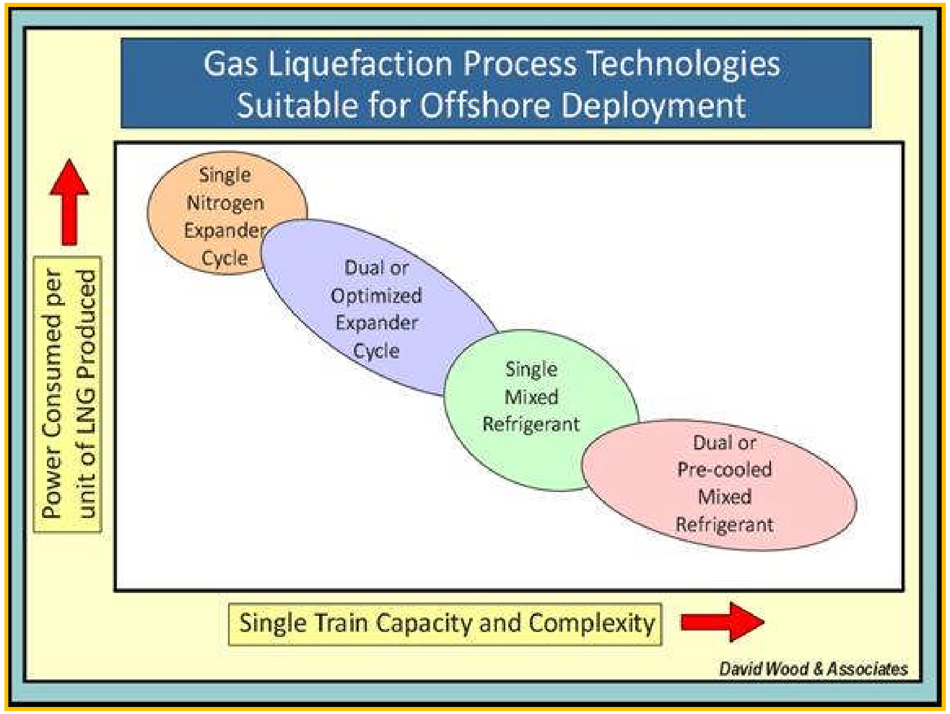
LNG process train designs depend upon whether the gas is coming from a non-associated (quite dry) gas reservoir or an associated (quite wet) gas from an oil reservoir. Many process providers are claiming technology enhancements leading to larger single train sizes (e.g. Kanfa Aragon from 0.9 mtpa in 2007 to 1.2 mtpa in 2009). A single pre-treatment train is usually proposed to supply several LNG trains in one vessel design.

PARALLEL TRAINS	LNG PRODUCT	FEED GAS
1 LNG TRAIN	UP TO 1.2 MTPA	UP TO 167 MMSCFD UP TO 4.7 MSm3/d
2 LNG TRAINS	UP TO 2.4 MTPA	UP TO 333 MMSCFD UP TO 9.3 MSm3/d
3 LNG TRAINS	UP TO 3.6 MTPA	UP TO 500 MMSCFD UP TO 14 MSm3/d
4 LNG TRAINS	UP TO 4.8 MTPA	UP TO 667 MMSCFD UP TO 18.7 MSm3/d

Source: Kanfa Aragon, March 2009

Process Comparisons: Balancing Energy Efficiency, Plant Capacity and Complexity

Four distinct generic process technologies are being proposed for LNG FPSO deployment and it is useful to compare performance expectations.



David Wood, E&P Magazine (Hart) May 2009

For the larger capacity vessels process efficiency is likely to be a higher priority than plant simplicity and equipment count.

Conclusions

- Floating natural gas liquefaction deployed on a LNG FPSO is now recognised as an economically and technically viable solution for monetizing remote gas resources (not just offshore resources).
- Remote gas resources include large and small fields, wet and dry accumulations, and clusters of reservoirs with variable feed gas compositions.
- Gas liquefaction processes and facilities capable of developing a wide-range of gas reservoir types are therefore required.
- DMR, SMR and multi-cycle nitrogen expander technologies are all likely to offer viable solutions to specific reservoirs in certain geographic conditions.
- Whereas major IOCs are interested primarily in a few very large stranded offshore gas fields, the LNG technology providers are wise to develop a suite of processes also suitable for small and mid-scale projects including associated gas developments under no-flaring rules.

Thank You!

Floating gas liquefaction: Competing technologies make progress
David Wood, E&P Magazine (Hart) May 2009

- This recent review article is available online at: http://www.epmag.com/Magazine/2009/5/item37209.php
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