

# NATURAL GAS LIQUEFACTION TECHNOLOGY FOR FLOATING LNG FACILITIES

***Dr. Justin D. Bukowski***  
Lead Process Engineer  
Dr. Yu Nan Liu  
Technical Director, LNG  
Dr. Mark R. Pillarella  
Senior Process Manager, LNG  
Stephen J. Boccella  
Lead Mechanical Design Engineer  
William A Kennington  
LNG Major Account Manager  
Air Products and Chemicals, Inc.  
Allentown, PA, USA 18195-1501  
bukowsjd@airproducts.com

**KEYWORDS:** FLNG, refrigeration cycles, DMR, nitrogen recycle

## **ABSTRACT**

Forecasts for the LNG industry indicate that a large segment of growth will occur through floating LNG (FLNG) development. FLNG facilities present special challenges over those facilities on land. Among these challenges are the response of equipment and processes to wave induced motion of the vessel, weight and space limits for the process equipment on the vessel topsides, difficulty of equipment maintenance and repair or replacement, handling of flammable component inventories, and corrosion. Meeting these challenges requires a mix of analysis, testing, and innovation.

To qualify coil wound heat exchangers (CWHE) for FLNG applications, Air Products performed an extensive design verification program. The program included rigorous mechanical analysis of the exchanger, as well as experimental testing of components which were not amenable to analysis. The program also addressed the effects of motion on mixed refrigerant liquefaction process performance through an integrated analytical and experimental investigation of two-phase flow within a CWHE. The results of the mechanical and process verification programs have been applied to CWHE designs for FLNG, including the Shell Prelude FLNG and Petronas FLNG 1 projects.

Several process cycles suitable for floating LNG applications are presented. Mixed Refrigerant (MR) processes combine high production and high efficiency for FLNG applications. An all-nitrogen refrigeration process eliminates hydrocarbon refrigerant inventory with an LNG production capacity greater than 1 MTPA in a single natural gas train. Several different precooling schemes are discussed, with advantages and disadvantages of each.

## **1 INTRODUCTION**

The LNG industry has seen robust growth in the past several decades, from a worldwide demand of 50 million tons in 1990 to over 240 million tons in 2011.[1] This remarkable growth was primarily supported by the monetization of the world's large conventional gas fields. Future growth of the LNG industry is expected to be divided between the remaining conventional fields and two sources that up to now have been considered too difficult or expensive to monetize: unconventional gas such as shale gas and coal bed methane, and deep offshore fields. The phenomenal growth of shale gas production assures that new land-based LNG facilities will continue to be constructed for the foreseeable future as these resources are exploited. At the same time, the development of remote offshore gas reserves will require the construction of floating LNG (FLNG) facilities, as many of these fields are located far enough offshore or in water too deep to make pipeline delivery to a land-based plant economically attractive.

The design, construction and operation of an LNG facility on a floating vessel presents a number of special challenges when compared to a land-based plant: ocean induced vessel motions, equipment size/weight/layout concerns, equipment marinization and the harsh marine environment.

Wave and wind induced vessel motions must be considered in the design of the process equipment both from mechanical integrity and process operation viewpoints:

- The required strength and fatigue resistance of the equipment will be determined by the severity of the vessel motion, which itself is a consequence of the vessel size and design as well as the local sea conditions. The equipment design must not only consider the typical conditions while the vessel is on station, but also motion while in transit to the site, severe storms, and survivability of catastrophic events such as blast loads and damaged vessel list.
- Process equipment with two-phase flow may be affected by the vessel motion, and the possible reduction of performance must be considered in the process design to ensure that the facility can meet operational targets.

Compared to a land-based LNG facility, weight and space limits for the process equipment are very important for an FLNG facility. The space limitations can lead to difficulty with equipment maintenance, and repair or replacement can be difficult as well, even before considering the remote location.

The vessel confines make it difficult to separate the sections of the facility containing flammable inventories and those locations which are frequently occupied by personnel. This and the desire to minimize the risk of catastrophic loss therefore suggest that flammable inventory on the vessel should be minimized. Process selection is an important first step for reducing inventory.

Another important consideration is the corrosive marine environment. The continual salt water spray upon equipment and piping is a condition which must be taken into account when material selections are made. While land-based cryogenic equipment may be constructed from aluminum, FLNG equipment may use other chloride resistant materials such as grade 316L stainless steel.

These challenges influence the selection of the FLNG liquefaction process. Adapting the land-based LNG process to the difficult marine environment requires innovation to meet these challenges, and the risks added by the innovations must be carefully managed by analysis and testing. This paper will discuss specific benefits of various process cycles for FLNG service, with an emphasis on the dual mixed refrigerant (DMR) cycle options.

## **2 LIQUEFACTION HEAT EXCHANGERS FOR FLNG**

In an LNG process, the cooling and liquefaction of the natural gas takes place in one or more heat exchangers, depending on the cycle selected. All of the following processes utilize a coil wound heat exchanger (CWHE) as the equipment in which the liquefaction takes place. CWHEs can be manufactured to provide high LNG capacity in a single train, while having excellent turndown capability. By their basic design they are robust and have been proven to be able to tolerate the high thermal stresses created by the high heat transfer rates when the natural gas is condensed. In addition, in the very rare case where tube leaks occur, the leak is fully contained by the pressure vessel shell of the CWHE, preventing leakage of natural gas or refrigerant directly to the environment. Unlike other types of heat exchangers, which can leak directly to the environment and therefore must be shut down immediately, a CWHE may continue to operate until such time as a repair can be scheduled, typically during a major LNG facility maintenance overhaul. For FLNG, this dual containment provides an extra level of protection.

Air Products has performed an extensive mechanical design verification program to qualify our CWHEs for FLNG applications, including both rigorous analysis as well as experimental testing of mechanical

components.[2] The results of the mechanical and process verification programs have been incorporated into Air Products' CWHE designs for FLNG, including the Shell Prelude FLNG and Petronas FLNG 1 projects. For FLNG service, the CWHE design uses a stainless steel shell for strength and corrosion resistance, with aluminum internals to maintain excellent heat transfer performance and lower exchanger weight.

### **3 REFRIGERATION PROCESS CYCLE DESCRIPTIONS**

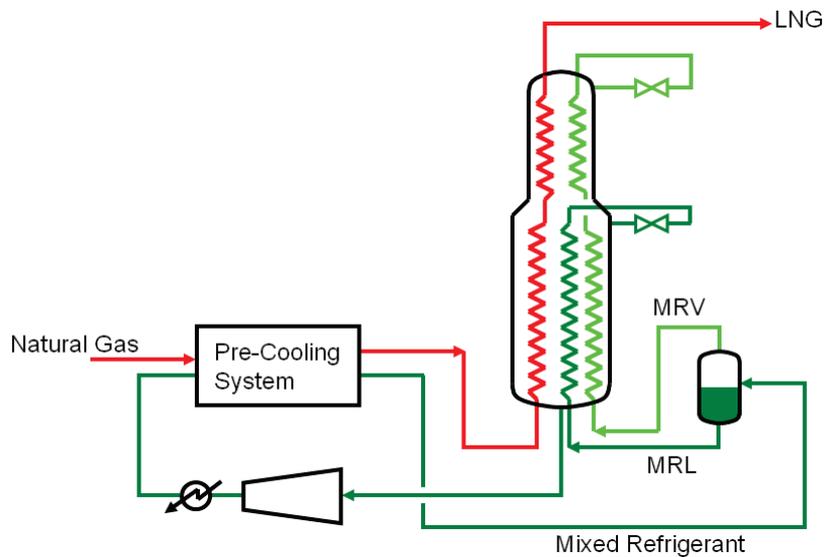
The heart of the FLNG vessel is the liquefaction section, in which natural gas is liquefied for storage and eventual transport. The refrigeration required to liquefy the gas is provided by one or more refrigeration circuits operating in a process cycle in which:

- a refrigerant is compressed
- cooled against a heat sink such as air or cooling water
- reduced in pressure to achieve a cold temperature
- warmed against the heat load

The choice of process cycle is important, since it determines the equipment requirements for a large section of the FLNG facility and will have a great impact on the overall vessel design. Before discussing the relative benefits of the various cycles, it is useful to review the cycles themselves.

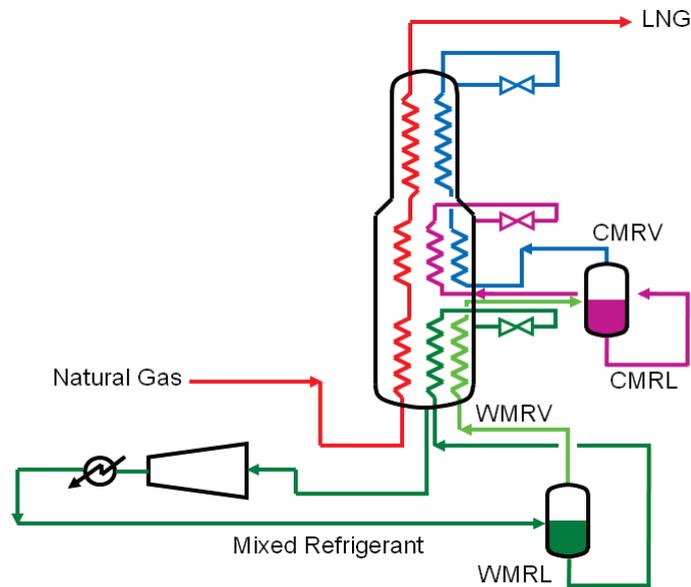
#### **Precooled MR and Single MR**

The precooled mixed refrigerant (precooled MR) cycle is the most widely used LNG process for land-based facilities (Figure 1). The natural gas feed is first precooled to about -30°C by a precooling refrigerant circuit, for which there are several choices possible. Liquefaction and subcooling are performed in a CWHE with a refrigeration circuit utilizing a cold mixed refrigerant (CMR) composed of nitrogen, methane, ethane, and propane. The majority of the world's LNG is liquefied in the AP-C3MR™ LNG Process, in which the precooling circuit is a propane system, typically utilizing multiple kettle-type evaporators. For FLNG, for large production rates, there has been a lot of interest in dual mixed refrigerant (DMR) processes, in which the precooling is performed in one or more CWHEs with a high boiling point warm mixed refrigerant (WMR). The WMR composition may include methane, ethane, propane and butane, or a subset of those components, depending on the particular precooling configuration and preference of the FLNG owner. The reduction of propane inventory for the DMR process, compared to C3MR, is a major reason why attention has been focused on it. Air Products offers several variations of the AP-DMR™ LNG Process, for which precooling schemes are discussed later. Another option for precooling is the AP-HMR™ LNG Process, in which the propane in the precooling circuit is replaced with a nonflammable hydrofluorocarbon (HFC) such as HFC-410A.



**Figure 1. Basic Precooled MR Process**

The single MR (SMR) cycle uses only one MR circuit for precooling, liquefaction, and subcooling in a single CWHE (Figure 2). This provides the benefit of reduced equipment count, but comes at the cost of lower power efficiency than precooled MR. SMR has been used for land-based LNG plants, typically for capacities less than 1 million tons per annum (MTPA) per train. For larger capacities, multiple trains may be required, but by using a single gas turbine driver for each train, this offers the opportunity to improve plant availability over a plant with a single large train using multiple gas turbines. In addition to the configuration shown in Figure 2, Air Products has developed several variations of the AP-SMR™ LNG Process to enable increased efficiency.



**Figure 2. Air Products AP-SMR™ LNG Process**

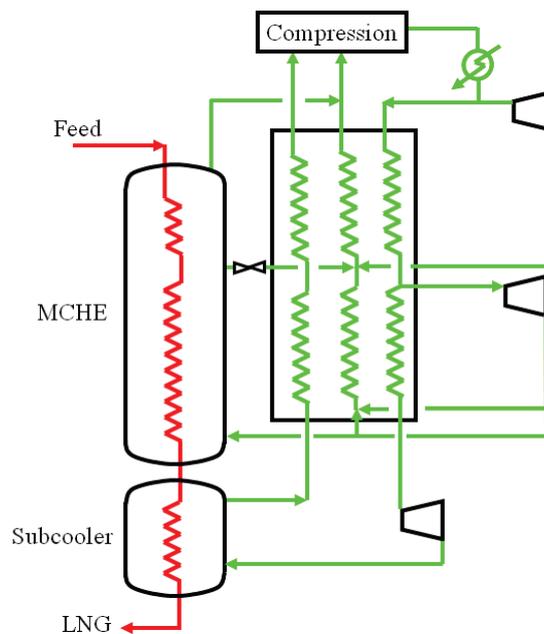
### Nitrogen Recycle

The nitrogen recycle process is a well-proven technology for producing liquid N<sub>2</sub> and O<sub>2</sub>. The process uses the reverse Brayton cycle to create refrigeration by:

- compressing nitrogen
- removing the heat of compression
- expanding the nitrogen through a turbo-expander to create a cold stream
- warming the stream against the heat load

The cycle has been used in hundreds of Air Separation Units and dozens of LNG peakshaver plants. However, the refrigeration duty requirement for either is significantly less than that required for a baseload LNG facility. Therefore scaling up to larger capacities for an LNG facility requires careful engineering. This was successfully accomplished for the first time on the AP-X<sup>®</sup> LNG Process trains in Qatar, for which the subcooling refrigeration loop utilizes a N<sub>2</sub> process that has equivalent refrigeration duty to liquefy 1 to 2 MTPA of natural gas if it were a stand-alone liquefier.[3]

Air Products has developed several variations of the N<sub>2</sub> recycle process for an LNG plant. These trade off the number of expanders, pressure and temperature levels with process power efficiency. Figure 3 shows an Air Products AP-N<sup>™</sup> LNG process with two pressure levels and three expander temperatures. The nitrogen refrigerant is compressed and cooled with ambient temperature coolant (air or water). The refrigerant stream is then split with most entering an economizer in which it is further cooled. The remaining warm stream is expanded to an intermediate pressure through a turbo-expander to reduce its temperature and provide cooling to the economizer. Most of the economizer nitrogen stream is withdrawn at the midpoint, expanded through a second turbo-expander to the same intermediate pressure, and sent either to the MCHE to provide the majority of the refrigeration duty to liquefy the natural gas, or to the cold end of the economizer. Since the MCHE liquefaction section requires more refrigerant than the precooling section, excess refrigerant is withdrawn at the midpoint of the MCHE and the refrigeration value is recovered in the economizer. The remaining economizer nitrogen is further cooled before being expanded to a low pressure to provide refrigeration to the subcooling cryogenic heat exchanger (SCHE), and from there to the economizer for refrigeration recovery. The two CWHEs therefore operate with different shellside refrigerant pressures. The compression work is performed in several stages, with the first stage recompressing the low pressure refrigerant from the SCHE, the second stage recompressing the intermediate pressure refrigerant from the MCHE, and the last stage driven by the turbo-expanders (componders).



**Figure 3. Air Products AP-N<sup>™</sup> LNG Process (2-Pressure, 3-Temperature)**

The reverse Brayton cycle is well suited to create the cold temperatures required for the liquefaction and subcooling sections of the LNG process. However, since N<sub>2</sub> is a less efficient precooling refrigerant, a separate precooling refrigerant circuit will improve the overall process power efficiency. The choices for precooling refrigerant are nominally the same as those for the precooled MR cycle, but obviously a flammable refrigerant negates much of the advantage of the N<sub>2</sub> recycle process. Several precooling refrigerants have been proposed to improve process efficiency: HFCs, lithium bromide (LiBr), and carbon dioxide (CO<sub>2</sub>), all of which maintain the completely nonflammable refrigeration nature of the N<sub>2</sub> recycle process.

The AP-HN<sup>TM</sup> LNG Process combines an N<sub>2</sub> recycle section for liquefaction and subcooling, with an HFC precooling circuit, to provide improved efficiency over the AP-N process. HFC refrigerant systems are widely used in marine and industrial applications. While the scale of an FLNG precooling system with HFC may be a step-out from previous experience, the compressors aerodynamic performance is well within proven capabilities.[4] The key consideration regarding the implementation of an HFC refrigerant circuit is refrigerant loss and makeup, since all the refrigerant is imported to the FLNG vessel.

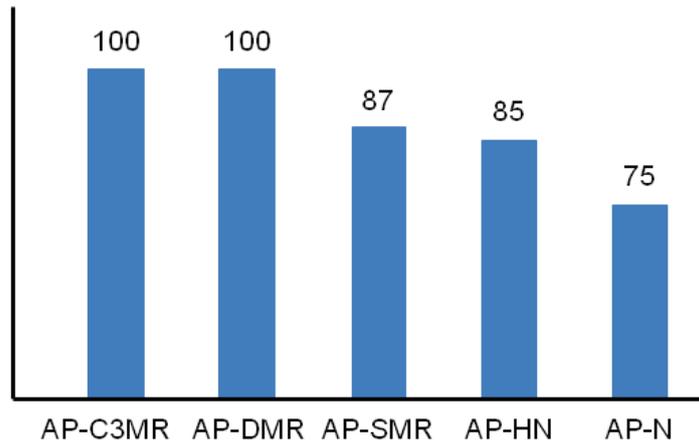
Another nonflammable precooling option is an absorption refrigeration process which uses water as the refrigerant with aqueous lithium bromide (LiBr) to regenerate the refrigerant. Because it uses an aqueous refrigerant, the precooling is limited to an end temperature of above 0°C, rather than the typical -30°C to -40°C of other precooling schemes. However, the absorption refrigeration process can be driven by waste heat, by which the overall process efficiency can receive an added boost.[5]

#### **4 CYCLE SELECTION FOR FLNG**

Selection of the liquefaction process will be influenced by the needs of the owner and the relative desirability of the various process features. These features include the process efficiency, production capacity, refrigerant type, and impact of vessel motion.

##### **Process Power Efficiency**

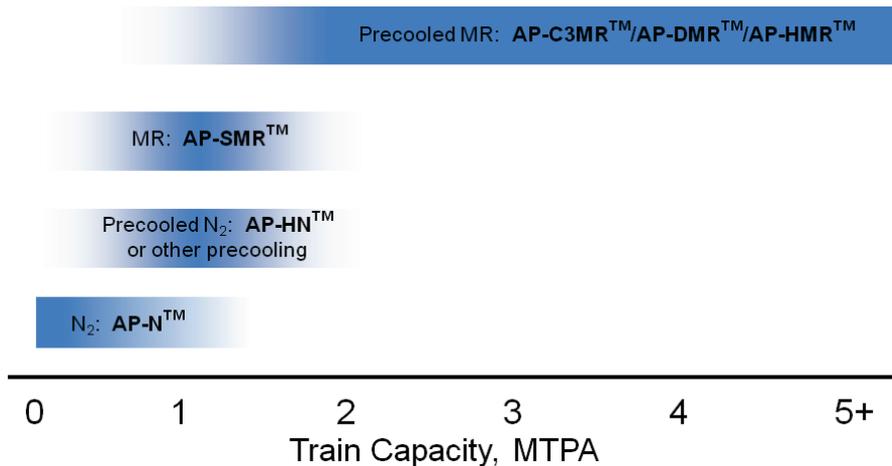
The power efficiency of the refrigeration cycle can be expressed as the plant production divided by the power required for the refrigerant compressors. Typical efficiencies for the liquefaction cycles described above are shown in Figure 4. With a fixed selection of gas turbine drivers for the refrigerant compressors, the plant production is directly proportional to these efficiencies. The AP-C3MR and AP-DMR LNG Processes have similar high efficiencies, due to the ability to match the MR boiling curve to the feed condensation curve. The high efficiency of the precooled MR process makes it a good candidate for FLNG development. As noted above, when the precooling step is incorporated into the mixed refrigerant section, as in the AP-SMR cycle, the process efficiency is reduced. The efficiency of the AP-N cycle is somewhat below the various MR cycles. The lower efficiency of the N<sub>2</sub> recycle process can be improved nearly to that of the AP-SMR cycle by the use of a separate precooling circuit such as in the AP-HN process, but it is still less efficient than a precooled MR process.



**Figure 4. Relative Process Efficiency for Several Liquefaction Processes**

### Production Capacity and Equipment Size

Figure 5 shows the approximate range of single train production capacity in MTPA for the cycles. The precooled MR cycles have the largest capacities, easily 5 MTPA or more. However, such a large capacity may not be feasible for FLNG, due to FLNG vessel constraints. The other process cycles are each limited to about 1 or 2 MTPA per train, suitable for processing about 1-2 trillion cubic feet (TCF) of natural gas over a 20 year life.



**Figure 5. Single Train Capacity for Several Liquefaction Processes**

Nominal capacity doesn't provide a complete picture for equipment size.

- The C3MR process typically uses multiple kettle-type evaporators for the propane circuit, which require relatively large plot space.
- The DMR process uses a CWHE for the precooling MR circuit, which reduces plot space over the C3MR process.
- The SMR uses the CWHE for precooling, as well as liquefaction and subcooling. This makes the CWHE taller and larger than that for a precooled MR process of similar capacity and the topside module must be designed to accommodate this larger CWHE.
- The N<sub>2</sub> recycle process requires proportionately larger heat exchangers and piping than an MR process, because the N<sub>2</sub> refrigerant is entirely vapor and the heat transfer entirely sensible. It also requires parallel rotating machinery due to limitations on compander horsepower sizes.

## Refrigerant Composition and Flammability

For FLNG, some owners have a preference to minimize the flammable inventory in the refrigeration circuits. In particular, propane is the greatest concern because of its high volatility combined with its dense vapor which can accumulate at low elevations, in hull spaces, etc. The C3MR process has a large inventory of propane refrigerant in the precooling circuit, especially when kettle-type exchangers are used. This reduces the attractiveness of the C3MR process for FLNG service.

As noted before, the DMR process replaces the pure propane with a second mixed refrigerant, which significantly reduces the propane inventory on the FLNG vessel. Furthermore, the optimized WMR composition may contain little or no propane, with minimal or no efficiency penalty to eliminate propane. In addition, propane may be eliminated from the CMR as well, with the use of butane. The effect on process efficiency of the elimination of propane, however, depends upon the selection of both the precooling configuration and the other MR components. More detail on this topic follows later.

The N<sub>2</sub> recycle process has the advantage of using entirely nonflammable refrigerant. Selecting this process then reduces the flammable inventory in the process section of the FLNG vessel. A nitrogen generator will provide the nitrogen for the refrigeration circuit inventory. In normal operation, makeup requirements for the refrigeration circuit will be small, due to advanced machinery features such as dry gas seals. However, larger makeup quantities will be needed when the refrigerant circuit is completely depressurized for any reason, such as maintenance or a major plant upset. In order to reduce the size of the nitrogen generator, it is useful to provide storage facilities for liquid nitrogen on the vessel. During normal operation, the LNG liquefaction equipment can be used, via a small liquefaction circuit included in the CWHE, to liquefy the generated nitrogen for storage. In this manner, the time to restart the liquefaction process can be minimized.

## Impact of Vessel Motion

The FLNG vessel presents a moving platform for the liquefaction process and its associated equipment, and this motion creates acceleration forces and mechanical fatigue which both have to be accounted for in the equipment and process design. The severity of the motion is a function of the sea conditions in conjunction with the design and size of the FLNG vessel. The consequences of vessel motion upon the CWHE mechanical design and mitigation of the process effects have been thoroughly investigated by Air Products.[2,6] For any MR refrigeration cycle, the primary effect of motion is on two-phase fluid flow. The research program carried out by Air Products to understand and mitigate the process effects from motion enables the design of MR processes for FLNG service. Minor optimizations in the design relative to land-based CWHE are able to account for all the FLNG vessel motion data encountered to date. The N<sub>2</sub> recycle process, with its use of solely gaseous refrigerant, avoids the process effects on two-phase flow.

With consideration of the foregoing, the AP-DMR<sup>TM</sup> AP-SMR<sup>TM</sup> and AP-N<sup>TM</sup> LNG Processes have attracted great interest for FLNG:

- the DMR process due to its high efficiency and large production capacity in a single train, as well as its reduced propane inventory compared to C3MR
- the SMR process due to its simplicity
- the N<sub>2</sub> recycle process due to elimination of flammable refrigerants and insensitivity to FLNG vessel motion.

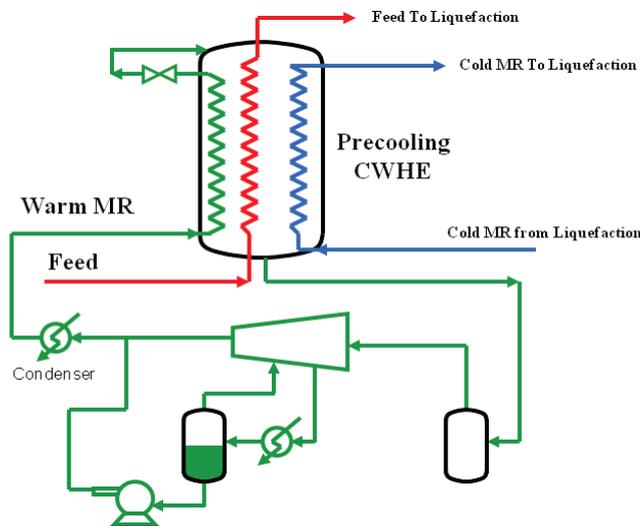
The final section of this paper will present several of the features and options of the AP-DMR process.

## 5 DMR OPTIONS

As stated above, the defining difference between C3MR and DMR is the use of a mixed refrigerant for precooling in the latter. Air Products has developed several different precooling configurations to provide an optimized solution which meets the needs of the FLNG owner. Several are discussed below, along with their advantages and disadvantages.

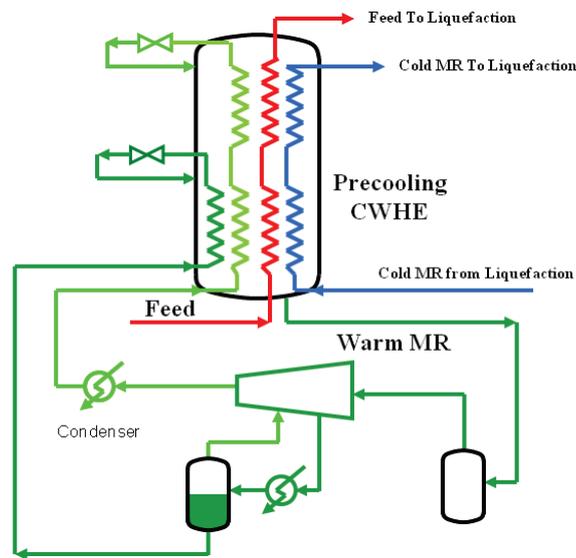
### Single Pressure Precooling

Figure 6 shows a DMR precooling configuration with a single CWHE, and therefore a single shellside refrigerant pressure. The WMR is first compressed, then fully condensed by ambient cooling, subcooled in the precooling CWHE, and let down in pressure through a Joule-Thompson (J-T) valve to provide refrigeration to precool the feed and CMR. The compression is performed in two stages, with partial condensation in the intercooler and pumping of the liquid around the second stage. The WMR has a constant composition through the process, except for the second compression stage and pump-around. This process offers good efficiency, and the WMR contains no significant propane. This may be an attractive feature to further reduce propane inventory for FLNG. However, butanes are required in the WMR to maintain efficiency.



**Figure 6. Single Pressure DMR Precooler with Liquid Pump-around**

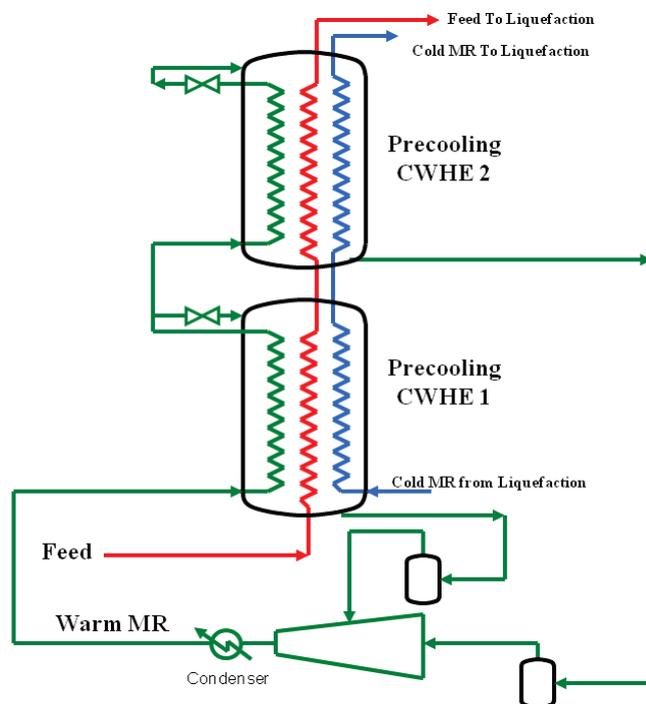
Figure 7 shows another single pressure configuration, this one with no liquid pump-around. Instead, the interstage liquid is sent directly through the precooling CWHE in a separate tube circuit. This design may be desired as it eliminates a piece of rotating machinery (the pump) and may have slightly improved efficiency over the process in Figure 6, but with the increased cost of a 2-bundle CWHE. A single-bundle CWHE can be used, with the liquid WMR refrigerant circuit running all the way to the cold end, with some decrease in efficiency compared to the process in Figure 6. In both single pressure configurations the second stage of the WMR compressor has a saturated vapor inlet stream, and therefore requires a separator design which will always prevent liquid carryover into the compressor.



**Figure 7. Single Pressure DMR Precooler, no Liquid Pump-around**

### Two-Pressure Precooling

In Figure 8, a two-pressure DMR precooler design is shown. The WMR is fully condensed and sent through a first precooling exchanger. Some of the WMR is used to provide refrigeration at an intermediate pressure, while the balance is cooled further in a second precooling CWHE and then used to provide the final precooling refrigeration at a low pressure. The low pressure WMR is compressed in the first stage of the compressor, and joined by the intermediate pressure WMR before the second stage of the compressor. If butanes are not available for the WMR, this process may provide better efficiency than the single-pressure process, but it has a significant efficiency penalty if propane is eliminated from the WMR composition.



**Figure 8. Two Pressure DMR Precooler**

## Effects of Other MR Components

The cold MR of a DMR (or other Precooled MR) process that is used to liquefy and subcool the LNG is typically composed of nitrogen, methane, ethane and propane. The warm MR precooling refrigerant in the DMR process is typically composed of methane, ethane, propane and butanes. The ethane, propane, and butanes may be recovered from the natural gas feedstock by a fractionation system, or imported to reduce capital expenditure or in the case of a lean feed gas. When refrigerant must be imported, it may be easier to locate and ship ethylene in place of ethane. Before making this decision, the effect of the substitution on the process should be investigated.

Table 1 provides results for the calculated efficiency and MR compositions for a DMR process using the single pressure process of Figure 6. The process has been constrained by the allowable refrigerant component selection to show the effect of ethane, ethylene and propane on process efficiency. In each case, the overall CMR and WMR compositions have been varied to optimize the process for highest power efficiency. A comparison of Case A and Case B shows that the substitution of ethylene for ethane in this process results in no change in efficiency. The use of ethylene is accompanied by a large increase in the required propane concentration, due to ethylene's lower boiling point temperature compared to ethane.

**Table 1. Effect of Refrigerant Composition on DMR Process Efficiency**

Case	A	B	C	D
C2 component	Ethane	Ethylene	Ethane	Ethylene
Propane Allowed	Yes	Yes	No	No
CMR mol % C3	11.5	17.7	--	--
WMR mol % C3	5.4	33.3	--	--
CMR mol% C4's	--	--	7.8	3.2
WMR mol% C4's	21.9	10.8	23.1	19.3
Efficiency (relative)	100	100	100	86

In Case C, eliminating propane entirely from ethane-based WMR and CMR does not reduce efficiency for this study. Note that some butanes are used in the CMR to compensate for the missing propane. However, Case D shows that when ethylene is used in place of ethane, eliminating propane comes at a significant cost to efficiency. One attempts to replace the propane with a blend of low-boiling ethylene and much higher-boiling butane, but this is only partially successful at matching the MR boiling and feed condensation curves. Efficiency suffers as a result. The conclusion is that for this DMR process, eliminating propane from the mixed refrigerants only slightly reduces efficiency when ethane is available; however, using ethylene imposes a significant efficiency penalty.

## 6 SUMMARY

In this paper, a number of liquefaction processes that are suitable for FLNG were discussed:

- The DMR process offers high efficiency and high single-train capacity
- The SMR process offers good efficiency with reduced equipment count
- The N<sub>2</sub> recycle process eliminates flammable refrigerant
- The precooled N<sub>2</sub> recycle process improves LNG capacity over the base N<sub>2</sub> recycle process, without losing the nonflammable nature of the refrigerant

Air Products can supply process designs and critical equipment (i.e. CWHEs, companders, cold boxes) for any of the processes, to meet the specific requirements and constraints of the FLNG owner. These processes and equipment have undergone significant marinization work to be qualified for FLNG service, and all known issues have been solved. Within each of the processes, there are many options that allow the process to be tailored to the owner's specific needs and situation.

## 7 REFERENCES

- 1 Walker, Andrew, "The Global LNG Market – a Look Back and a Look Forward", LNG Industry, Summer 2012
- 2 Gehringer, Joe., "The MCR<sup>®</sup> Cryogenic Heat Exchanger in FPSO Service", LNG Journal, Jan/Feb 2001
- 3 King, Dean, William P. Schmidt, "Success and Challenges of Operation of the AP-X<sup>®</sup> Liquefaction Unit", Gastech, Amsterdam, March 2011
- 4 Roberts, Mark J., James C. Bronfenbrenner, David R. Graham, William A. Kennington, "Process Design Solutions for Offshore Liquefaction", Gastech, Abu Dhabi, May 2009
- 5 <http://www.modec.com/fps/flng/index.html>
- 6 Bukowski, Justin D., Yu Nan Liu, Stephen J. Boccella, Leo J. Kowalski, "Innovations in Natural Gas Liquefaction Technology for Future LNG Plants and Floating LNG Facilities", IGRC, Seoul, October 2011