The design, construction and operation of a LNG facility on a floating vessel presents a number of unique challenges when compared to a land based plant including ocean induced vessel motions, equipment size/weight/layout concerns, equipment marinisation, and the harsh marine environment. Through careful analysis, innovation and testing, land based LNG processes can be adapted to meet the challenges of the difficult marine environment.

Liquefaction heat exchangers for FLNG

In a 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 outlined in this article utilise 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. Through their basic design, they are robust and have been proven to tolerate the high thermal stresses created by the high heat transfer rates when the natural gas is condensed. In addition, in the extremely rare occurrence of tube leaks, 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 floating LNG (FLNG), this dual containment provides an extra level of protection.

Air Products has performed an extensive process and mechanical design verification programme to qualify its CWHEs for FLNG applications, including both rigorous analysis and experimental testing of mechanical components. The results of the mechanical and process verification programmes have been incorporated into the company’s CWHE designs for FLNG, including the Shell Prelude FLNG and Petronas FLNG projects. For FLNG service, the CWHE design uses a stainless steel shell for strength and corrosion resistance, with aluminium internals to maintain excellent heat transfer performance and lower exchanger weight.

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. 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.

Precooled MR and single MR

The precooled mixed refrigerant (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 utilising 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 utilising multiple kettle-type evaporators. For large production rates in FLNG, there has been considerable interest in dual mixed refrigerant (DMR) processes, in which the precooling is performed in one or more CWHEs with a higher 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, represents a major factor in the increased attention on it.

Air Products has developed several different precooling variations of the AP-DMR™ LNG Process to provide an optimised solution that meets the needs of the FLNG owner. One of these is shown in Figure 2. A CWHE is used to precool the feed with a MR. The feed is liquefied and subcooled in another coil wound exchanger with another MR. This process and configuration has the benefit of providing high efficiency and reduced plot space, compared to precooling processes utilising a series of kettle reboilers.

The single MR (SMR) cycle uses only one MR circuit for precooling, liquefaction and subcooling in a single CWHE (Figure 3). 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 tpy per train. For larger capacities, multiple trains may be required. However, using a single gas turbine driver for each train can help to improve plant availability over a plant with a single large train using multiple gas turbines. In addition to the configuration shown in Figure 3, Air Products has developed several
variations of the AP-SMR™ LNG Process to enable increased efficiency.

**Nitrogen recycle**
The nitrogen recycle process is a well-proven technology for producing liquid N₂ and O₂. 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 (ASUs) 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 a LNG facility requires careful engineering. This was successfully accomplished for the first time on the AP-X™ LNG Process trains in Qatar, for which the subcooling refrigeration loop utilises a N₂ process that has the equivalent refrigeration duty to liquefy 1 - 2 million tpy of natural gas if it were a stand-alone liquefier.²

Air Products has developed several variations of the N₂ recycle process for a LNG plant. These trade off the number of expanders, pressure and temperature levels with process power efficiency. Figure 4 shows an Air Products AP-N™ LNG Process with two pressure levels and three expander temperatures. The configuration of the nitrogen refrigeration loop, including the turbo-expanders and economiser, is developed to optimise the balance between process efficiency and equipment count to achieve the desired capacity and the available power. Precooling, liquefaction and subcooling of the feed are accomplished in a CWHE utilising the nitrogen refrigeration. The reverse Brayton cycle is well suited to create the cold temperatures required for the liquefaction and subcooling sections of the LNG process. Process efficiency can be further improved by adding a separate precooling refrigerant. The choices for precooling refrigerant are nominally the same as those for the precooled MR cycle, although a flammable refrigerant negates much of the advantage of the N₂ recycle process. Several precooling refrigerants have been proposed to improve process efficiency: hydrofluorocarbons (HFCs), lithium bromide (LiBr) and carbon dioxide (CO₂), all of which maintain the completely nonflammable refrigeration nature of the N₂ recycle process.

**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 relative efficiencies for the liquefaction cycles described above are shown in Figure 5. 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 MR 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 N₂ recycle process can be improved so that it is close to that of the AP-SMR cycle by the use of a separate precooling circuit as shown in Figure 5 (AP-PNTM LNG Process), although it is still less efficient than a precooled MR process.

**Refrigerant composition and flammability**
For FLNG, some owners have a preference to minimise the flammable inventory in the refrigeration circuits. In particular, propane is the greatest concern because of its high volatility combined with its dense vapour 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 MR, which significantly reduces the
propane inventory on the FLNG vessel. Furthermore, the optimised 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, 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. The N₂ recycle process has the advantage of using an 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. 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 minimised.

Impact of vessel motion
The FLNG vessel presents a moving platform for the liquefaction process and its associated equipment. This motion creates acceleration forces and mechanical fatigue that must both 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. For any MR refrigeration cycle, the primary effect of motion is on two-phase fluid flow. The research programme carried out by Air Products to understand and mitigate the process effects from motion enables the design of MR processes for FLNG service. Optimisations in the design relative to land based CWHE are able to account for all the FLNG vessel motion data encountered to date. Since the N₂ recycle process relies solely on a gaseous refrigerant, there is no two-phase flow and therefore no impact of motion on the process.

Conclusion
In this article, a number of liquefaction processes that are suitable for FLNG have been discussed:
- The DMR process offers high efficiency and high single-train capacity, as well as reduced propane inventory compared to C3MR.
- The SMR process offers good efficiency with reduced equipment count.
- The N₂ recycle process eliminates flammable refrigerant and reduces motion effects.
- The precooled N₂ recycle process improves LNG capacity over the base N₂ recycle process, while maintaining the nonflammable nature of the refrigerant.

References