In recent years, process selection studies for baseload LNG production have grown in scope and have increasingly considered multiple cycle options. The reasons are varied and include interest in larger train capacities, a desire to minimise CO₂ emissions, different compressor driver arrangements, plus specialised applications such as floating production storage and offloading (FPSO) plants, LNG peak shaving and associated gas liquefaction. This article describes the work process used in aiding the LNG plant owner to select the optimal process technology, along with some specific examples of applications.

**Work process**

Typically, a process selection study will start with a design basis prepared by the plant owner or his representative that defines many of the design parameters to be used in the study, such as ambient conditions; feed composition and conditions; process equipment design assumptions such as pressure drop and heat exchanger approach temperatures; fuel balance requirements; possible driver configurations and desired production of LNG and LPGs. The owner will also give some information on the criteria to be optimised in the design, for example, maximise production, minimise power, or minimise CO₂ emissions. Preferably, the owner will provide the basis for a cost function that can incorporate several parameters. This allows the process licensor to optimally trade off capital investment for efficiency. By receiving as much information as possible from the plant owner on the criteria that it will be used for the evaluation, the process licensor can provide an optimised design that will best meet the owner’s objectives.

The first step after the design basis is established is to perform process simulations. Even when the licensor is provided with a highly detailed design basis, there are several unspecified equipment performance parameters that need to be defined for the process simulation. In particular, parameters that define the performance and capacity of the compressors and the main cryogenic heat exchanger (MCHE) are crucial to assessing the performance of a cycle. Ideally, such parameters are calculated with a model that is embedded in the process simulation rather than being calculated in another software application. This approach can save time and result in a more optimal design, particularly if numerical optimisation techniques are used.

For several years Air Products has been using proprietary sequential quadratic programming based techniques to optimise process designs. Several (typically 20 - 50) flowsheet parameters are varied to optimise performance relative to an objective function, while incorporating multiple constraints. The objective function used in the optimisation can be simply to maximise production or minimise power at fixed production; or a more sophisticated cost based objective function can be used that considers both capital and operating costs. The method is superior to older design optimisation methods such as parametric studies. This is particularly true for optimising flowsheets that have a large number of variables that are not linearly independent, like for LNG plants. Air Products has found that the use of these numerical techniques not only allows the process engineer to produce significantly better designs, but perhaps just as important, they also serve as a check against any unconscious biases the process designer may have.

To assess compressor performance, Air Products utilises an in-house compressor efficiency correlation...
(ICEC™). ICEC™ is a program that accurately predicts inline compressor efficiency and impeller size. The program calculates performance as a function of impeller size, stage shape characteristics, and Mach number related effects. ICEC™ predicts compressor efficiency within 2 percentage points accuracy, and can be adjusted to reflect known differences between manufacturers.

Air Products has integrated ICEC™ into the process simulation models so that constraints on parameters such as inlet flow coefficient, peripheral Mach number and impeller diameters can be met in the converged and optimised simulation. The optimisation routine 'considers' the effect of the flowsheet variables (pressures, compositions etc) and the compressor speed on the compression equipment efficiency and design. Compressor design constraints are periodically updated to reflect the latest proven technology available from the compressor suppliers. The use of ICEC™ eliminates time consuming iterations with the suppliers, and assures a feasible and near-optimal design on the first pass. The information from ICEC™ can then be translated into known manufacturers frame sizes. After the final process selection is made, compressor performance parameter specifications are sent to the vendors to verify both the aerodynamic and mechanical considerations, and to validate the calculated design.

**Applications of process technology**

**Baseload LNG plants**

The propane pre-cooled, mixed refrigerant LNG process (C3MR) has been the workhorse of the LNG industry for more than 30 years. It has been applied in LNG plants producing from 1 - 5 million tpy of LNG per train, using steam and gas turbine drivers, sea water and air cooling, rich and lean feeds containing varying levels of nitrogen, with and without LPG extraction. The process has proven to be efficient, flexible, reliable and cost competitive.

For many cases, the C3MR process remains the optimal solution. In some cases however, depending on the design basis and owner preference, other solutions should be considered. For example, with very cold ambient conditions a dual MR process can offer advantages over C3MR.

In recent years, interest has grown in ever larger train capacities so that economies of scale can significantly reduce the unit cost for LNG. To meet this requirement, Air Products has developed and patented the AP-X™ LNG process.

The AP-X™ LNG process will increase single train capacities to 7 - 10 million tpy. By producing warmer LNG at pressure, today’s C3MR or dual MR process capacity can produce up to 80% more LNG with the same proven equipment in use today. In the AP-X™ process, the warmer LNG is then subcooled to storage temperature by a gaseous nitrogen refrigerant in the same compression/expansion cycle that has been used for years to liquefy oxygen, nitrogen, and for peak-shaver natural gas liquefiers. The efficiency of this process is as high as any in the industry, while the capital cost of the liquefier per unit of LNG is reduced significantly.

The C3MR version of the AP-X™ process cycle is depicted in Figure 1. Similar to the traditional C3MR process, propane is used to provide cooling to a temperature of approximately -30 °C. The feed is then cooled and liquefied by mixed refrigerant, exiting the MCHE at a temperature of approximately -120 °C. Final subcooling of the LNG is performed using cold gaseous nitrogen from the nitrogen expander. Figure 2 shows the equipment layout for the liquefaction and subcooling sections of an AP-X™ LNG train. Coil wound heat exchangers are used to liquefy and subcool the LNG, while the nitrogen economiser uses brazed aluminium plate fin heat exchangers.

The power split between C3, MR, and N2 is flexible, and can be manipulated by changing the temperature range of the three refrigerant loops. This feature, and the use of the Split-MR™ machinery configuration, allows considerable flexibility in matching compressor driver sets, whether Frame 7s, Frame 9s, electric motors or combinations of the above. The use of electric motors as compressor drivers is gaining increasing interest in the LNG industry. Electricity can be
generated in a combined cycle power plant to greatly reduce the CO₂ emitted per unit LNG produced. Electric motors are also a very flexible drive system for the baseload LNG production. Single train liquefaction capacities from 7 - 10 million tpy can be easily achieved using electric motors with the AP-X™ process, with the specific arrangement depending upon the desired capacity and the maximum motor size considered proven by the LNG owner. Systems may also be considered, which use combinations of electric motor and gas turbine drive for the refrigeration compressors. With the use of variable frequency devices, the speed of each compressor can be optimised not only to achieve maximum compressor aerodynamic efficiency at a design point, but also across the range of ambient temperature extremes to maximise annualised production.

**FPSO Plants**

There is continued interest in a Floating Production Storage and Offloading (FPSO) facility for base-load LNG service. The design of such a facility presents significant technical challenges, not the least of which is the selection of the liquefaction cycle. Developing and selecting a liquefaction cycle suitable for a FPSO facility presents unique challenges to the process licensor. Safety and compactness are particularly important criteria for FPSO service. Due to the very limited space available aboard a FPSO vessel, there is increased emphasis on compactness. The heightened concern with safety is related to the geographical isolation and compact nature of a FPSO plant. Inevitably, operating personnel will be located closer to the plant equipment than on a land based plant, and evacuation on a floating plant facility is problematic.

In addition to the special emphasis on compactness and safety, the typical issues guiding the selection of a liquefaction cycle for a land based plant such as flexibility, efficiency and operability apply to FPSO facilities as well. The cycle selected should have the operating flexibility to handle varying feed compositions and ambient temperatures, high efficiency in order to maximise production for a given driver configuration, and simplicity and operability to enable operating personnel to maximise production and avoid downtime.

To some extent the above considerations can be competing objectives. For example, more efficient cycles often require more pieces of equipment, which can lead to a less compact design. To further complicate issues, FPSO facilities have been proposed to handle a wide variety of feed compositions and capacities. Air Products has received inquiries for facilities to handle feed compositions from rich to lean and at design capacities from 1 - 5 million tpy LNG production. For these reasons, it is not possible to select a single cycle as the preferred one for all FPSO opportunities. The cycle selected for a particular opportunity will depend on the train capacity, driver selection (gas turbine or electric drive), project economics (capital versus power) and owner preference.

The Air Products DMR2™ cycle is a recently developed dual mixed refrigerant cycle. It represents a good compromise between the competing objectives at a size range of approximately 2 - 4.5 million tpy. A simplified schematic of

![Figure 3. Air Products DMR2™ cycle.](image3)

![Figure 4. Air Products DMR2™ process plant layout.](image4)

![Figure 5. Peak shaver LNG cycle.](image5)
this cycle is shown in Figure 3. The condensation of liquids between compression stages of the warm (pre-cooling) mixed refrigerant allows this cycle to achieve very close alignment of cooling curves in the warm heat exchanger (HX1), resulting in a high thermodynamic efficiency.

This cycle offers safety advantages over the propane pre-cooled mixed refrigerant cycle (C3MR) or cascade cycles. The primary reason is the use of a mixed refrigerant rather than propane for pre-cooling. In the C3MR and cascade cycles, there is a significant inventory of propane refrigerant in multiple vessels and interconnecting piping runs, with the potential (however remote) for leakage. The Piper Alpha offshore gas processing platform disaster of 1988 provides much of the basis for this concern. In that incident, an explosion occurred after dense propane gas accumulated at a low point on the platform.

The use of a single vapourising pressure for the pre-cooling mixed refrigerant leads to a more compact design compared with other dual mixed refrigerant cycles that use multiple vapourising pressures in the pre-cooling circuit. This allows the use of a single wound coil heat exchanger for pre-cooling, saving space compared with multiple pressure designs with multiple pre-cooling exchangers and interconnecting piping. Figure 4 shows the equipment layout for the liquefaction and subcooling sections of a DMRZ™ train.

Peak shaving LNG plants
Small LNG plants producing 5 - 20 MMSCFD of LNG are common in industrialised countries. Typically, these plants are used for ‘peak shaving’ in that they produce LNG from pipeline gas during warm months to be re-vapourised and consumed during peak demand winter months.

Figure 5 shows a process flowsheet for a typical peak shaving plant. A closed-loop nitrogen expander cycle provides refrigeration for making LNG. Advances in compressor loaded expander, or compander technology over the last 15 - 20 years have made this type of cycle particularly attractive for small plants. State-of-the-art high efficiency compander designs allow this type of cycle to be competitive in efficiency for small plants. The use of pure nitrogen as a refrigerant also saves significant cost over a mixed refrigerant cycle, since there is no need to procure or store hydrocarbon refrigerant components. The use of nitrogen also saves cost in the refrigerant recycle compressor. Efficient, relatively inexpensive integral gear compressors that are typically used in the air separation industry can be used for peak shaver LNG plants using nitrogen recycle technology.

Conclusion
The selection of the optimal LNG liquefaction technology in the early phases of a project can have a large impact on the overall profitability. To provide the best possible solution, it is important that the process licensor has not only a complete and detailed design basis, but also as much information as possible on the objective criteria used by the LNG owner to evaluate proposed solutions. There are several different cycle and equipment options that can be considered depending on the project specifics. Air Products’ objective as a process licensor is to provide proven process and equipment technology that maximises return on investment to the LNG owner.

References