Mark J Roberts*, *Lead Process Engineer, Air Products & Chemicals, Inc

Mr. Roberts joined Air Products in 1996 and has 13 years experience developing cryogenic cycles for gas separation and liquefaction. He has several U.S. and international patents issued in his name. His current responsibilities include developing and evaluating new approaches to LNG liquefaction and technical support of sales estimates in support of Air Products' LNG business.

James C. Bronfenbrenner*, *Senior Process Manager, Air Products & Chemicals, Inc

Mr. Bronfenbrenner currently manages the Air Products process design group responsible for the cryogenic separation and liquefaction of hydrocarbon gases. This includes baseload LNG, LNG peakshavers, liquid Helium, liquid Hydrogen, and natural gas processing (nitrogen removal and liquids recovery). He has participated in design, performance testing, and operating evaluations for many LNG plants using the APCI C3-MR process. He is also responsible for the research and development program aimed at improving LNG heat exchanger productivity and developing a MCHE design for the FPSO market. He joined Air Products in 1981, after nine years in the petroleum refining industry.

Yu-Nan Liu*, *Technical Director LNG, Air Products & Chemicals, Inc.

Dr. Liu provides technical direction of the process engineering activities for baseload LNG plants. This includes consultation with plant owners and their selected contractors in the formulation of the Basis of Design for the liquefaction unit, the subsequent development of Air Products' process design packages, and the support of the detail engineering design of the plant. He has assisted in the start-up, performance tests, trouble-shootings, and debottlenecking studies of various existing LNG plants. He joined Air Products in 1976 and has participated in all of the major LNG projects that utilize Air Products' technologies and equipment.

Joseph M Petrowski*, *Lead Machinery Engineer, Air Products & Chemicals, Inc

Mr. Petrowski has over 30 years experience in the field of Rotating equipment. He has had assignments in the air separation business at Air Products for the Specification, Procurement, Design and Installation and Start Up of large compression trains for process air and recycle services. Presently he is supporting the LNG business in the area of driver selection and cycle support. Concurrently he is leading a worldwide training initiative in the area of compression and pumps for all engineering and plant personnel.

Previously Mr Petrowski worked for Westinghouse Electric Corporation and DeMag DeLaval in the area of Steam Turbine design and Project Management.

PROGRAMME

Large Capacity Single Train AP-X^{TM} Hybrid LNG Process

Mark J. Roberts, Joseph M. Petrowski, Dr. Yu-Nan Liu, James C. Bronfenbrenner

Air Products and Chemicals, Inc

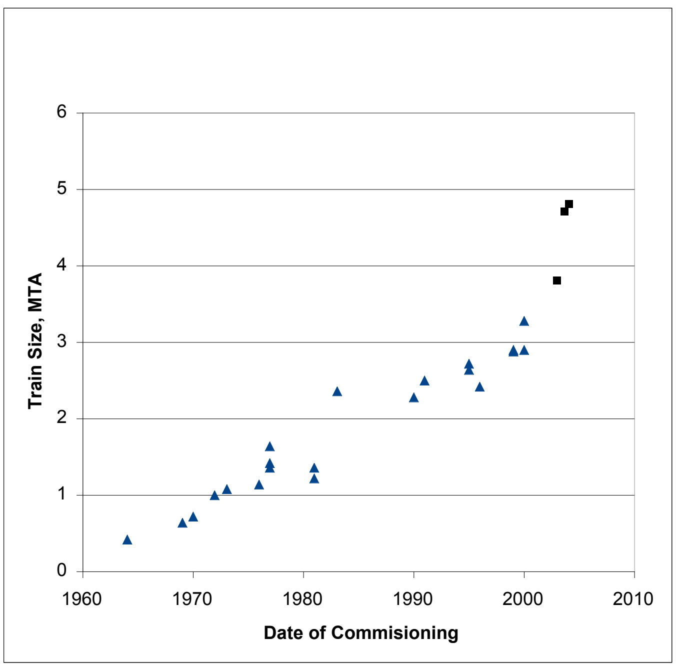
PROGRAMME

Introduction

Economies of scale continue to favor increasing train size for baseload LNG plants in order to drive down the unit cost of LNG. Figure 1 illustrates this historical trend. To meet this demand for lower cost, LNG liquefaction technology has and will continue to evolve.

Air Products is the leader in supplying process technology and MCR Main Cryogenic Heat Exchangers (MCHE's) to the LNG industry. As the industry has grown, the solutions offered by Air Products have evolved to meet the increasing demand to lower cost. Air Products' involvement in the baseload LNG industry began with the first all mixed refrigerant (single-MR) liquefier for Esso, Libya. That first plant was commissioned in 1970 and has capacity of 0.6 Mta per train. Since that time Air Products' leadership in the industry has continued from the successful introduction of the propane precooled, mixed refrigerant process (C_3-MR) in 1972 at Brunei, to trains currently under construction utilizing the Split-MR™ machinery configuration[1] with capacities approaching 5 Mta. This paper will describe a new liquefaction process that Air Products believes is key to meeting the challenge of increased demand and lower unit cost for LNG production.

Figure 1
LNG Train Size Growth



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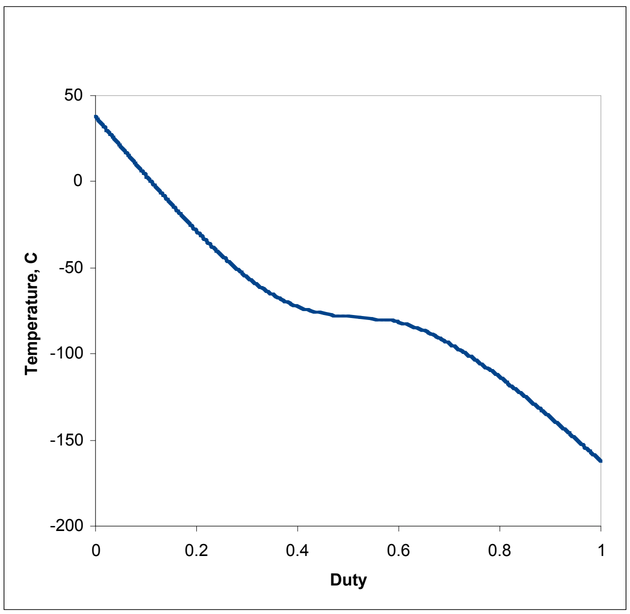
 MCR is a registered trademark of Air Products and Chemicals Inc.
™ Split MR is a trademark of Air Products and Chemicals Inc.

Evolution of LNG Technology

Single MR Process

The Single MR process using coil wound heat exchangers was a substantial improvement over the Cascade Processes existing at the time, simplifying the process and minimizing the number of equipment items. The advantage resulted from the use of a mixed component refrigerant rather than pure fluids to efficiently provide refrigeration over the temperature range required. Natural gas at liquefaction pressures in the neighborhood of 50-60 bars exhibits complex cooling behavior (Figure 2). Mixed refrigerants offered a way to provide the required refrigeration over the temperature range efficiently by tailoring the composition of the mixed fluid so as to boil over a temperature range closely matching the refrigeration demand. The single MR process proved to be simple and relatively efficient, and it represented a major step forward in baseload LNG technology.

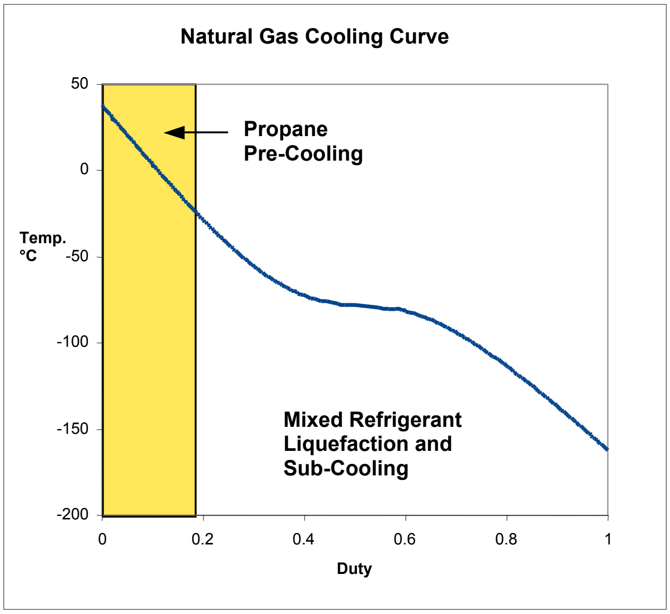
Figure 2
Natural Gas Cooling Curve



C_3-MR Process

Following on the successful introduction of Single MR for baseload applications, Air Products developed the C_3-MR process. The C_3-MR process improved upon the Single-MR process by using a simple propane refrigeration loop for pre-cooling (Figure 3)

Figure 3 C_3-MR Process



With the introduction of propane precooling to the mixed refrigerant cycle, efficiency was greatly improved and a substantial increase in capacity per train became possible. Whereas the first baseload Single MR train at Libya had a capacity of about 0.6 Mta per train, the train capacity at the first C_3-MR Plant (Brunei) is over 1.0 Mta per train. This increase in capacity is largely due to the reduction in mixed refrigerant volumetric flow due to the use of propane precooling. The reduction effectively de-bottlenecked the design of both the MCHE and the mixed refrigerant compression equipment.

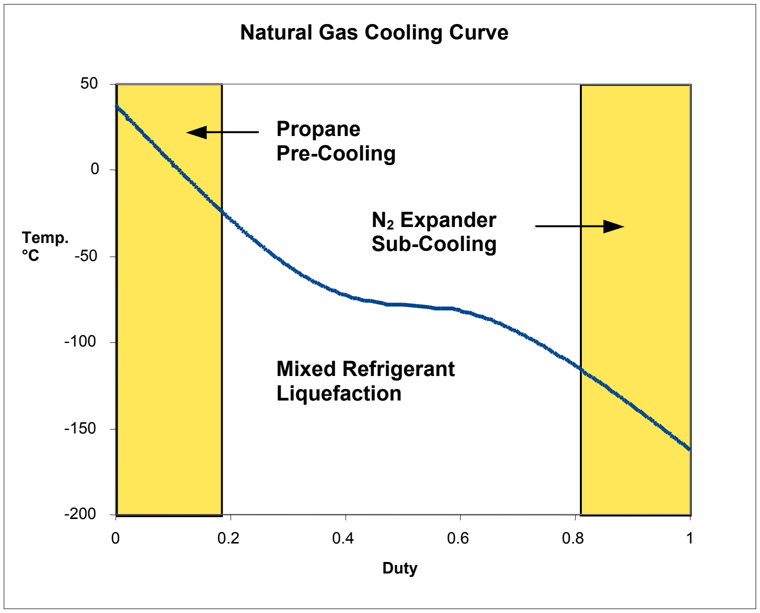
C_3-MR LNG train sizes have continued to grow with the availability of larger drivers and compressors, larger MCHE manufacturing capability, and continued process development. One recent advance that has allowed further increase in capacity is the Split MR™ machinery configuration that allows full utilization of two equal gas turbine drivers. Recent trains under construction utilizing this concept with two GE Frame 7 gas turbine drivers have liquefaction capacities of 4.5 to 5 Mta.

AP-X™ Hybrid LNG Process

While the C_3-MR process remains the preferred option in many cases, there exists substantial developing demand for larger train sizes than can easily be achieved with C_3-MR. For example, trains using multiple GE Frame 7 or Frame 9 gas turbine drivers or large electric motors can be configured. While it remains feasible to further increase train capacity with a C_3-MR process, new designs must be developed for several major equipment items at capacities exceeding 5.0 Mta. For example, the propane and centrifugal MR compressors are approaching single casing flow limits at current world scale LNG plant production levels.

In response to continuing customer demand for increased LNG train capacity and lower unit cost, Air Products has developed and patented[2] the AP-X™ Hybrid LNG Process. The AP-X™ process cycle is an improvement to the C_3-MR process in that the LNG is subcooled using a simple, efficient nitrogen expander loop instead of mixed refrigerant (figure 4). Other embodiments include a dual MR version where nitrogen is likewise used for subcooling.

Figure 4 AP-X™ Hybrid Process



In addition to improving the efficiency, the use of the nitrogen expander loop makes greatly increased capacity feasible. It does this by reducing the flow of *both* propane and mixed refrigerant. Volumetric flow of mixed refrigerant at the low-pressure compressor suction is about 60% of that required by the C_3-MR process for the same production. Mass flow of propane is about 80% of that required by the C_3-MR process.

With the new AP-X™ process, train capacities up to 8 Mta are feasible in tropical climates, in existing compressor frame sizes, without duplicate/parallel compression equipment, and using a spool-wound MCHE of a size currently being manufactured.

The nitrogen expander loop is a simplified version of the cycle employed by Air Products in hundreds of air separation plants and nitrogen liquefiers worldwide. Experience has shown these plants to be simple to operate and very reliable. Many of these plants are remotely operated, including shutdowns and restarts. The nitrogen cycle has also been employed by Air Products with similar success in small, stand-alone LNG peak-shaving plants.

The AP-X™ process cycle is depicted below in figure 5. As is the case with C_3-MR process, propane is used to provide cooling to a temperature of about -30 °C. The feed is then cooled and liquefied by mixed refrigerant, exiting the MCHE at a temperature of about -120 °C. Final subcooling of the LNG is done using cold gaseous nitrogen from the nitrogen expander.

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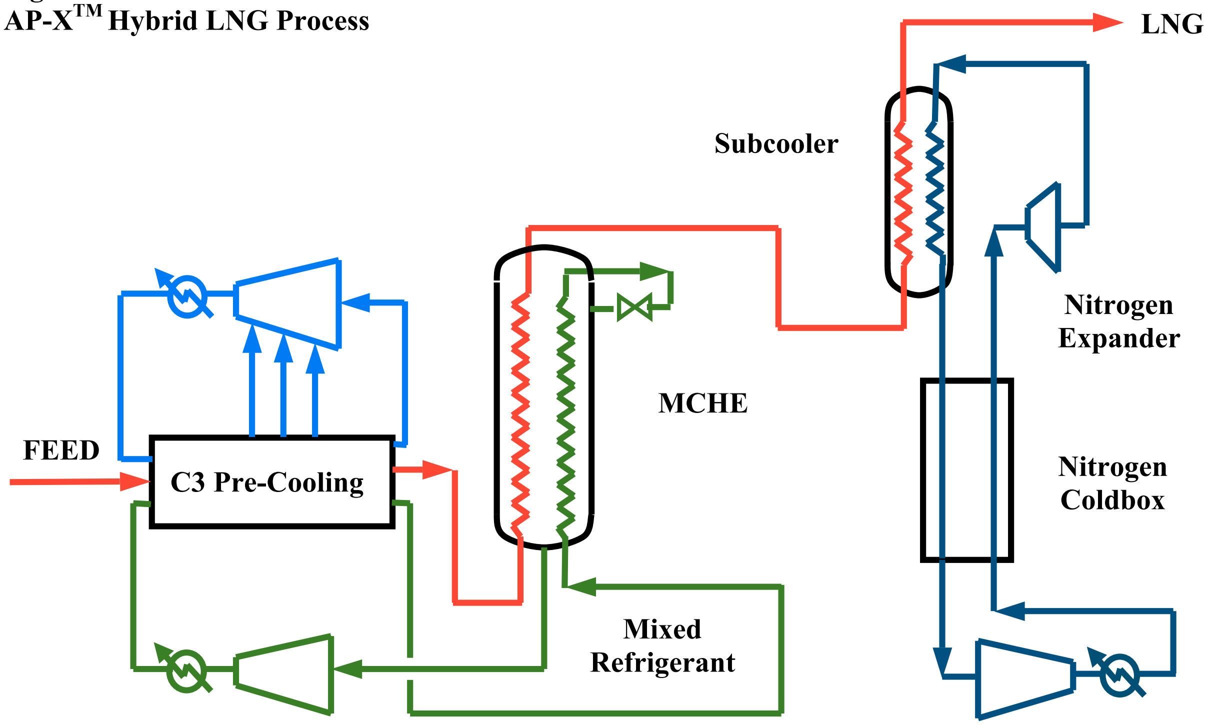
Figure 5
AP-X^{TM} Hybrid LNG Process



Gas Expander Cycle

Gas expander processes have been used for years in peak shaving natural gas liquefiers. In these applications, the simplicity and low cost are attractive. For larger applications however, processes using gas expanders alone or gas expanders with precooling are less attractive due to lower efficiency, although this has been mitigated somewhat in recent years by improving expander technology.

Gas expander cycles have an inherent efficiency disadvantage relative to pure or mixed fluid boiling cycles when providing warm refrigeration. Conversely, they are very efficient at providing cold refrigeration and are widely used for applications such as nitrogen, helium and hydrogen liquefaction where very cold refrigeration is required.

The AP-X^{TM} process is a hybrid of gas expander and fluid boiling cycles. The process achieves a high efficiency and low cost by using both cycles to their best advantage.

Why Nitrogen?

Nitrogen is the preferred working fluid for the expander cycle primarily because of its physical properties. Nitrogen has a vapor pressure of 17 to 23 bara at the required natural gas liquefaction temperature and has several advantages over a fluid that has a lower vapor pressure (e.g. methane). For example, the elevated pressure results in a relatively small volumetric flow rate in the low pressure nitrogen circuit. This decreases the size and therefore the cost of the associated equipment. To put it in perspective, the volumetric flow of nitrogen entering the nitrogen compressor is about 35% percent of the volumetric flow of low pressure mixed refrigerant at the compressor suction.

In addition, elevated pressure improves the efficiency by reducing the effect of pressure drop losses. Pressure drop losses are proportional to the absolute pressure. As a result, a given pressure drop has 10 times the impact at 2 bara as the same ΔP would have at 20 bara.

Expandable and Flexible

It is possible to operate an AP-X™ train at a reduced production rate of about 65% without the nitrogen expander loop by adjusting the composition of the mixed refrigerant inventory.

The ability to operate an AP-X™ process plant in C_3-MR mode can also be exploited as an expandable plant. For example, a producer may choose to invest in a nominal 5 Mta C_3-MR train with plans to expand production later to a level of up to 8 Mta by adding the nitrogen expander cycle as the market develops.

Retrofitting an existing plant with a nitrogen expander cycle to subcool the LNG is also possible, although the production increase will be more modest due to bottlenecks with existing equipment.

The power split between C_3, 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.

Summary

Economies of scale continue to favor increasing train size for baseload LNG plants. In response to continuing producer demand for increased LNG train capacity, Air Products has developed the AP-X™ LNG process. The AP-X™ process is a hybrid of a C_3-MR cycle for precooling and liquefying LNG and a nitrogen gas compressor/expander cycle for subcooling LNG. The process achieves high efficiency and low production cost by using both cycles to their best advantage.

Table 1 presents a comparison of the C_3-MR and AP-X™ processes. With the new AP-X™ process, train capacities up to 8 Mta are feasible in tropical climates, using existing compressor frame sizes without split casing or duplicate compression equipment, and using a spool-wound MCHE of a size currently being manufactured.

Table 1

Relative Comparison of AP-X™ and C_3-MR Processes

	C_3-MR	AP-X™
Capacity, Mta	Up to 5	Up to 8
MR Compressor volumetric flow per unit production (relative)	1.0	0.6
Propane compressor mass flow per unit production (relative)	1.0	0.8
Specific Power (relative)	1.00-1.05	1.0

Endnotes

1. Liu, Y.N., et. al. “Reducing LNG Costs by Better Capital Utilization” LNG 13 International Conference 2001, Seoul, Korea
2. Roberts, et. al. “Hybrid Cycle for the Production of Liquefied Natural Gas” US Patent 6,308,521