

**LARGE LNG TRAINS: DEVELOPING THE OPTIMAL PROCESS CYCLE**

Mark R. Pillarella

Lead Process Engineer, LNG

James C. Bronfenbrenner

Senior Process Manager, LNG

Yu-Nan Liu

Technical Director, LNG

Mark J. Roberts

Lead Process Engineer, LNG

Air Products and Chemicals, Inc.

Allentown, PA 18195-1501

## INTRODUCTION

Increases in energy demand and the need for cleaner burning fuels have caused an unprecedented increase in global demand for liquefied natural gas. In meeting the increased demand, developers of new LNG projects can benefit from the economies of scale and improved efficiencies achievable from larger train sizes.

LNG train capacity has continued to increase substantially as shown in Figure 1. This has been due to advancements in both process equipment and cycle design. For train capacities up to 5 mta, the C3-MR process has been the dominant technology. Recent advances in main exchanger manufacturing capabilities have made it possible to extend the range of the C3-MR process to over 6 mta. In addition, the industry is poised to make a significant increase in train capacity to 7.8 mta with the introduction of the Air Products AP-X™ process in Qatar, which is expected to start operation in 2007. Studies have shown that single train capacities up to 10 mta are feasible with the AP-X™ process.

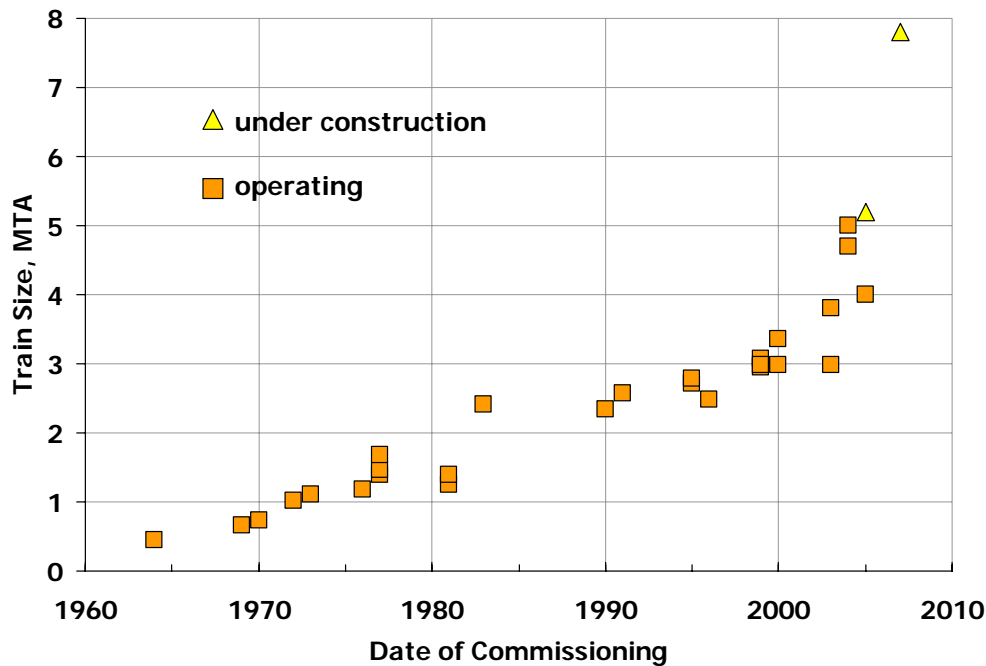


Figure 1: LNG train size growth

When extending the range of existing processes or developing new processes, the task of finding the optimal design point in a reasonable time can be daunting. The flow schemes are complex with many interdependent variables and constraints. Using conventional simulation tools, the quality of a manual optimization exercise is both limited and time consuming.

To address these issues, Air Products utilizes sophisticated, proprietary numerical optimization routines and techniques specifically developed for the difficult multivariable optimization encountered in LNG liquefaction processes. Customized engineering models for major equipment components (e.g. refrigerant compressors, exchangers) are also incorporated.

When increasing LNG train capacity, it is particularly important to develop an efficient process cycle in order to maximize the economies of scale. Exergy analysis has been used in the cryogenic industry to evaluate and improve the efficiency of process cycles. This technique is based on engineering fundamentals. It can identify the impact of the efficiency of individual equipment on the overall process and highlight areas in which improvements will produce the most benefits. Coupled with cost information, reliability data, and environmental requirements, this technique provides a fundamentally based method for selecting and improving the LNG flow scheme to best meet the specific project requirements.

This paper focuses on these key elements necessary for development of LNG process cycles: sophisticated optimization techniques incorporating customized engineering models and the application of exergy analysis. Although applicable to train capacities of all sizes, they are crucial to large train development in order to maximize the utilization of equipment operating within proven design parameters with the goal of maximizing production and minimizing cost.

## OVERVIEW OF PROCESS CYCLE DEVELOPMENT

An overview of the methodology for process cycle development is shown in Figure 2. Typically, a design basis prepared by the plant owner or representative is provided. It contains key project requirements and insures that the final process design will meet the project goals. Specifications in the design basis can include:

- (1) process requirements such as design feed conditions, product specifications, fuel balance specifications, ambient conditions, etc.;
- (2) reliability and flexibility requirements such as on-stream time, variations in feed conditions and ambient conditions, and potential for expansion;
- (3) environmental restrictions such as flaring limitations, CO<sub>2</sub> emissions, etc.;
- (4) economic factors including guidelines to allow engineering cost/benefit trade-offs;
- (5) driver and compressor requirements.

The design basis is used to develop a process flow scheme. The process engineer uses knowledge of the impact of the design basis specifications to develop a flow scheme most suitable for the specific requirements. This step is particularly important since the results of optimizing a particular process scheme can only be as good as the scheme itself.

Several engineering software tools are available in the public domain for simulating the flow sheet. Although these tools may contain their own optimization routines, customization for optimizing LNG process cycles is crucial due to the many variables and constraints in the process. Air Products utilizes a sophisticated successive quadratic programming based optimization technique specifically developed for the difficult multivariable optimization encountered in LNG liquefaction processes. The need and benefit of such customization is discussed in more detail in the next section.

When developing the simulation, it is important to include practical specifications and constraints to insure a realistic result. For example, Air Products has developed the ability to include design constraints for the refrigerant compressors in simulations to insure that the simulations results reflect realistic compressor performance. The effect of the spiral-wound main cryogenic heat exchanger (MCHE) geometry on heat transfer and pressure drop is also accounted for in order to insure an optimum MCHE design.

The results of the optimized simulation are evaluated based on the project requirements. Exergy analysis is used to assess where potential efficiency benefits may exist. Based on the exergy analysis, flow sheet modifications can be considered and evaluated as necessary.

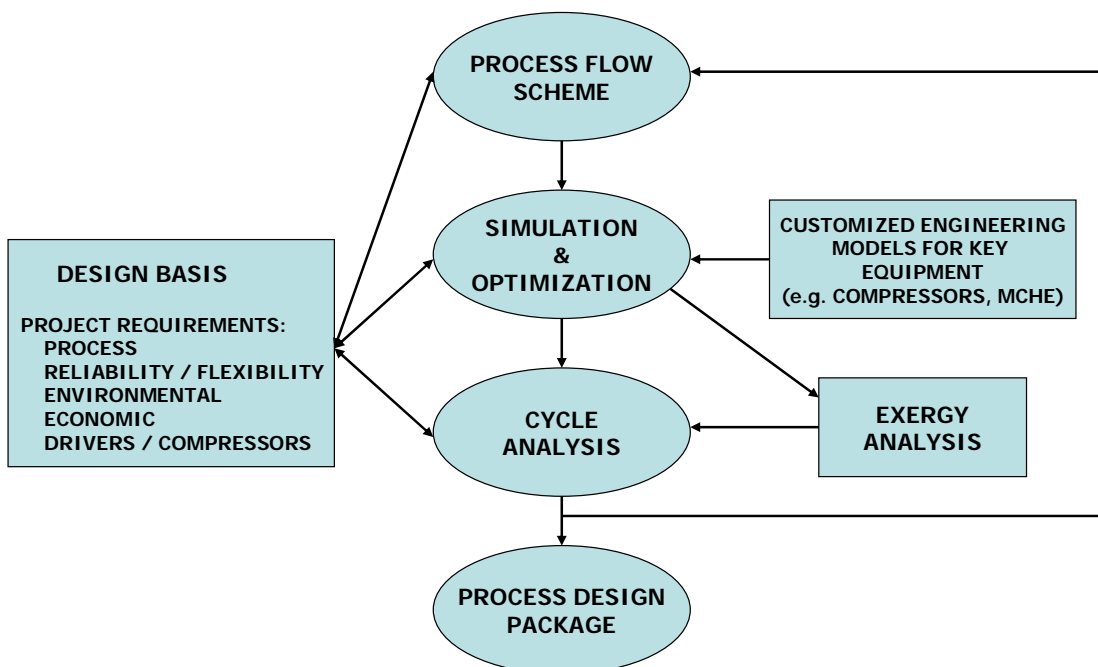


Figure 2: Overview of process cycle development

## SIMULATION AND OPTIMIZATION

Development of a LNG liquefaction process cycle involves multivariable optimization. The number of variables, typically ranging from 20 to 50, depends on the flow scheme and project specifications. Variables include temperatures, temperature approaches, pressures, pressure drops, flows, mixed refrigerant composition, and compressor speed. There are also additional variables associated with distillation columns used for LPG separation and recovery. Many of the variables are interdependent. Parametric studies, while helpful, are unwieldy and involve many simulations. Consequently, as the number of parameters increases the number of required simulations increases exponentially.

The variables should only be optimized within the constraints of proven equipment design criteria. More than 50 constraints are often associated with LNG optimization simulations. They include constraints on equipment such as refrigerant compressors, heat exchangers, and hydraulic expanders. They can be input into the optimization routine as simple expressions or elaborate functions involving multiple variables.

The illustrative example shown in Figure 3 for the AP-X™ process helps to demonstrate the complexity of the optimization process and the power of sophisticated optimization techniques. It shows the effect of a two variable parametric study (mixed refrigerant methane and ethane composition) on the overall specific power (kw-hrs/ton of LNG) of the liquefaction process. Changes in mixed refrigerant composition can have a substantial impact on specific power. The composition affects the efficiency of the main exchanger which in turn affects the specific power.

Over 50 simulations were required to create this *two* variable parametric study and adequately determine the minimum specific power. As the number of variables increases, rigorously finding the optimum quickly becomes infeasible. For example, a two interdependent variable parametric study involving ten values of each requires  $10^2$  (100) simulations. However, a three variable study requires  $10^3$  (1000) simulations. Also, the number of values chosen for each variable directly impacts the quality of the result; i.e. if too few are chosen the true optimum will not be found.

Even standard optimization techniques have trouble with complex multivariable simulations involving many constraints. Conversely, using sophisticated simulation/optimization techniques, the optimum is more easily found, leaving valuable time for cycle analysis and alternate flow sheet considerations.

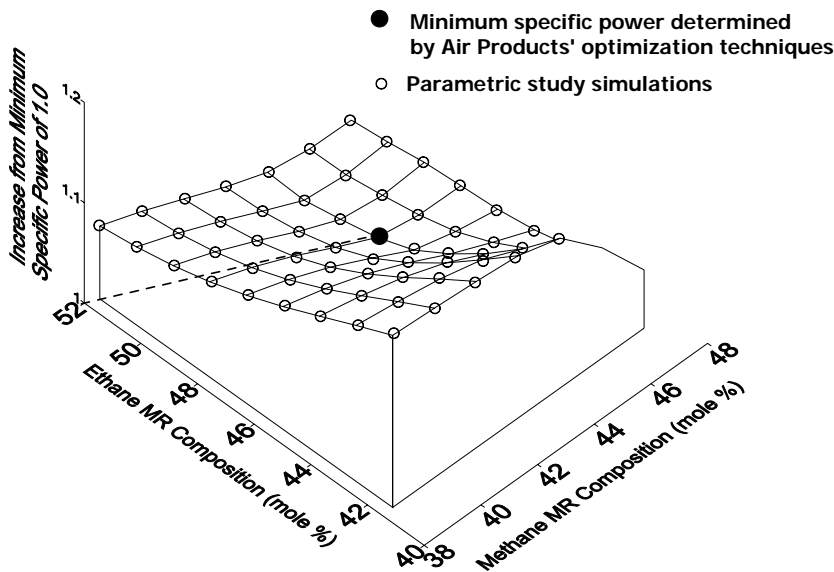


Figure 3: Effect of mixed refrigerant composition on specific power

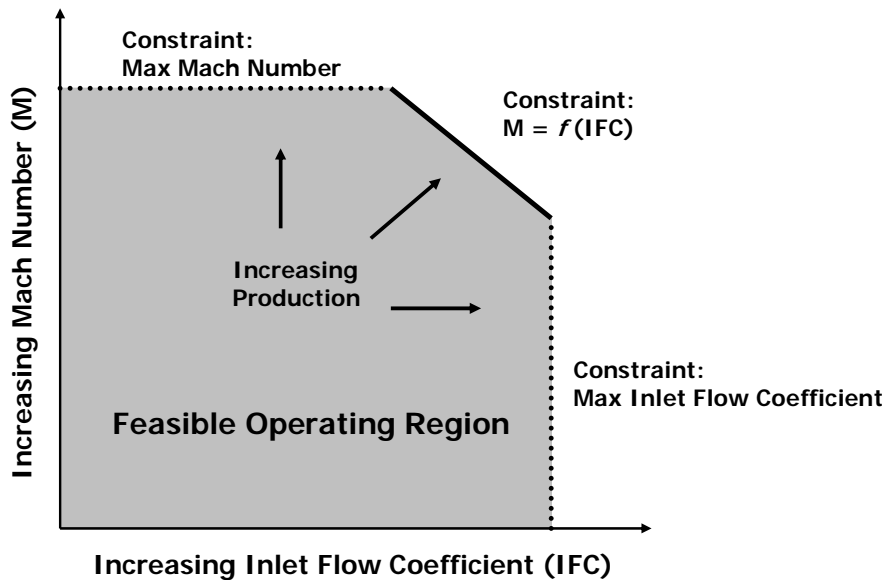
Most LNG projects require the flexibility and reliability to operate under various conditions. Cooling water temperature, ambient air temperature, feed composition, power availability, product demand can change. The impact of these on LNG production can be readily evaluated using the process simulation/optimization techniques described previously. For these cases, equipment size is fixed and based on the chosen design case, and the process performance is rated for the off-design conditions<sup>1</sup>. However, variables that can be changed, such as mixed refrigerant composition, are more easily re-optimized.

Typically, optimization has been based on maximizing production, minimizing power, or minimizing specific power. In addition, the sophistication of the simulation/optimization process makes it possible to include actual equipment cost information. This permits the analysis of engineering cost/benefit trade-offs and thus provides an optimum *economic* design.

## CUSTOMIZED ENGINEERING MODELS

Certain design specifications and constraints must be met when developing the process cycle. These are the “rules” which must be abided by in order to have a “buildable” process that meets the project goals. Some are defined in the design basis, such as feed and product conditions, fuel requirements, ambient conditions, etc. Others are not included in the design basis and are typically equipment-related. The two most important are related to refrigerant compressors and main exchanger design.

To insure a robust, reliable refrigerant compressor design, compressor manufacturers have developed aerodynamic compressor design constraints for volumetric flow, equivalent head, impeller diameter, peripheral mach number, and inlet flow coefficient. As an example, an illustrative diagram of the relationship between mach number and inlet flow coefficient for refrigerant compressors is shown in Figure 4. The feasible operating region is bounded by constraints on the maximum mach number and inlet flow coefficient. In a portion of the boundary, the maximum allowable mach number is a function of the inlet flow coefficient. As train capacities are increased for a given flow scheme, the allowable limits are approached. In order to achieve maximum utilization of refrigerant compressor capabilities, the Air Products simulator uses an in-house customized compressor model which insures that the process is optimized within the given constraints. This provides realistic process specifications from which the compressor manufacturer can develop the mechanical design.



**Figure 4: Diagram of feasible operating region for refrigerant compressor mach number and inlet flow coefficient**

The simulator also incorporates an In-line Compressor Efficiency Correlation (ICEC™) based on actual compressor data. ICEC™ calculates performance based on impeller diameter, stage shape characteristics, and mach number related effects. It predicts compressor efficiency to within +/- 2 percentage points accuracy and can be easily modified to reflect manufacturer differences and future design improvements<sup>2</sup>. This minimizes time consuming iterations with the compressor manufacturers and insures a near optimal design on the first pass.

Design and manufacture of the spiral-wound main exchanger is a sophisticated, highly technical process. The internal geometry of the main exchanger impacts performance. Number of tubes, length of tubes, winding angle, number of tube layers, spacing between tube layers, etc. affect the heat transfer and pressure drop in the exchanger and ultimately production. Air Products has developed tools that provide for a smooth interface between the process design and the mechanical design. Integration of these tools into the simulation and optimization process insures that the main exchanger design is mechanically viable, efficient, and optimized for the project requirements.

This intertwining of the process and mechanical design has also been critical in determining when and how the design could be enhanced to accommodate larger train sizes. An excellent example of this is the AP-X™ process in which train capacity was increased over 50% compared to a typical C3-MR process. Knowledge and experience of both process and

mechanical/aerodynamic design were utilized to greatly increase train capacity while still staying within the experience-base, significantly minimizing risk.

## EXERGY

Exergy analysis is useful for evaluating and improving the efficiency of process cycles. It can identify the impact of the efficiency of individual equipment on the overall process and highlight areas in which improvements will produce the most benefits.

Exergy is defined as: 
$$\text{Exergy} = H - T_0S$$

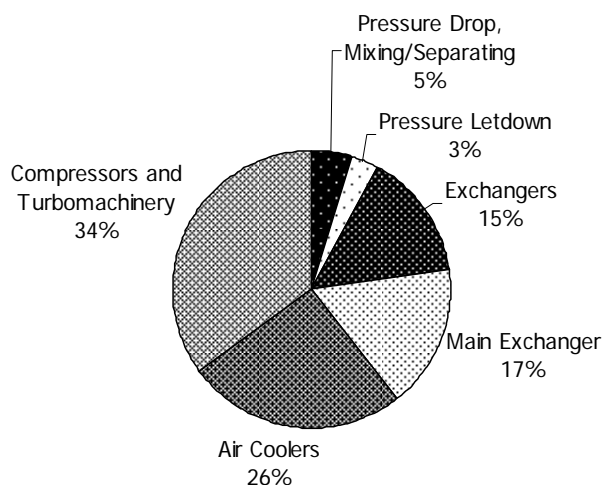
where H is enthalpy, S is entropy, and  $T_0$  is the absolute temperature of the heat rejection sink. For LNG processes,  $T_0$  is the temperature of the ambient air or cooling water since this is the ultimate heat sink for the process.

The overall change in exergy of the streams flowing in and out of an equipment unit (e.g. heat exchanger, compressor) is the amount of lost work for that unit. The thermodynamic efficiency can be determined as follows:

$$\text{Efficiency}(\%) = \frac{\text{Total work required} - \text{Lost work}}{\text{Total work required}} * 100$$

In order to improve cycle efficiency, lost work must be reduced. Exergy analysis indicates where the greatest potential improvements to the cycle can be achieved. The engineering cost/benefit trade-offs must be evaluated to determine the economic optimum. Coupled with cost information, reliability data, and environmental requirements, this technique provides a fundamentally based method for optimizing the LNG liquefaction process for the specific project requirements.

The evaluation of the lost work components for a typical AP-X™ process is shown in Figure 5. Refrigerant compressors, air coolers, and heat exchangers have the largest exergy losses and, therefore, the largest impact on efficiency.

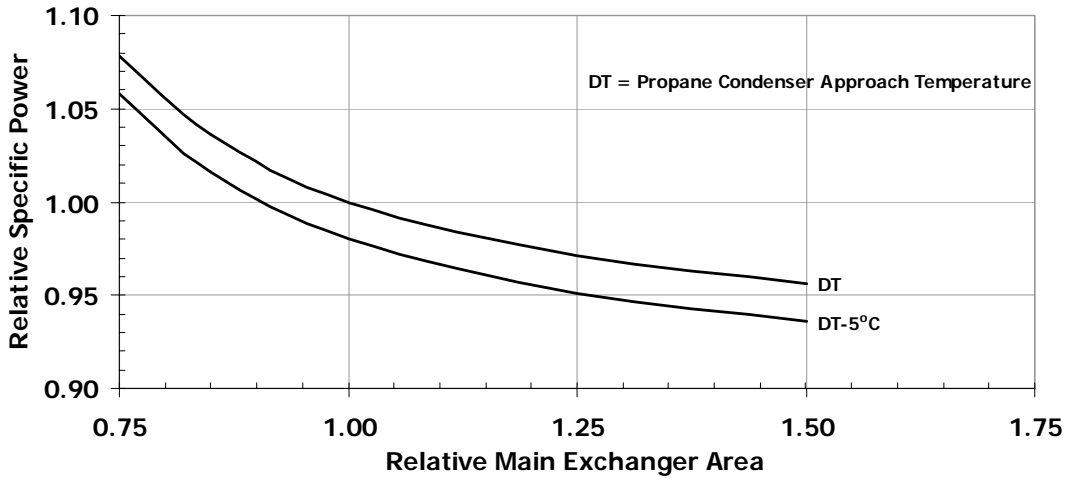


**Figure 5: Components of lost work for a typical AP-X™ process cycle**

Integration of the process optimization with the compressor capabilities using the customized engineering model incorporating compressor constraints and the ICEC™ efficiency correlation minimizes the amount of lost work in the compressor strings.

Efficiency in the main exchanger can be improved (lost work reduced) by reducing the temperature approach between the hot and cold streams. This leads to a reduction in specific power for the liquefaction process. This can be accomplished by increasing main exchanger surface area as illustrated in Figure 6. As the area is increased, the specific power is reduced. However, as the minimum achievable specific power is approached, the exchanger area increases substantially, indicating that there is an economic optimum.

Specific power can also be reduced by decreasing the propane condenser approach to ambient temperature as shown in Figure 6. Since condenser surface area is increased, the results must be evaluated in conjunction with condenser cost as well as available plot space.



**Figure 6: Effect of main exchanger area and propane condenser approach temperature on specific power for a typical LNG liquefaction process**

## ECONOMIES OF SCALE

Typically, cost per ton of LNG decreases as train capacity increases. The transition to two trains usually results in an increase in cost per ton. Larger train sizes can benefit from economies of scale through equipment capacity increases and process cycle improvements. The techniques described previously have been used to address the challenge of developing larger capacity process cycles that maximize the utilization of proven equipment such that the costs of larger equipment and possibly additional equipment are more than offset by capacity increases.

For example, extending the C3-MR plant capacity to 6 mta and beyond can be achieved with increases in installed power and heat exchanger capacity. The LNG industry has begun using GE frame 9 gas turbine drivers to increase installed power. The power is increased by about 40% over the GE frame 7 drivers (typically used for 3 to 5 mta C3-MR processes) with a reduction in the driver cost per installed kilowatt. Studies carried out by Air Products have demonstrated that main cryogenic heat exchangers of the required size can be manufactured and shipped as a single unit from the port currently used for shipping. The heat exchanger would be larger and heavier than those built to date, but would have no significant changes to the design or construction.

As LNG train capacity continues to increase, the AP-X™ process offers a cost effective single train option. A schematic of the AP-X™ process<sup>3</sup> is shown in Figure 7. It debottlenecks the traditional C3-MR process in that the LNG is subcooled using a simple, efficient nitrogen expander loop instead of mixed refrigerant. The use of the nitrogen expander loop makes greatly increased capacity feasible while using proven equipment. It does this by reducing the flow of both propane and mixed refrigerant. Other embodiments include a dual mixed refrigerant version in which another mixed refrigerant loop is used for pre-cooling and nitrogen is likewise used for subcooling.

The AP-X™ process takes advantage of the economies of scale that can result from larger single train capacities. Merlin Associates has completed an independent study comparing the cost of a single 8 mta AP-X™ train to that of two 4 mta C3-MR trains<sup>3</sup>. It was concluded that the unit cost of LNG production is lowered significantly with the AP-X™ process.

Expansion of existing plant capacity can also benefit from economies of scale and improved efficiency. Using actual plant data and the process simulation/optimization techniques and methodology discussed previously, several debottlenecking studies have been completed on existing LNG plants.

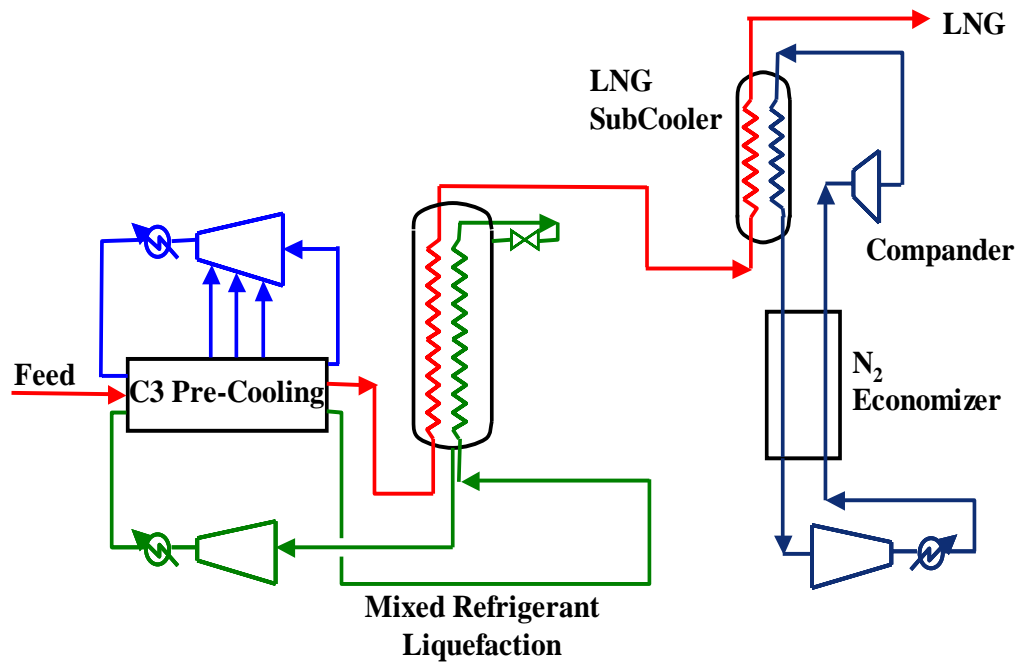


Figure 7: AP-X™ LNG process

## SUMMARY

LNG train capacity is continuing to increase due to advancements in both process equipment and cycle design. Increasing market demand for LNG is driving the development of LNG liquefaction processes with even larger train capacity. This is evident in the implementation of the 7.8 mta AP-X™ process in Qatar.

Sophisticated process design and optimization tools and techniques are being employed to determine the optimal design for LNG liquefaction plants. The simulation tools incorporate customized models for major equipment based on actual field/test data. A fundamental engineering approach using exergy analysis is used along with the state-of-the-art optimization methods to develop efficient, economic designs that meet the project cost, reliability, flexibility and environmental requirements. In this way, a technology driven approach is utilized to satisfy the demand in the LNG industry for more LNG at a lower cost.

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