

REDUCING LNG CAPITAL COST IN TODAY'S COMPETITIVE ENVIRONMENT

REDUCTION DU COUT D'INVESTISSEMENT DU GNL DANS LE CLIMAT DE CONCURRENCE ACTUEL

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ABSTRACT

The Air Products 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 to 5 Mta of LNG per train, using steam and gas turbine drivers, sea water and air cooling, rich and lean feeds containing a broad range of nitrogen, with and without LPG extraction. The process has proven to be efficient, flexible, reliable, and cost competitive.

The AP-X™ LNG Process will increase single train capacities to 7-10 Mta. This capacity expansion has the potential to bring down the capital cost of LNG significantly. By producing warmer LNG at pressure, today's C3MR process capacity can be increased up to 80% with the same proven equipment in use today. The warmer LNG is then subcooled to storage temperature by an all vapor, nitrogen refrigerant in a compression/expansion cycle that has been used for years to liquefy oxygen, nitrogen, and natural gas. The efficiency of this process is as good as what has been achieved in the industry by any other process, while the capital cost of the liquefier is reduced significantly.

This paper will present applications of the AP-X™ LNG Process to achieve not only maximum capacity in a single train with a variety of compressor drivers, but also high LPG recovery, lower LNG heating value for new markets, and maximum efficiency. This range of applications demonstrates that the AP-X™ LNG Process brings significant economies of scale to the industry, reducing the capital cost of LNG while maintaining the efficiency, flexibility, and reliability of the C3MR process.

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RESUME

Le procédé de réfrigérant mixte de production du GNL au propane pré-refroidi d'Air Products (C3MR) a été la constante de l'industrie du GNL depuis plus de trente ans. Il est appliqué dans les usines de GNL produisant 1 à 5 Mtpa de GNL par chaîne, utilisant des turbines à gaz et à vapeur, le refroidissement par air et eau de mer, et des alimentations riches ou pauvres contenant une quantité variée d'azote, avec ou sans extraction de LPG. Ce procédé s'est révélé efficace, souple, fiable et rentable.

Le Procédé de GNL AP- XTM augmentera la capacité de 7 à 10 Mtpa par chaîne. Cette expansion de capacité a le potentiel de faire baisser les coûts d'investissement de manière significative. En produisant du GNL plus chaud à la pression, la capacité actuelle du C3MR peut être augmentée de 80% avec le même équipement éprouvé utilisé de nos jours. Ensuite, le GNL plus chaud est refroidi à la température de stockage par un refroidissant d'azote tout à la vapeur au moyen d'un cycle de compression/expansion utilisé depuis des années pour liquéfier l'oxygène, l'azote et le gaz naturel. Etant donné que les propriétés thermodynamiques de l'azote et l'équipement utilisé conviennent bien à l'application de refroidissement, l'efficacité de ce procédé est aussi bonne que celle obtenue par tout autre procédé industriel tout en permettant de réduire le coût d'investissement du liquéfacteur de manière significative.

Cet exposé présente les applications du procédé GNL AP-XTM pour obtenir non seulement la capacité maximum en une seule chaîne avec une variété de compresseurs, mais aussi un taux de récupération élevé de LPG, une valeur de réchauffement plus faible du GNL pour les nouveaux marchés et une efficacité optimale. Cette gamme d'applications démontre que le procédé GNL AP-XTM procure des économies significatives, tout en réduisant le coût d'investissement du GNL et en conservant l'efficacité, la souplesse et la fiabilité du procédé C3MR.

INTRODUCTION

Air Products is the leader in supplying liquefaction 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 pre-cooled, mixed refrigerant process (C3MR) in 1972 at Brunei, to trains currently under construction utilizing the Split-MRTM 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.

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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.

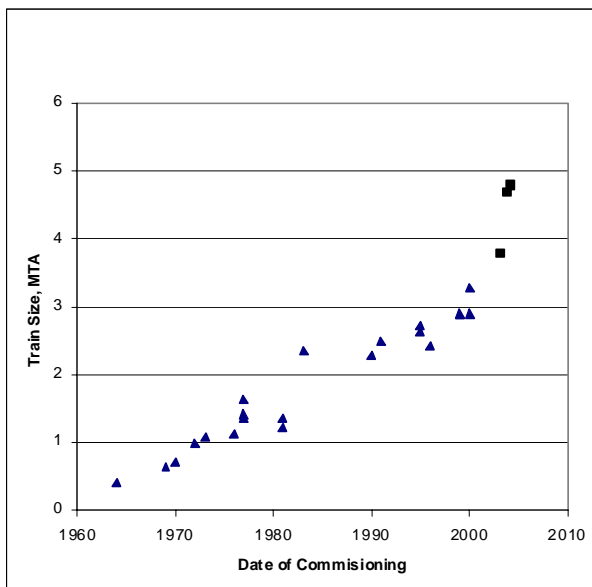


Figure 1: LNG train size growth

The AP-X™ LNG Process achieves not only high capacity in a single train, but also can incorporate high LPG recovery, lower LNG heating value for new markets, and maximum efficiency. This range of applications demonstrates that the AP-X™ LNG Process brings significant economies of scale to the industry, reducing the capital cost of LNG while maintaining the efficiency, flexibility, and reliability of the C3MR process.

AP-X™ LNG PROCESS

While the C3MR process remains the preferred option in many cases, there exists substantial developing demand for larger train sizes. 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 C3MR 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™ LNG Process. The AP-X™ process cycle is an improvement to the C3MR process in that the LNG is subcooled using a simple, efficient nitrogen expander loop instead of mixed refrigerant. Other embodiments include a dual MR version where another MR refrigeration loop is used for pre-cooling and nitrogen is likewise used for subcooling.

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 C3MR process for the same production. Mass flow of propane is about 80% of that required by the C3MR process.

With the new AP-XTM process, train capacities in excess of 8 Mta are feasible in tropical climates, in existing compressor frame sizes, without duplicate/parallel compression equipment, and using a single 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-XTM process cycle is depicted below in figure 2. As is the case with C₃-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. Figure 3 shows the equipment layout for the liquefaction and subcooling sections of an AP-XTM train. Coil-wound heat exchangers are used to liquefy and subcool the LNG, while the nitrogen economizer uses brazed aluminum plate-fin heat exchangers.

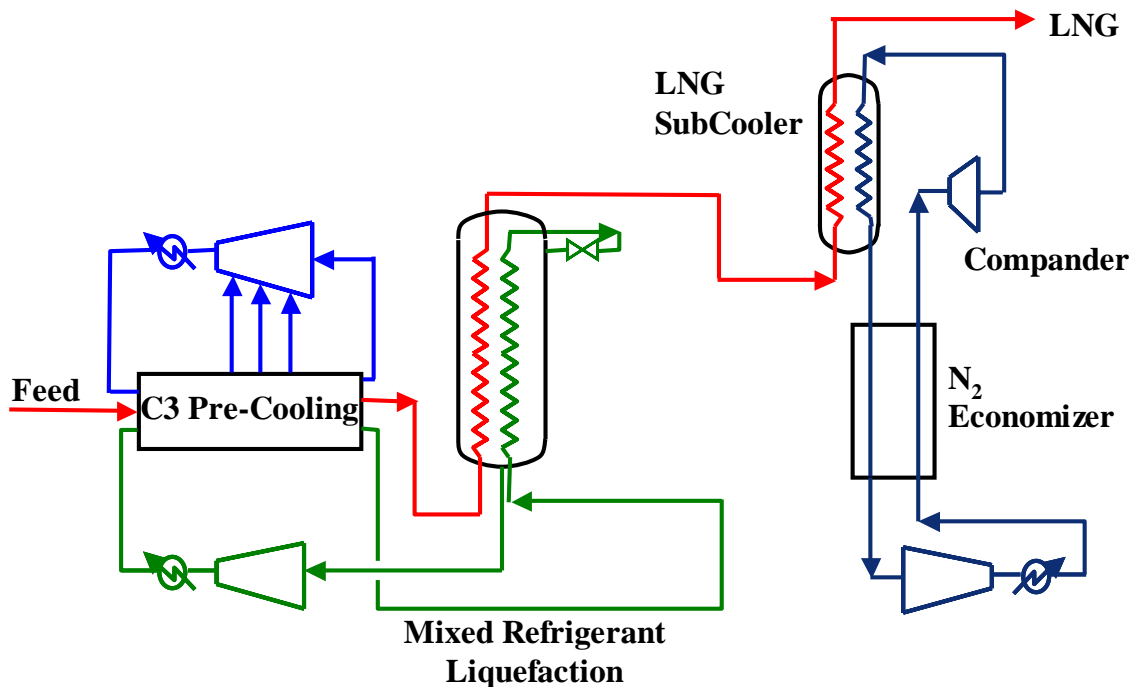


Figure 2: AP-XTM LNG process

Expandable and flexible

MCR[®] Cryogenic Heat Exchanger

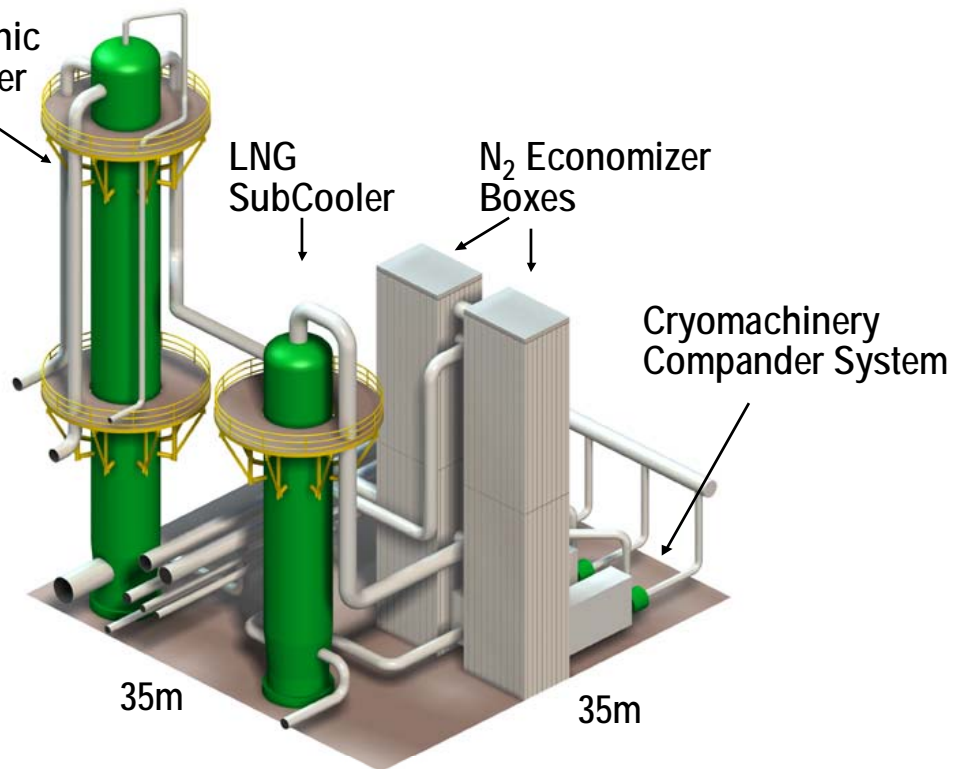


Figure 3: AP-X™ LNG process layout

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 C3MR mode can also be exploited as an expandable plant. For example, a producer may choose to invest in a nominal 5 Mta C3MR 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.

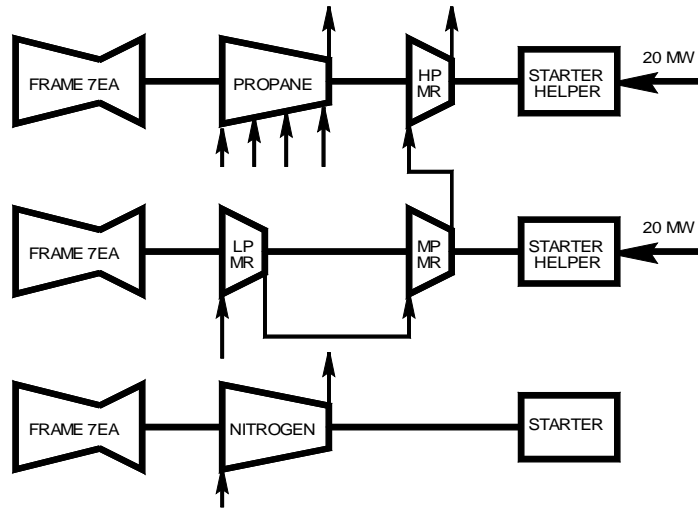
POSSIBLE DRIVER CONFIGURATIONS

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 7's, Frame 9's, electric motors or combinations of the above.

Three Frame 7EA drivers

A nominal production of 7.5 Mta in a tropical environment is possible using the AP-X™ process with three Frame 7 drivers. The configuration of drivers is shown in figure 4.

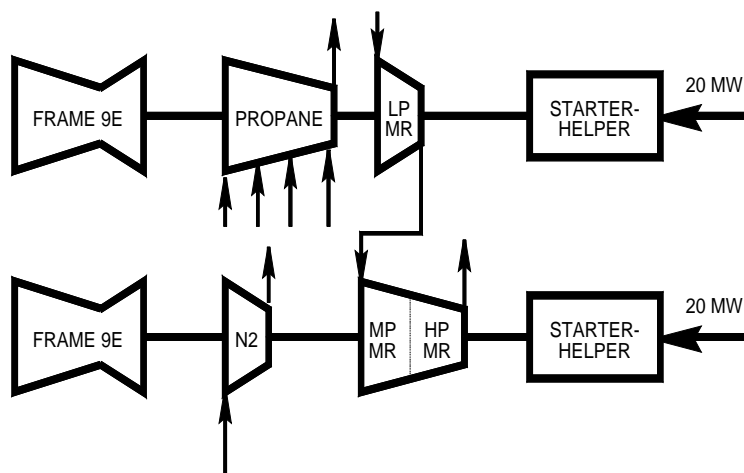
In this case, the Split-MR™ machinery configuration is used with 20 MW starter/helper motors on two of the drivers.



**Figure 4: Three Frame 7 drivers
Nominal 7.5 Mta train capacity**

Two Frame 9E drivers

Frame 9 drivers are very attractive for large trains. They provide 50% more power than a Frame 7 driver at a cost increase of less than 20%. It is possible to achieve the same production from two Frame 9 drivers as from three Frame 7 drivers. Frame 9 drivers also have an advantage in that their lower operating speed (3000 RPM) allows larger capacities in a single propane compressor casing. Figure 5 shows a configuration producing a nominal 7.5 Mta using two Frame 9 drivers and 20 MW helper motors. This configuration uses a modification of the Split-MR™ machinery configuration in which propane and LP MR compressors are on one driver with nitrogen and MP/HP MR compressors on the other driver.



**Figure 5: Two Frame 9 drivers
Nominal 7.5 Mta train capacity**

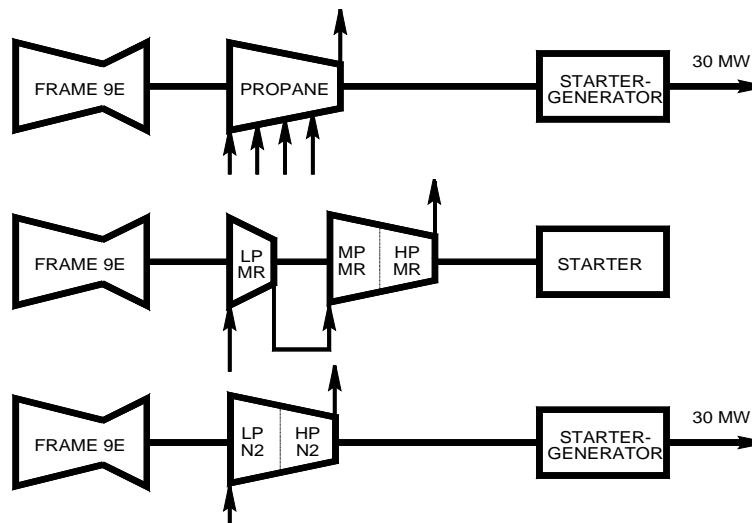
Three Frame 9E drivers

With the AP-X™ process, three Frame 9 drivers can be used to achieve a nominal production in the range of 8-10 Mta in a tropical environment. It is also possible to use a combination of Frame 9 and Frame 7 drivers at the low end of this range, depending on the specific project requirements.

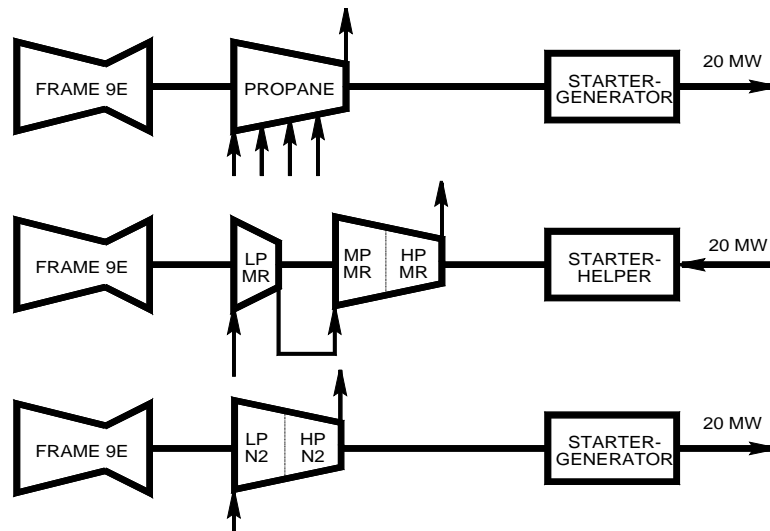
At the low end of the 8-10 Mta production range, a significant amount of power can be generated from starter/generator motors using three Frame 9 drivers thus unloading the power requirement of the power generation facility. Each compression service (propane, mixed refrigerant and nitrogen) can be driven separately allowing maximum operational simplicity.

To achieve a production rate at the high end of the 8-10 Mta range, the Split-MR™ machinery configuration can be used to balance the driver power requirement of the three Frame 9 drivers and to reduce the size of the starter/helper and starter/generator motors. For a production rate approaching 10 Mta two propane compressor casings will be required to stay within the limits of proven compressor designs.

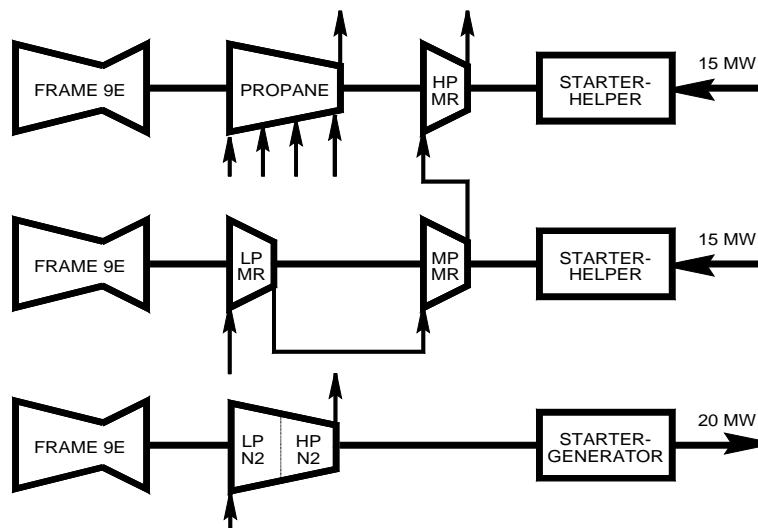
Figures 6,7 and 8 show configurations utilizing three Frame 9 drivers for liquefaction capacities of 8,9 and 10 Mta respectively. At the low end of the range (figure 6) a train will export about 60 MW of electricity, while at the high end of the range (figure 8) a train will import about 10 MW of refrigeration power from the grid.



**Figure 6: Three Frame 9 drivers
Nominal 8 Mta train capacity**



**Figure 7: Three Frame 9 drivers
Nominal 9 Mta train capacity**



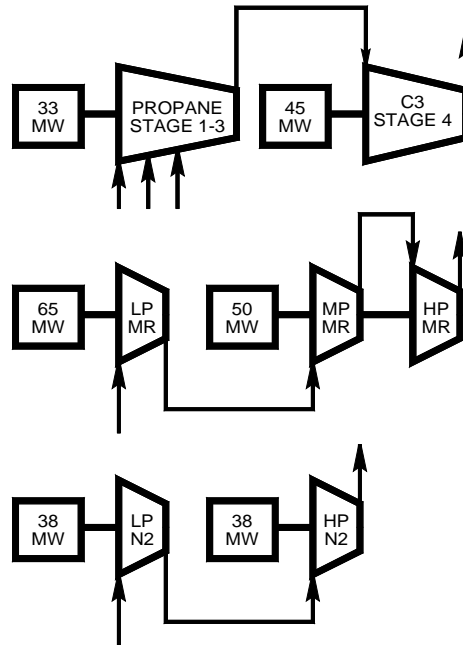
**Figure 8: Three Frame 9 drivers
Nominal 10 Mta train capacity**

Electric motor drive

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 AP-X™ process. Liquefaction capacities from 7-10 Mta can be easily achieved, 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 a Variable Frequency Devices, the speed of each compressor can be optimized not only to achieve maximum compressor

aerodynamic efficiency at a design point but also at the warm and cold ambient temperature extremes.

Depending on the desired capacity and the maximum electric motor size, many different configurations are possible. Figure 9 shows one example; for a train producing 8 Mta using electric motors up to 65 MW in size.



**Figure 9: Electric motor drive
65 MW maximum motor size**

LPG RECOVERY

In general, the AP-XTM LNG process offers the same flexibility with regard to LPG recovery as the C3MR process. The AP-XTM LNG process can be configured to achieve nearly any desired level of LPG recovery. Modest LPG recovery can be achieved using a conventional scrub column with cold (lower than propane) condenser refrigeration provided by a tube circuit in the MCHE.

LPG recovery using lean oil recycle

If greater LPG recovery is desired, a lean oil wash stream can be used. 85-90% propane recovery can be obtained using this approach. As shown in figure 10, a lean oil stream from the fractionation system is recycled to the scrub column a few trays below the top. The top section of the scrub column then functions as a rectifier, removing lean oil components from the product, while the section of the scrub column below the recycle functions as an absorber to recover LPG's.

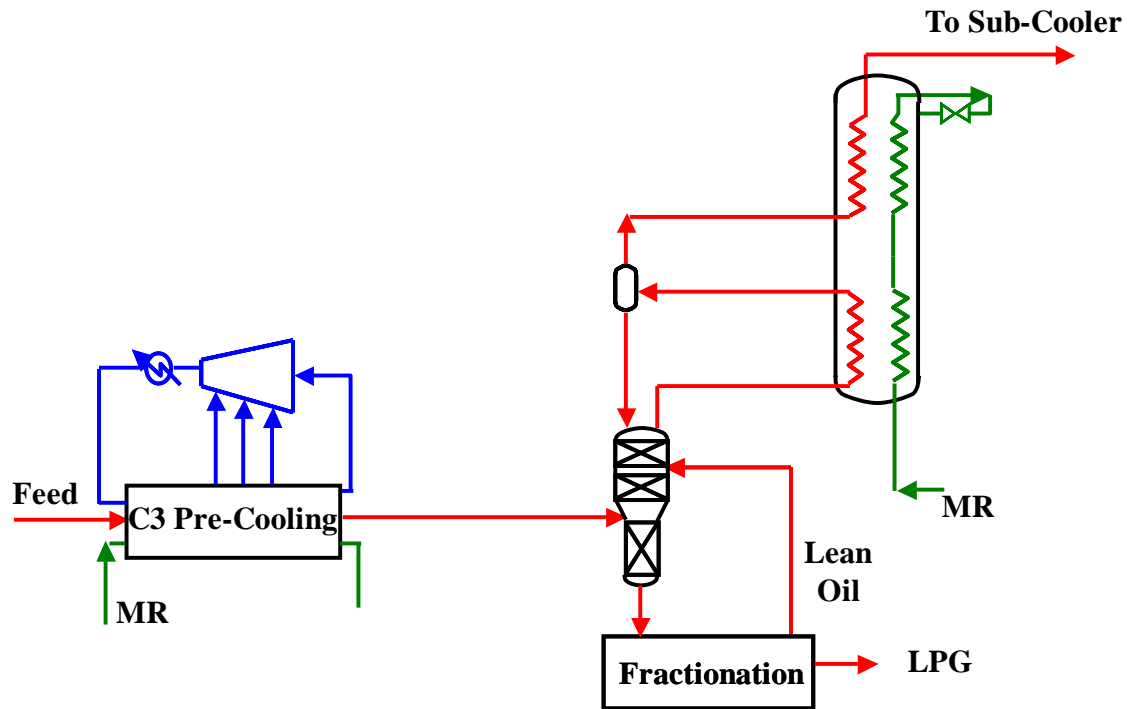


Figure 10: LPG recovery using lean oil recycle

LPG recovery using an integrated expander cycle

If a higher level of LPG recovery is desired, an LPG recovery expander cycle can be integrated into the refrigeration train. Depending on the feed pressure, feed composition and the desired recovery, different configurations can be used. Figure 11 shows one configuration. In this case, the pre-cooled feed to the scrub column is expanded using a compander. The scrub column condenser is refrigerated using the MCHE. The overhead stream from the scrub column is then compressed by the compander, and re-introduced into the MCHE for cooling and liquefaction. For higher recovery or when processing lower pressure feeds, additional compression besides that provided by the compander may be provided to the scrub column overhead stream.

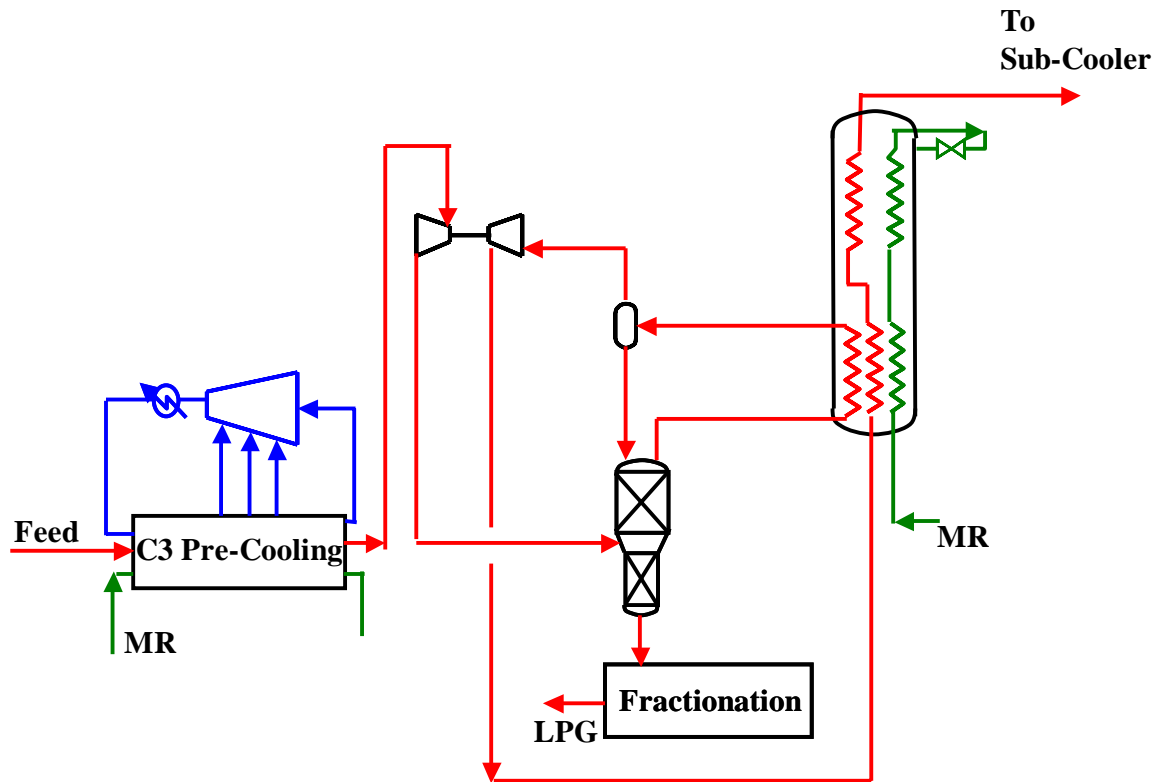


Figure 11: LPG recovery using an integrated expander cycle

LPG recovery using a front-end expander plant

It is also possible to simply configure a conventional gas expander LPG plant ahead of the liquefaction train. In this case the discharge pressure of the residue gas compressor can be optimized to minimize the unit production cost of LPG and LNG. Because a scrub column is not required in the liquefaction train, the feed pressure from the residue gas compressor can be 65 bar or higher. A higher feed pressure to the liquefaction train reduces the specific power for liquefaction, but this benefit has to be balanced against the cost and power requirement of the residue gas compressor, and any machinery or driver constraints that may exist. With a front-end expander plant, a common fractionation unit can be used to produce LPG product and refrigerant makeup.

CAPITAL COST

The AP-XTM meets the industry demand for the economies of scale that can result from larger single train capacities. The unit cost of LNG production is lowered significantly with the AP-XTM process. Merlin Associates have recently completed an independent study comparing the cost of a single 8 Mta AP-XTM train to that of two 4 Mta C3MR trains. The results are summarized in Table 1. Overall plant facility costs are reduced by about 11% with a total cost saving of about 140 MM\$. For the C3MR option, some process units such as acid gas removal and the endflash system could potentially be combined depending on owner preference. The resulting savings are only about 10 MM\$³ however.

Table 1: Capital cost comparison

Estimate Basis ⁽¹⁾		
Process	C3MR	AP-X TM
Plant Capacity, mtpa	8	8
No. Trains	2	1
Train Capacity, mtpa	4	8
Capital cost -millions US\$ ⁽²⁾		
Plant Facilities	1,272	1,131
Marine Facilities	24	24
Temporary Infrastructure	52	52
Total	1,348	1,206
US\$/tpa	168	151

Notes:

(1) Air cooled plant; Warm climate

(2) Merlin Associates estimate in constant 7/1/03 US\$

SUMMARY

The AP-XTM LNG process is a hybrid of two proven refrigeration process, a C3MR process for pre-cooling and liquefaction followed by a gas expander cycle for LNG subcooling. The process is very flexible and can be implemented using Frame 7's, Frame 9's, or electric motors as main drivers for the refrigeration compressors to achieve capacities from 7-10 Mta. The process can also be configured for LPG recovery using a variety of approaches depending on the feed, the desired recovery and Owner preference. The Capital savings for one AP-XTM LNG process train as compared to two C3MR trains is greater than 10%

REFERENCES CITED:

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