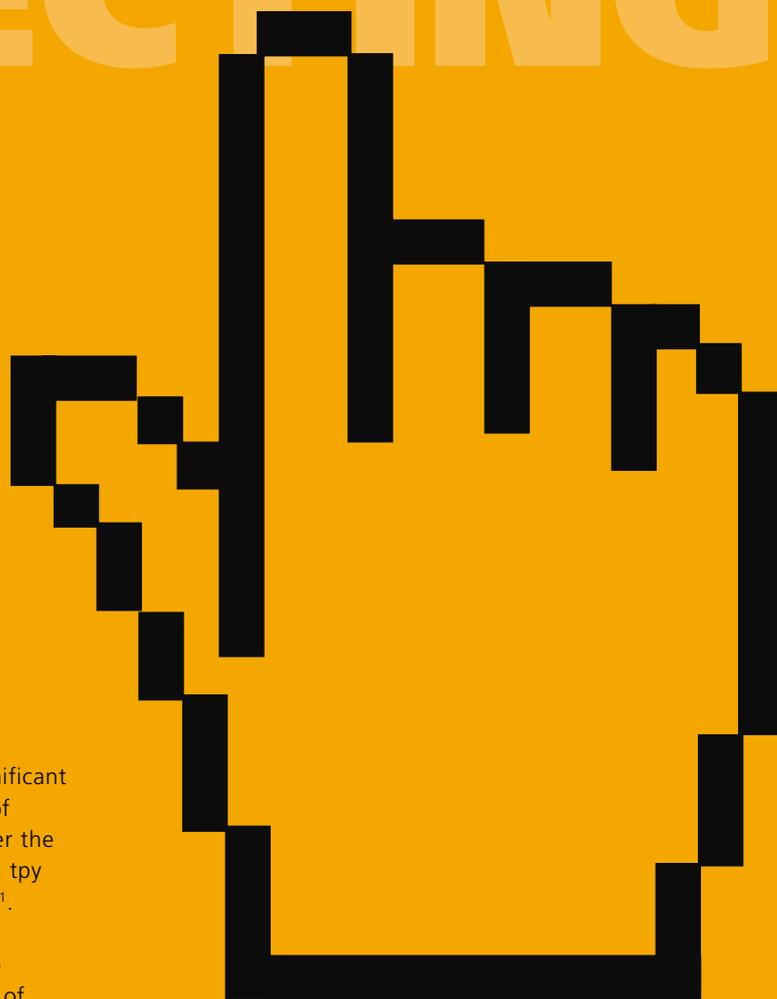


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USA, REVIEW THE PROCESS TECHNOLOGY
OPTIONS AVAILABLE FOR THE
LIQUEFACTION OF NATURAL GAS.



SELECTING

a suitable process



The LNG industry has experienced significant growth, with nearly 100 million tpy of capacity slated to come onstream over the next four years and up to 300 million tpy additional capacity planned to follow¹.

This growth has attracted a number of new entrants to the LNG marketplace wishing to participate in the industry's success. As anyone who has attended one of the numerous conferences targeting the LNG industry can attest, project developers today are faced with a dizzying array of 'new' liquefaction process technologies. What are the real differences in these technologies, and how can project developers determine what is the best option for their opportunity? This paper will review the process technology options available for the liquefaction of natural gas, and discuss the factors that should be considered by project developers in order to select the ideal process for their situation. This article will review options for small plants and mega trains, land based and floating plants, and tropical and arctic conditions.

shown in Figure 4, the cooling curve of the single component propane closely matches the precooling requirement of the feed, and since the temperature range that must now be covered by the MR is narrower, its composition can be better optimised to match the cooling requirement of the feed, thus increasing overall process efficiency.

As an alternative to propane, precooling can also be accomplished by using a separate MR loop in a variant known as a dual mixed refrigerant (DMR) process. While operating a MR precooling system may be more complicated than the simple single component propane system, the advantage is that two MR systems in series allow more

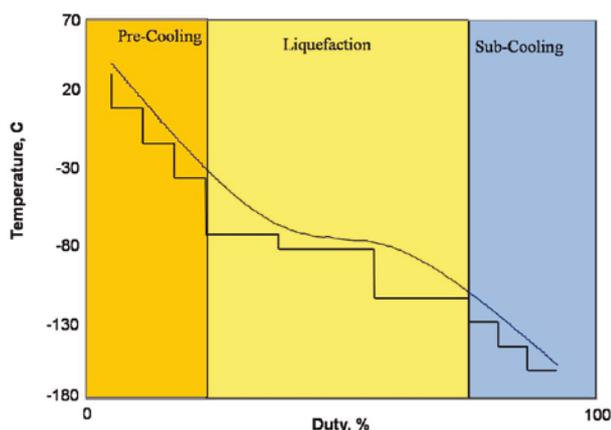


Figure 2. Classical cascade process.

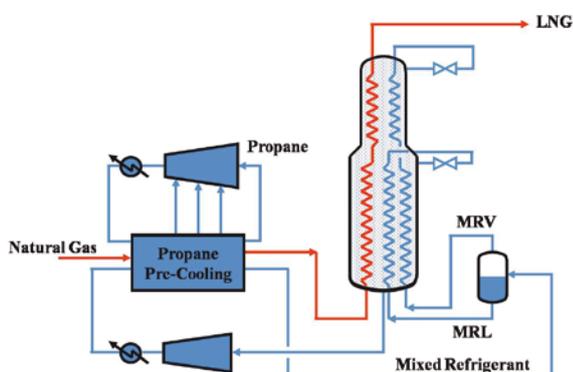


Figure 3. The C3MR process.

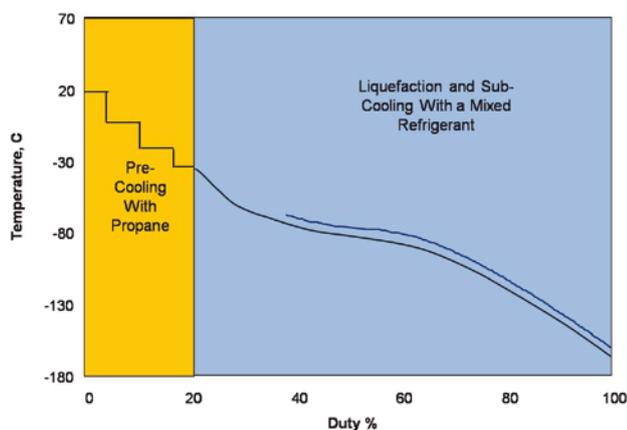


Figure 4. Propane precooled MR process.

flexibility in selecting the precooling temperature. With certain feeds or ambient conditions, this may allow a more optimum selection of compressors and drivers.

Precooling by ammonia absorption refrigeration utilising available waste heat has also been considered, although never commercialised³. Since overall plant efficiency can always be improved by recovering waste heat via conventional methods, the perceived benefits of using the ammonia absorption refrigeration process were not sufficient to justify the added risk of using the unproven process.

Numerous other configurations are possible based on the basic refrigeration building blocks described above. One notable example is the AP-X[®] process as depicted in Figure 5. Similar to the traditional propane precooled MR process, propane may be used to provide precooling refrigeration. The feed is then cooled and liquefied by MR, and final subcooling of the LNG is performed using a closed loop nitrogen refrigeration system⁴.

Selecting the proper process

So, given the number of potential cycles, how does a project developer evaluate and select the best one for his given application? A detailed process selection study, often involving a qualified and experienced contractor, should be carried out in order to evaluate the possible options. Typically, a process selection study will start with a design basis that defines many of the design parameters to be used in the study, such as ambient conditions, feed composition and conditions, and product specifications. In conjunction with the plant owner, initial studies are carried out to define optimum process equipment design assumptions, fuel balance requirements, possible driver configurations, cooling medium, etc. The owner should also provide guidance on his objectives, for example, whether it is most important to maximise production, minimise power or minimise emissions. Ideally, the owner will provide the basis for a cost function that can incorporate several parameters. This allows the process licensor to optimally trade off CAPEX and OPEX, i.e. capital investment versus operating efficiency and other factors. The more information and sensitivity criteria that can be provided by the owner, the better opportunity the process licensor will have to provide an optimised design that will best align with the owner's needs.

From the perspective of a process licensor with over 40 years of experience in providing process technology and liquefaction equipment for LNG plants throughout the world, some general process selection guidelines are outlined below.

Baseload LNG plants

A typical land based LNG train being built today will produce between 3 - 8 million tpy. For these large trains, efficiency may be the most important consideration. Operators know that every BTU of natural gas that is burned as fuel is one less BTU that can be sold. But safety, operating flexibility and plant availability are also important considerations. Historically, product from these plants is sold on the basis of long terms sales and purchase agreements, which are often used as security for financing. Plants are operated continuously at or above nameplate capacity in order to meet contractual commitments and maximise revenue. A process design from an experienced

process licensor, based on well proven components and a demonstrated record of availability is preferred.

The propane precooled MR (C3MR) process has been the workhorse of the LNG industry for many years owing to its high efficiency and proven track record. It has been applied in LNG plants producing from 1 - 5 million tpy of LNG per train, using steam and gas turbine drivers, seawater 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 competitive⁵.

For train sizes greater than 6 million tpy, the AP-X process is well suited. By using a separate nitrogen refrigeration cycle to subcool the LNG, the duty of the MR system is greatly reduced, allowing the production of up to 80% more LNG with proven equipment. The flexibility of the AP-X process also allows for the use of a MR or other precooling options if desired.

The cascade process, despite its inherent lower process efficiency, is also still finding acceptance. The process is generally configured in parallel driver/compressor trains to provide refrigeration to each liquefaction unit consisting of multiple parallel heat exchangers. Although this doubles the number of required compressors and drivers, some project developers believe that this configuration provides higher onstream availability than a single large train without parallel compression. However, this parallel machinery approach can be implemented on any other liquefaction processes if there is concern about one driver/compressor train trip shutting down all production.

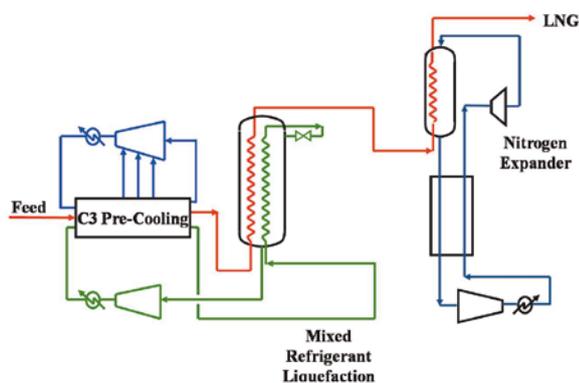


Figure 5. AP-X® process.



Figure 6. Artist's impression of dual MR FPSO LNG plant layout.

Arctic locations

Process design of natural gas liquefaction plants in arctic climates presents some unique challenges. Although arctic conditions have a low average annual temperature approaching freezing, the temperature variation over any given year can be more extreme than warmer climates. The cold climate does reduce the overall liquefaction power requirement compared to a liquefaction plant located in a tropical location, but the wide variation in ambient temperature may result in the precooling load varying significantly during the year.

For the propane precooled MR system, most of the power reduction occurs in the precooling system. Propane precooling temperatures are usually limited to approximately -35 °C to avoid vacuum suction on the propane compressor. Since the heat sink in arctic plants is at such a low temperature to start with, reducing the precooling temperature will allow for a better power balance and thus better machinery selection between precooling and liquefaction duty. Replacing propane refrigerant with propylene accomplishes this and enables a liquefaction train to be designed to have a larger capacity using the same proven components as in a propane precooled MR process. For a water cooled liquefaction plant in arctic conditions, ethane could be considered as the precooling refrigerant to achieve the same advantage. A further benefit can be provided by going to a DMR process; that is, replacing the pure component precooling refrigerant with a MR. Although this introduces a precooling system that is more complex than a single component system, it also provides additional precooling flexibility since the composition of the MRs can be changed seasonally to adjust for the wide seasonal variation of heat sink temperatures. This is especially desirable in an air cooled plant⁶.

Floating plants

Although the concept has been around for decades, floating production storage and offloading (FPSO) facilities for LNG seem closer to reality now than ever before. The design of such a facility presents significant technical challenges, not the least of which is the selection of the liquefaction cycle. Due to the limited availability of deck space, there is increased emphasis on safety and compactness. In addition, ease of operation and maintenance, and robustness of equipment have increased importance on an FPSO, along with the typical considerations such as flexibility and efficiency. Floating plants are being considered for LNG production from natural gas feeds with compositions ranging from rich to lean and at design capacities from 1 - 5 million tpy. 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.

Most owners/operators prefer to minimise or eliminate the propane inventory on the FPSO due to the possibility of a leak resulting in propane vapour accumulating on or below the deck of the ship, creating a safety hazard. In the propane precooled MR and cascade cycles, there is a significant inventory of propane refrigerant in multiple vessels and interconnecting piping runs making these cycles less acceptable for FPSO service. For larger floating

plants (greater than 1 - 2 million tpy) a viable option is a DMR process in which the MRs are specially formulated to eliminate propane. An artist's rendition of major equipment layout is shown in Figure 6 for the DMR process on an FPSO vessel. This process benefits from years of MR process experience and should achieve efficiencies and availabilities that can make a single train FPSO plant practical. Although less efficient than DMR, a SMR system can also be designed without the need for propane and may be applicable for FPSOs of smaller scale.

Finally, although lower in efficiency, the nitrogen recycle process eliminates the need for hydrocarbon refrigerants completely, and with it the need for generating, importing and storing them onboard. The elimination of hydrocarbon refrigerants carries with it the added advantage of greatly reducing the flare load in the event of plant shutdown. Adding precooling to the nitrogen recycle process can improve efficiency, and by utilising one of the newer environmentally acceptable, nonflammable 'Freon' replacement compounds such as R410A and R507, the advantage of completely eliminating hydrocarbon

refrigerants is maintained. However, even with precooling, the applicability of the nitrogen recycle system to FPSOs will be limited to trains of smaller capacity due to the fact that refrigerant exists entirely as vapour, making pipe sizes very large as train capacity increases.

Medium sized plants

There is currently renewed interest in medium sized LNG plants producing between 0.5 - 2.5 million tpy as a way to monetise stranded gas reserves at reduced cost. Although the trend in recent years has been toward larger plants, the LNG industry has substantial experience in designing processes for this size range. In fact approximately half of the LNG plants operating today are smaller than 2.5 million tpy. Many of these plants utilise the well proven propane precooled MR process. And indeed, this process is as applicable for this size range as it ever was. When a plant is designed for continuous operation, downtime is costly and reliability commands a premium. A medium sized LNG plant must minimise downtime, maintenance and lost production just like a large plant. The precooled MR plants currently in service in this size range are very efficient plants with high onstream factors using single compressor trains. There has been no need for parallel compression trains to achieve high reliability.

In hopes of reducing costs, many new LNG plant promoters are considering small nitrogen expander cycles because they are simple and easy to operate. Attractive as these attributes are, it is important to recognise that the largest nitrogen expander, single LNG train operating today is smaller than the medium size range. The majority of these plants are less than 0.1 million tpy, and are used in interruptible service. Plus, while these plants may be simple, they are much less efficient than MR plants operating today, effectively limiting their practical size. To make up for inefficiencies, more expander refrigeration is required. However, commercially available expanders are limited in size, and a 0.5 million tpy nitrogen expander liquefier uses the largest ones commercially available. To produce more LNG, parallel equipment can be incorporated into the overall plant design, but the plant is no longer as simple or easy to operate and the reliability associated with incremental pieces of equipment must be evaluated.

As an alternative to the simple nitrogen cycle described above, Figure 7 shows a nitrogen expander cycle, which utilises three levels of expanders in a process with efficiency comparable with the SMR process. It uses commercially available compressor loaded expanders, or companders, to make 0.5 - 1.0 million tpy LNG. This more efficient nitrogen expander cycle will reduce footprint and the number of pieces of equipment over multiple parallel trains.

While SMR LNG processes are more efficient than nitrogen expander cycles, they are still significantly less efficient than precooled, MR cycles. Again, this inefficiency limits the practical size of a single train before parallel equipment is required. Almost all SMR LNG plants operating today are in the less than 1 million tpy size range. Nevertheless, for the 0.5 - 1.0 million tpy LNG facilities the SMR LNG process (Figure 8) aims to provide proven performance and reliability⁷.

Small sized LNG plants

Small LNG plants producing 0.03 - 0.50 million tpy LNG are common in industrialised countries. Typically, these plants

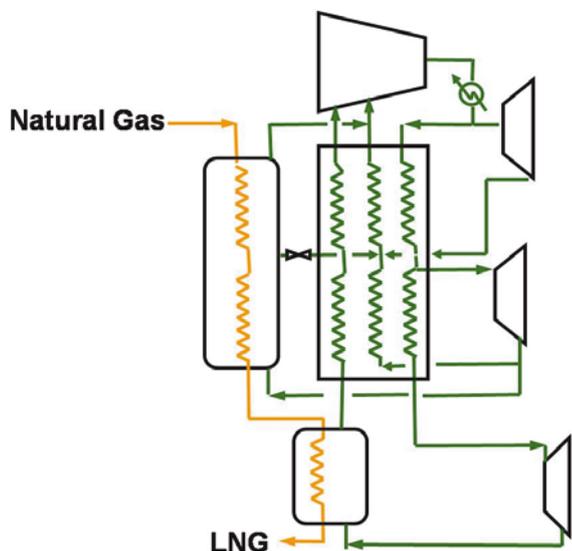


Figure 7. Three stage nitrogen expander LNG process.

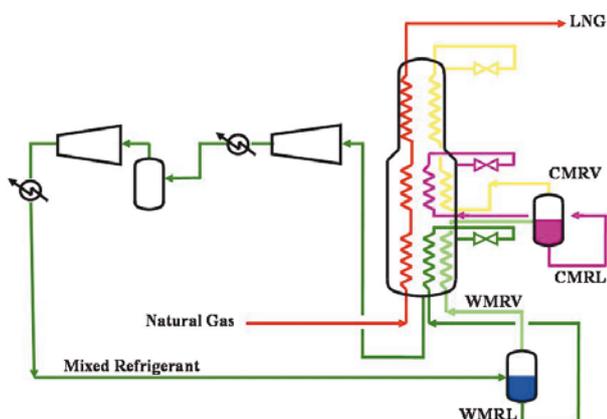


Figure 8. SMR LNG process.

are used for 'peak shaving' in that they produce LNG from pipeline gas during low demand periods such as the warmer months to be revaporised and consumed during peak demand winter months. Because these plants are small and are typically not operated on a continual basis, low capital cost becomes much more important than high efficiency. These plants have typically been designed as either nitrogen recycle or SMR plants.

Figure 1 shows a process flowsheet for a typical peak shaving plant. A closed loop nitrogen expander cycle provides refrigeration for making LNG. Advances in compressor technology over the last 15 - 20 years have made this type of cycle particularly attractive for small plants. The use of pure nitrogen as a refrigerant also saves significant cost over a MR 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.

Certain plants in this size range are not true peak shavers in that they are designed to operate continuously to supply LNG to niche markets such as for transportation fuel. For these applications efficiency tends to be weighted more heavily in the process evaluation, making SMR or precooled nitrogen systems relatively more attractive.

Conclusion

Selecting the optimum liquefaction process can have a large impact on the overall profitability of an LNG project. To provide the best possible solution, it is important that the process licensor starts with a complete and detailed design basis and as much information as possible on the criteria being used by the LNG owner to evaluate proposed solutions. There are numerous process cycles that can be considered depending on the project specifics but the overall objective is to select proven process and equipment technology that will maximise the return on investment to the LNG owner. Although there is no simple answer to the question posed by this article, there are a number of general guidelines and considerations to be followed.

First of all, it should be recognised that efficiency is important when producing LNG from any gas source. Poor efficiency wastes resources, increases emissions, and from a strictly economic standpoint, is the lost opportunity to produce and sell more LNG. Figure 9 compares the well known LNG process cycle thermodynamic efficiencies (power/t LNG required) on a relative basis. The precooled, MR cycles are highest, followed by the cascade, SMR, and nitrogen expander cycles. Even after the process is selected, there are always tradeoffs between additional capital investment and improved efficiency, and these tradeoffs are highly dependent on specific site conditions. Higher efficiency can help make a project economically attractive, and the resulting capacity will almost always justify the costs. Secondly, the processing capacity and other project specific factors will help narrow down the process choices. Figure 10 shows the most applicable process choices for a given capacity.

Finally, the LNG project developer should carefully consider operability and reliability when selecting an appropriate process. These are factors that directly affect

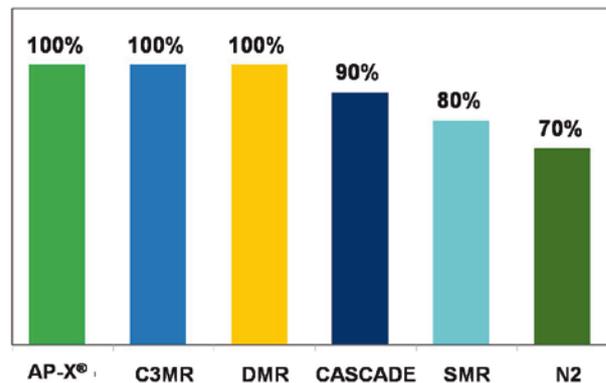


Figure 9. LNG process cycle efficiency comparison (LNG production per unit power).

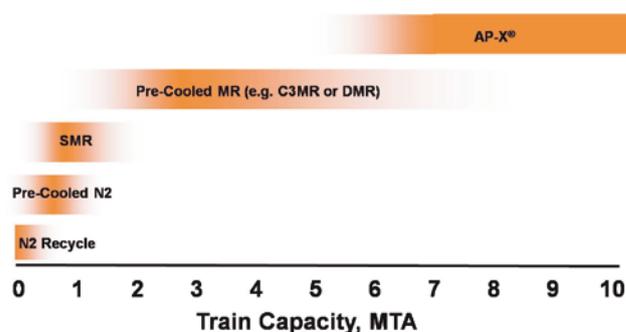


Figure 10. Liquefaction technology versus scale.

the revenue stream. While medium sized plants and FPSOs on the surface may be viewed as smaller investments than the mega trains being built today, the hundreds of millions of dollars that are still at risk demand that careful consideration be given to process selection. **LNG**

References

- TRUE, Warren R. 'CERA Week: Global LNG Supply on Rise; Project Costs Falling'. OGJOnline. 12 February 2009. www.ogj.com/display_article/353261/120/ARTCL/none/Trasp/1/CERAWeek:-Global-LNG-supply-on-rise;-project-costs-falling.
- HAMMER, Georg, et al. 'Natural Gas'. Ullman's Encyclopedia of Industrial Chemistry. 15 July 2006. www3.interscience.wiley.com/emrw/9783527306732/ueic/article/a17_073/current/html.
- AOKI, I. et al. U.S. Patent 3,817,046. 'Absorption Multi-component Cascade Refrigeration for Multi-level Cooling of Gas Mixtures.' 1974.
- ROBERTS, M.R. et al. U.S. Patent 6,308,531. 'Hybrid Cycle for the Production of Liquefied Natural Gas'. 2001.
- BRONFENBRENNER, James C. 'The Air Products Propane Pre-Cooled MR Process.' *The LNG Journal*. November/December 1996.
- KENNINGTON, W., YU-NAN LIU, J. PETROWSKI and SPILSBURY, C. 'Evolution of Liquefaction Technology for Today's LNG Business'. 7o Journees Scientifiques et Techniques. Hotel Sheraton, Oran, Algeria. 28 - 29 November 2006.
- BRONFENBRENNER, James C. and MILLER, Warren, R. 'On a Smaller Scale'. *LNG Industry*. Winter 2008.