Small-scale LNG – what refrigeration technology is the best?

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Currently, low natural gas prices are allowing multiple secondary players in the U.S. market to consider investments in small-scale LNG plants. As one of the leading technology providers and EPC contractors in this business, Linde is frequently questioned about what refrigeration technology is the best for LNG production. At first glance, there are numerous process alternatives on the market. However, when taking a closer look, the choice simplifies to either single mixed refrigerant (SMR) or nitrogen expander technology. These technologies dominate the small-scale plant capacity range between about 50,000 and 500,000 gallons of LNG per day.

Linde is one of the few players in this business that have experience with and also offer both technologies. This makes Linde ideally suited to provide an unbiased comparison. As usual, there is no simple response to a complex technical matter, so this article is meant to cover a broad range of aspects and guide towards what technology is most suited for what type of application. Other technologies may become relevant for LNG plants with capacities below and beyond the range indicated above, meaning that our observations and conclusions apply only to the mentioned capacity range.

1 Refrigeration Process Design

Two processes have been selected as representative for the two competing liquefaction technologies; both are based on brazed aluminum plate-fin heat exchangers (PFHE) as the main heat exchanger in the liquefaction unit:

• For the SMR, Linde's proprietary single cycle, Multi stage Mixed refrigerant process LIMUM®

• For the Nitrogen Expander, BHP Billiton's licensed dual nitrogen expander process, abbreviated N_2DExp

Though an arbitrary choice, it is believed that the above processes are representative of the marketplace.

For the SMR, the LIMUM process is similar to competing alternatives e.g. enhanced PRICO (Black & Veatch).

On the expander process side, the high specific power requirements limit single expander processes as a widely acceptable option. Other dual expander processes either have different detail process topology or use hydrocarbon components mixed with N_2 as refrigerant or are combinations of MR and N_2-Expander technology. Hence, the above selection is believed to represent the cornerstones of the modern LNG technology range.

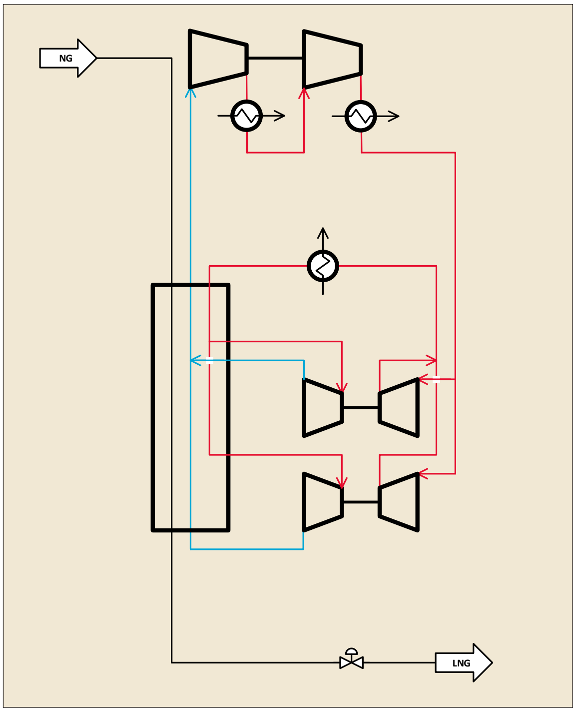

Figure 1 process sketch dual N_2 expander

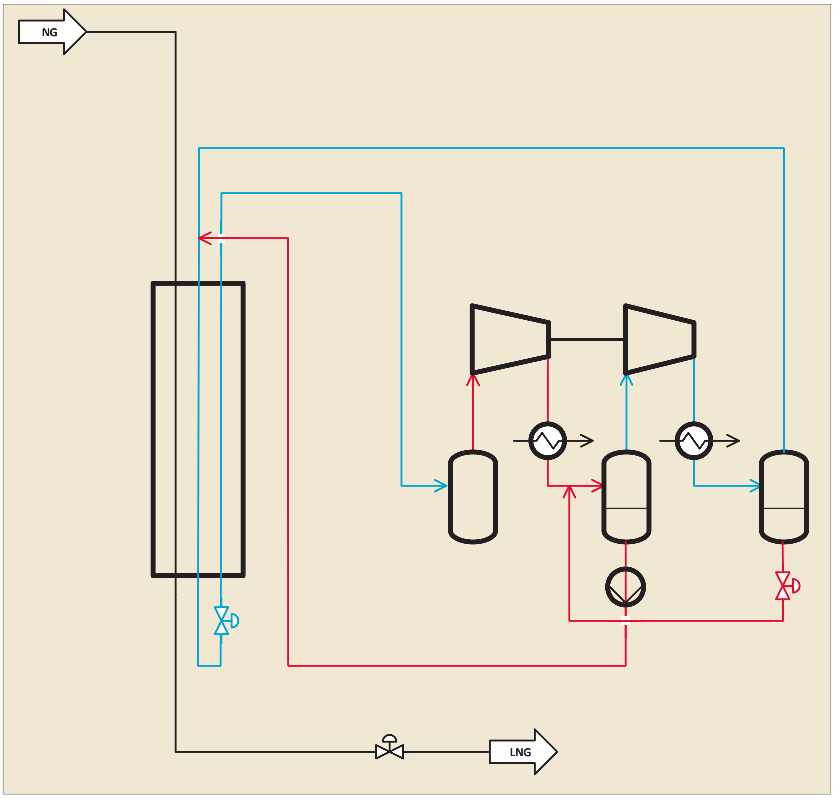

Figure 2 Process sketch single mixed refrigerant

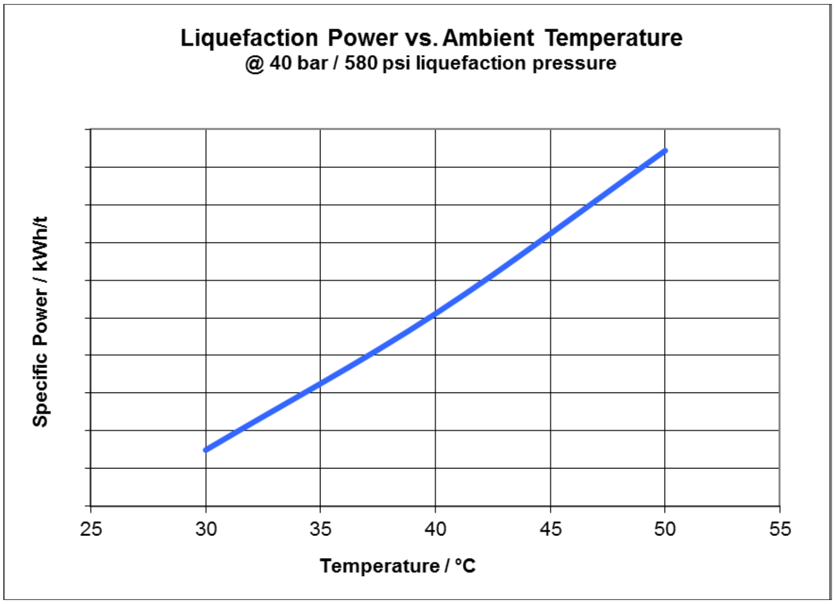

Figure 3 Liquefaction Power vs. Ambient Design Temperature

The above process sketches (Figures 1 and 2) include the following differences in equipment count:

2 Refrigeration Process Performance

Selection of plant design parameters, such as ambient design temperature, feed gas pressure and composition, storage tank pressure, flash gas rate, etc. have a significant (+/-20%) impact on the specific power requirement of an LNG plant. So, for a meaningful performance comparison, it is fundamental to use an equal set of design parameters or, since different processes have their optimum at different conditions, an equal range. For this reason a range of such design parameters has been studied rather than a single arbitrarily chosen point. Also, indication of absolute performance numbers has been avoided for being potentially misleading. Instead, relative differences are provided in the following.

Selection of machinery efficiencies also has quite an impact on such a process comparison. Some literature sets these efficiency values at 100%, pretending to thereby establish an equal basis of comparison. This will, however, lead to a false conclusion: Theoretically, the N_2DExp would have up to 15% less power than SMR. To provide a comparison that matches reality, we have selected typical actual machinery efficiencies. We therefore accounted for N_2 compressors typically showing better efficiencies (82.5%) than MR compressors (80%), whilst both processes make use of an integrally geared turbo-compressor as cycle compressor, providing optimum, state-of-the-art compression efficiency. For the expander turbines, 85% efficiency was selected.

2.1 Sensitivity Analysis

Figures 3 and 4 show how design ambient temperature impacts the process performance. While the left chart displays that power consumption of any refrigeration process increases with rising ambient temperature, the right chart shows how the N_2DExp performs relative to the SMR .

On average the N_2DExp cycle requires around 30% more power than the SMR cycle. This power consumption difference is reduced as the ambient temperature increases.

Figures 5 and 6 show how design feed gas pressure impacts on the process performance. The left chart demonstrates that power consumption of any refrigeration process is lower with higher feed gas pressure. The right chart shows how the N_2DExp cycle performs relative to the SMR1.

On average the N_2DExp cycle requires around 30% more power than the SMR cycle. This power consumption difference is reduced as the feed gas pressure increases.

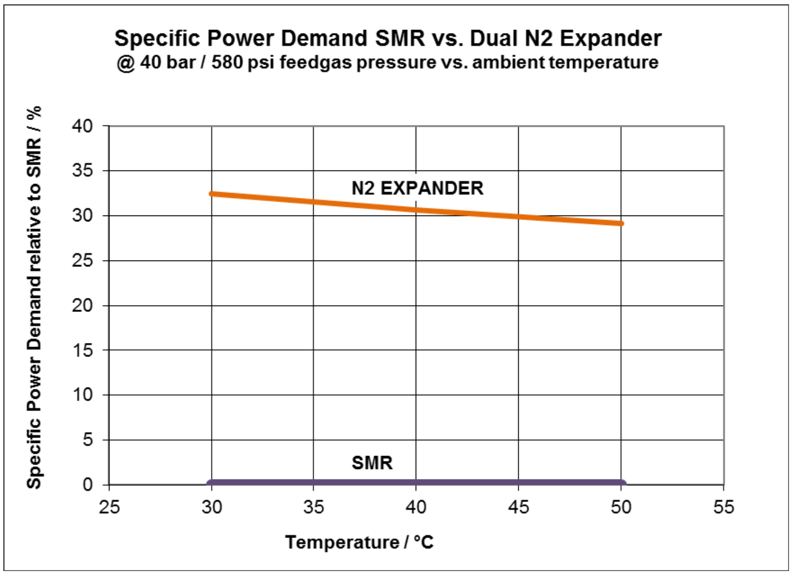

Figure 4 Specific Power Demand SMR vs Dual N_2 Expander

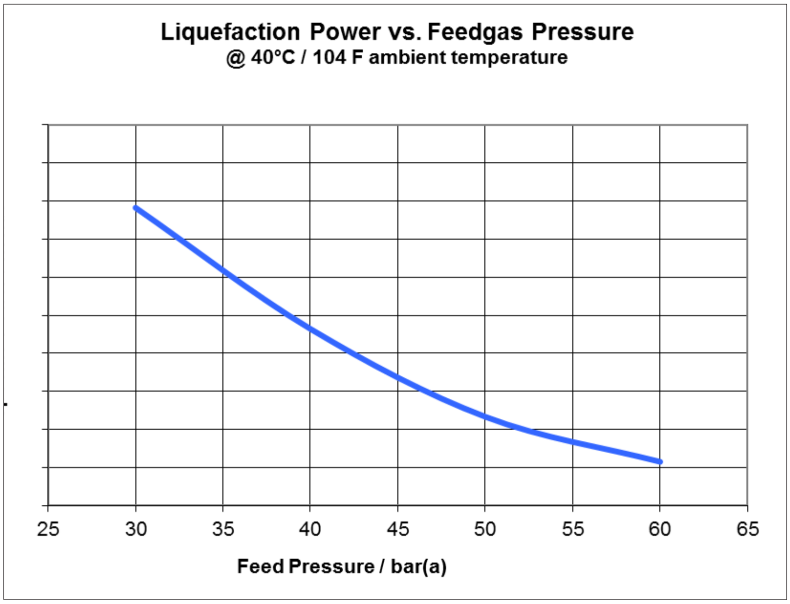

Figure 5 Liquefaction Power vs. Feed Gas Pressure

Overall it can be concluded that the power disadvantage of the N_2DExp cycle is lowest for a plant with low design feed gas pressure and high design ambient temperature: Nearly 25% power consumption difference can be reached in such a favourable case, whereas up to 35% power consumption difference may result for the other extreme.

Since refrigeration process efficiency is improved by obtaining a close match between the feed gas and refrigerant (Q/T) cooling curves, composition of the feed gas has an impact too. Analysis of this parameter has been performed and, in our conclusion, only has a moderate effect. The N_2DExp cycle tends to perform slightly better on lean feed gases. The improvement may be up to 5% with reference to the difference stated earlier.

The background of this observation is that nitrogen works as a highly efficient refrigerant in cryogenic applications (e.g. the sub-cooling section of Air Product's AP-X process) but shows

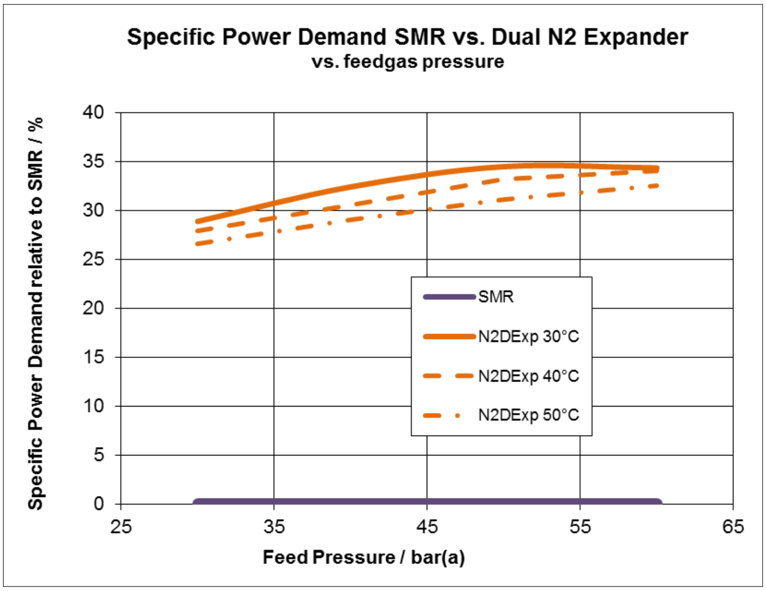

Figure 6 Specific Power Demand SMR vs. Dual N_2 Expander

poor efficiency at higher temperature levels of the liquefaction process.

2.2 Precooling

For this reason, many N_2-expander liquefiers include a precooling unit, thereby providing refrigeration duty at higher temperature levels of the liquefaction process. Fundamentally there are three options for precooling:

- Precooling of the feed gas
- Precooling of the refrigerant
- Precooling of both feed gas and refrigerant

Also, different precooling technologies exist, thus opening a wide range of options. Ammonia (R717) and propane (R290) chilling are still considered the most common options – in the simplest case within a single cycle, single stage refrigerant process. Adding further stages will improve efficiency, but also increase cost and complexity.

Based on some exemplary calculations for a simple propane chiller, we conclude there is improvement potential for the N_2DExp cycle of up to 15% compared to the above values for the uncooled cycle. Feed gas precooling is technically quite simple whereas refrigerant precooling is more complex, but also more rewarding.

In a best case scenario, the power disadvantage of a precooled N_2DExp cycle may be as low as 10 to 15% above a (non-precooled) SMR cycle refrigeration process.

2.3 Further Observations

Besides power consumption, two other parameters with impact on investment cost are significantly different for both refrigeration processes. Whereas the SMR cycle uses a two-phase refrigerant, the nitrogen refrigerant in the N_2DExp cycle is always in the gas phase. So it is not surprising that volumetric flows – and therefore pipe diameters – are larger in the N_2DExp cycle than in the SMR cycle at any given duty. Also, refrigerant pressures (and thus pipe schedules) typically need to be significantly higher in order to get to reasonable pipe diameter and process efficiencies. In reference to the given example:

- The suction line diameter of the refrigerant compressor is 20 inches for the SMR cycle and 24 inches for the N_2DExp cycle
- The high pressure refrigerant operates around 40 bar (600 psi) for the SMR cycle and 70 bar (1000 psi) for the N_2DExp cycle, resulting in class 300 piping for the SMR cycle and class 600 for the N_2DExp cycle.

3 Technical and Operational Pros and Cons

A number of further aspects should be considered when comparing both technologies, because a more thorough response also needs more technical background information:

3.1 Refrigerant Consumption and Make-up System Design

Both SMR and N_2DExp refrigeration cycles operate in closed loops, i.e. they do not “consume” refrigerant during operation. But typically, the compressors and seal systems used in such refrigeration cycles are not absolutely leak tight and thus, leakage needs to be replaced by “make-up”. A make-up system is required in every case. For the N_2DExp cycle this system may consist of a liquid nitrogen (LN_2) tank with an evaporator as the simplest solution. Additionally, for the SMR cycle, make-up storage of the hydrocarbon components C_2 to C_5 is also required (C_1 make-up is sourced from the feed gas).

Refrigerant make-up rates are typically significantly higher for N_2DExp plants. This higher make-up rate is due to design differences between the SMR cycle and N_2 cycle compressor seals:

• N_2 compressors and expander/boosters are traditionally a product of the air-separation industry where leakage losses are considered an efficiency loss. Therefore, inexpensive labyrinth seals are a standard solution. Labyrinth seals offer leakage rates of around 3 to 6% of the flow. Alternatively, carbon ring seals offer a reduced leakage rate (around 0.2% of flow) at a slightly higher cost and are therefore typically used for N_2 refrigerant compressors.

• SMR compressors are products of the oil and gas processing industry where hydrocarbon leakage is considered a hazard and needs to be minimised. Dry-gas seals (DGS) are the standard design offering minimal leakage rates (only 1 to 10% of the leakage rate of wet gas seals). They are mostly independent from the compressor throughput. However, the dry gas seals feature significantly higher complexity and come at a much higher cost (about 0.25 million $US), which is why DGS are not commonly used for N_2 compressors.

On a side-note, hermetically sealed compressors, exhibiting zero refrigerant loss, have also been reviewed to complete the picture: In the analysed capacity range and at the assumed cost of make-up components they do not seem to be an economical escape route – neither for the MR- nor the N_2-compressor. On the other hand, hermetically sealed expander/boosters look more attractive, despite only contributing a minor part of the total leakage rate in an N_2DExp cycle.

Having said "refrigerant leakages from the cycle are unavoidable" does not automatically mean those losses have to be fully matched by external make-up imports. It is technically feasible to recover major parts of refrigerant losses. The question is whether or not this alternative is the most economical. Whereas large-scale LNG plants usually take the C_2 to C_5 make-up components from the fractionation process, in most cases this is not an economical option for small-scale LNG plants (though technically quite feasible and already successfully demonstrated by Linde). Therefore, Linde will usually consider make-up import from external sources and hence limit refrigerant components to C_2 and C_4. This comes at the expense of a small efficiency loss (considered in the efficiency comparison provided above). This small efficiency loss helps to minimise both the investment cost for the make-up system as well as logistical/procurement efforts for the plant operator.

While inexpensive/high-leak seal design is technically an option for N_2DExp cycle machinery, it is mostly an economic question which setup offers the best life-cycle cost – see chapter 4.

3.2 Make-up System Operation

In the N_2DExp cycle, the operator needs to monitor the cycle pressure and add nitrogen when the pressure drops below certain limits. The machinery seal type and resulting leakage rate of the system (see 3.1) set the frequency for adding make-up. This frequency may range from a continuous operation to a weekly occurrence.

Operating efforts may be doubled in case a C_3-precooling cycle is added to the N_2DExp cycle (again depending on C_3-compressor seal design).

For the SMR cycle, leakage and resulting make-up rates are lower by an order of magnitude. Nonetheless, the operator needs to monitor the refrigerant composition in addition to the cycle inventory. An on-line analyser (gas chromatograph) is provided to this end and bi-weekly checking of inventory and composition is recommended. (Contrary to statements in some other publications, Linde experience showed SMR cycle efficiency is quite forgiving to off-spec MR composition and is quite sufficient to get near the recommended component mix.) To add make-up components, automated functions can be activated by the operator on the control panel without any need for further field operator intervention. Operator failure to maintain refrigerant composition may result in slowly decreasing process efficiency.

3.3Operation at off-design conditions

For both refrigeration technologies, liquefaction capacity can be influenced. In principal, this is done through the refrigerant system inventory, e.g. reduced refrigerant system inventory will result in lower pressures, lower refrigerant mass flows and lastly, lower LNG production.

For the N_2DExp cycle such inventory adjustment is a widely used method to achieve very efficient part-load operation. Basically, the operator only needs to release or add inventory to decrease or increase plant load. By doing so, the refrigerant compressor anti-surge valves can remain closed over a wide load range. In this way, process efficiencies near design can be maintained. To avoid losing released refrigerant, a dedicated buffer drum is typically added for temporary storage. Depending on the plant capacity, this can be quite a large and expensive vessel, but operation of such a system is pretty simple. The typical N_2DExp process shown above can thereby reach part load as low as 30%.

The SMR technology features the maintenance of a two-phase refrigerant of a certain composition. Hence, releasing inventory is more complex and therefore only done occasionally. In view of its value, dumping of released refrigerant is usually not an option, so temporary storage is required. Without such optional extra equipment, part load operation is realised by reducing the compressor throughput e.g. via inlet guide vanes (IGVs) and, below a certain load, opening the recycle valves to protect the compressor from surge. Part load process efficiency will drop drastically when operating in recycle. To maintain correct two-phase flow patterns in the plate fin heat exchanger (PFHE), part load operation is limited to about 50% in this setup.

In the frequent cases where extended part-load operation is expected, mostly during the initial operating period of an LNG plant (e.g. because design capacity allowed for future growth of product off-take) no extra equipment is needed. In that case operations require to fill the SMR cycle inventory up to the level corresponding to the desired plant load. This step by step procedure allows highly efficient part-load operation (as low as 30%) at no extra cost.

Additionally, SMR technology gives the option to vary the refrigerant design composition in order to improve process efficiency at off-design operating conditions, i.e. typically ambient temperatures. This can be realised to a limited extent by modifying the ratio between heavy mixed refrigerant (HMR) and light mixed refrigerant (LMR) flow. Otherwise manual adjustment of the composition is required (see 3.2). To avoid loss of refrigerant (unless a refrigerant buffer is provided) such adjustment should be made in the normal frequency of adding make-up as described above. Therefore this method is not suitable for daily but only for longer-term (typically seasonal) adjustments but may still result in sensibly lower annual power consumption.

3.4 Start-up Time

Start-up from the warm condition to full load needs to be done slowly on SMR. This is necessary in order to keep thermal stress in the PFHE within permissible limits because liquid refrigerant has a far higher heat transfer coefficient than gas. With liquid refrigerants, the PFHE core temperature approaches refrigerant temperature faster. Typically, start-up of an N_2DExp process can be done in about half the time required for the SMR.

For a cold plant restart, e.g. after a trip where the PFHE remains cold, there is no difference in start-up time between the two refrigeration technologies.

3.5 Plant Maintainability

Compressors are the main focus when assessing plant maintainability. There are significant differences in rotating equipment quantities and design between refrigeration technologies:

For the SMR cycle, there is only one compressor and therefore only one set of capital spare parts to be procured. Maintaining the DGS is occasionally an issue in the gas processing industry, although DGS experience on our MR compressors has been excellent during the past decade.

The N_2DExp cycle comprises two additional expander/booster sets. So three machines require regular maintenance and three sets of capital spare parts need to be procured. The typical seal systems used here have very good operating records and spare parts are a much lower matter of expense than for DGS. Also, the likelihood of unscheduled maintenance issues is greater on three pieces of compression equipment versus just a single piece of compression equipment.

One possibility to get to at least equal maintainability is to use hermetically sealed expander/booster sets with magnetic bearings that are more or less maintenance-free in addition to their advantage of zero refrigerant leakage (see 3.1).

The N_2DExp cycle situation is more impacted when a precooling cycle is added to enhance process efficiency (see 2.2), as this configuration adds a fourth compressor.

Capital Cost

CAPEX Difference (in MM USD)	SMR	Dual N_2-Expander A) High Capex/Low Opex	Dual N_2-Expander B) Low Capex/High Opex
Natural Gas Liquefaction Unit	0	+0.15	+0.15
Refrigeration System			
• Rotating Equipment	+0.3	+0.8	0
• Static Equipment	+0.15	0	0
• Bulk Materials and Labour	0	+1.4	+1.4
Refrigerant Make-Up System			
• Static Equipment	+0.6	0	0
• Bulk Materials and Labour	+0.7	0	0
Total	+1.75	+2.35	+1.55

3.6 Environmental and Process Safety

Handling and storage of LNG is key when it comes to safety and permits of LNG plants. There is no difference between the two refrigeration technologies in that regard. The methodology of 49CFR193 respectively, NFPA 59A, for determining exclusion zones typically results in similar separation distances that are accounted for in a standard plant layout. Risks of explosion and jet fires resulting from high-pressure natural gas piping systems are also comparable as is the requirement for explosion or fire protection. The small advantage an N_2DExp plant may still have is obviously cancelled, when C_3-precooling, or even worse ammonia-precooling, is added. These considerations drove the novel CO_2-precooling system to appear on the agenda for floating LNG.

To achieve the same compact layout at equal level of safety, the SMR plant will only incur additional cost for safety measures when forced into a congested plant layout by the available plot space, e.g. in a floating LNG plant.

While some publications suggest the N_2DExp cycle is friendlier to the environment than SMR (because of its use of nitrogen as the refrigerant) this is at best only one part of the truth. As outlined above (see 3.1), the refrigerant is operated in a closed cycle, with the compressor seals as the only significant point of leakage. The small seal leakage from an SMR cycle compressor will usually be flared, i.e. result in CO_2-emissions, (or may alternatively be recycled). In this case, the N_2DExp cycle has an environmental benefit, since its seals will just release harmless nitrogen. However, when evaluating energy efficiency with a corresponding CO_2 footprint, this advantage is turned into the opposite and the SMR cycle has clear benefits (see 2).

4 Economics

Differences in investment and operating cost have been determined for some selected examples, making sure that evaluation of the different technologies is based on an equal basis. The example below is deemed representative and refers to a typical LNG liquefier (i.e. liquefaction, refrigeration and make-up units) in a U.S. gulf coast location with a capacity of 200,000 gallons per day.

For the N_2DExp cycle, two options are shown:

A) Process machinery, either seal less or fitted with refrigerant recovery, resulting in higher investment cost but lower utility consumption/ operating cost

B) Process machinery fitted with standard seal systems (C-rings on the refrigerant compressor, labyrinths elsewhere), resulting in lower investment cost but higher utility consumption/ operating cost

4.1 Capital Cost

Capital cost is for EPC, turnkey delivery of the LNG liquefier. In each cost line item, the lowest option has been set to zero and the incremental cost of the alternatives is indicated. Optional features, e.g. refrigerant buffer systems, have not been considered.

Observations:

- SMR compressors are comparatively expensive equipment compared to the ASU-type machinery of the N_2DExp cycle
- Piping quantities are more than 100% higher for the N_2DExp cycle compared to the SMR cycle (see 4.1), resulting in significantly higher materials and construction cost.

Operating Cost			
OPEX Difference (in MM USD/a)	**SMR**	**Dual N_2-Expander**	
		A) High Capex/Low Opex	**B) Low Capex/High Opex**
Electric Power (0.06 USD/kWh)	0	+0.7	+0.7
Refrigerant Make-up/Sealgas			
• MR hydrocarbon components (0.4 USD/lb)	+0.15	0	0
• Nitrogen (0.1 USD/lb)	+0.07	0	+0.75
Total	+0.22	+0.70	+1.45

• Total cost difference between all three alternatives is small, only about 5% when considering the absolute cost of the exemplary liquefier system or 1% when considering the absolute cost of the exemplary, complete LNG plant (greenfield).

4.2 Operating Cost

Operating cost assessed here accounts only for power and refrigerant make-up consumption and is based upon 8,000 hours per year. Cost for operating personnel will be identical, whereas cost differences for equipment maintenance are difficult to assess in an undisputable way.

Observations:

• The SMR cycle shows the expected benefits with respect to power consumption

• For option B) the N_2DExp cycle cost of LN_2 makeup reaches the same order as the cost of power.

• When considering a 15 year life-cycle cost, the relative OPEX disadvantage of N_2DExp cycle option B) to SMR reaches the same order of magnitude as the absolute cost of the exemplary liquefier system!

5 Conclusions and Recommendations

Having demonstrated only minor capital cost differences between the two refrigeration technologies, it can be concluded that a decision is best based primarily on operating cost and operability issues.

For applications with high annual operating hours near design load, such as base-load or peak-shaving LNG plants, the SMR technology has a strong advantage with respect to operating cost. Its disadvantages, like longer start-up time or reduced part-load capability, are less relevant.

For applications with low annual operating hours and wide load profile requirements such as boil-off gas re-liquefaction units, the N_2DExp cycle, with a refrigerant buffer system, offers significant advantages with short start-up time as well as wide part-load capability and efficiency, while low operating hours compensate for higher specific operating cost.

Also in remote areas where C_2 and C_4 make-up component delivery comes at high logistical effort and price, the OPEX-gap between the SMR cycle and the N_2DExp cycle will be smaller, but this situation will rarely arise in the U.S.

The extra investment in a N_2DExp cycle low-leakage system (Option A) will typically have attractive payback times of less than three years.

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