

## Choose the best refrigeration technology for small-scale LNG production

Low natural gas prices are allowing multiple secondary players in the US market to consider investments in small-scale LNG plants. A frequent question is which refrigeration technology is the best for liquefied natural gas (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 ( $N_2$ ) expander technology. These technologies dominate the small-scale plant capacity range between 50,000 gallons per day (gpd) and 500,000 gpd of LNG.

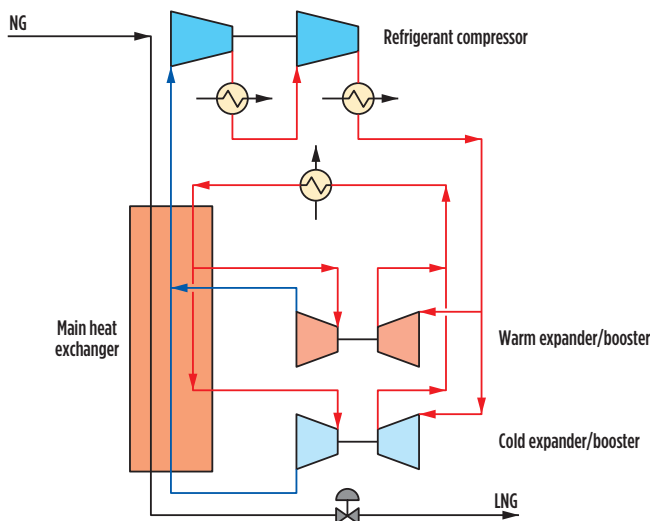
Here, a broad range of aspects and guidelines for which technology is best suited for what type of application is covered. Other technologies may be relevant for LNG plants with capacities below and beyond the range indicated, although the observations and conclusions presented here apply only to the aforementioned capacity range.

**Refrigeration process design.** Two processes<sup>1</sup> have been selected as representative for the two competing liquefaction technologies. Both processes are based on brazed aluminum plate-fin heat exchangers (PFHEs) as the main heat exchangers in the liquefaction unit. The processes are a single-cycle, multistage mixed-refrigerant process and a dual  $N_2$  expander process. **TABLE 1**

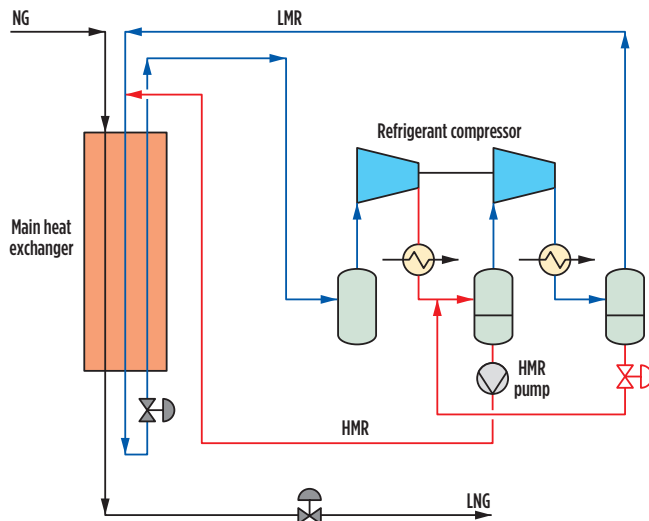
compares the primary components of these processes, while **FIGS. 1** and **2** present process flows for the two technologies.

The high specific power requirements limit single  $N_2$  expander processes as a widely acceptable option. Other dual-expander processes have different detail process topology, use hydrocarbon components mixed with  $N_2$  as refrigerant, or are combinations of MR and  $N_2$  expander technology. The classic dual  $N_2$  expander and the SMR technology used in this model are believed to represent the cornerstones of the modern LNG technology range.

**Refrigeration process performance.** The 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 ( $\pm 20\%$ ) impact on the specific power requirement of an LNG plant. To make a meaningful performance comparison, it is fundamental to use an equal set of design parameters—or, since different processes are optimum at different conditions, an equal range can be used. For this reason, a range of design parameters has been studied, rather than a single, arbitrarily chosen point. Also, indication of absolute performance numbers has been avoided so as not to present misleading data. Instead, relative differences are provided.



**FIG. 1.** Process flow diagram of the dual  $N_2$  expander process.



**FIG. 2.** Process flow diagram of the SMR process.

The selection of machinery efficiencies has a significant impact on this process comparison. Some literature sets these efficiency values at 100%, assuming an equal basis of comparison. However, this will lead to a false conclusion: Theoretically, the N<sub>2</sub> expander cycle would have up to 15% less power than the SMR. To provide a comparison that matches reality, typical machinery efficiencies have been selected. N<sub>2</sub> compressors typically show better efficiencies (82.5%) than MR compressors (80%), while both processes make use of an integrally geared turbocompressor as a cycle compressor, providing optimum compression efficiency. For the expander turbines, 85% efficiency was selected.

**Sensitivity analysis.** Design ambient temperature impacts the process performance, as shown in FIGS. 3 and 4. While FIG. 3 illustrates that power consumption of any refrigeration process increases with rising ambient temperature, FIG. 4 shows how the N<sub>2</sub> expander performs relative to the SMR.<sup>2</sup>

**TABLE 1. Main equipment components for the SMR and N<sub>2</sub> expander processes**

	SMR equipment	N <sub>2</sub> expander equipment
<b>Refrigeration unit</b>	1 cycle compressor	1 cycle compressor
	1 set of HMR pumps	2 expanders/booster compressors (mounted in insulation boxes)
	2 air coolers	3 air coolers
	3 compressor suction/receiving drums	
<b>Liquefaction unit</b>	1 coldbox	1 coldbox
	1 PFHE	1 PFHE
	1 phase-separator vessel	
<b>Makeup unit</b>	2 storage drums, including dryers	1 LN <sub>2</sub> tank with air-heated vaporizer
	1 air-heated vaporizer	
	1 LN <sub>2</sub> tank with air-heated vaporizer	

On average, the N<sub>2</sub> expander cycle requires approximately 30% more power than the SMR cycle. This power consumption difference is reduced as the ambient temperature increases. FIGS. 5 and 6 show how design feed gas pressure impacts the process performance. FIG. 5 demonstrates that power consumption of any refrigeration process is lower with higher feed gas pressure. FIG. 6 shows how the N<sub>2</sub> expander cycle performs relative to the SMR.<sup>2</sup>

On average, the N<sub>2</sub> expander cycle requires around 30% more power than the SMR cycle. This power consumption difference is reduced as the feed gas pressure increases. It can be concluded that the power disadvantage of the N<sub>2</sub> expander cycle is lowest for a plant with low design feed gas pressure and high design ambient temperature; a nearly 25% power consumption difference can be reached in this favorable case, whereas up to a 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 also has an impact. Analysis of this parameter has been performed and appears to have only a moderate effect. The N<sub>2</sub> expander cycle tends to perform slightly better on lean feed gases. The improvement may be up to 5% with reference to the aforementioned difference.

The background of this observation is that N<sub>2</sub> works as a highly efficient refrigerant in cryogenic applications, but shows poor efficiency at higher temperature levels of the liquefaction process.

**Precooling.** Since N<sub>2</sub> shows poor efficiency at high liquefaction temperatures, many N<sub>2</sub> expander liquefiers include a precooling unit that provides refrigeration duty at higher temperature levels. Fundamentally, three options for precooling exist:

- Feed gas
- Refrigerant
- Feed gas and refrigerant.

A variety of precooling technologies presents a wide range of options. Ammonia and propane chilling are still considered the most common options in the simplest case, within a single-cycle, single-stage refrigerant process. Adding more stages will improve efficiency, but it will also increase cost and complexity.

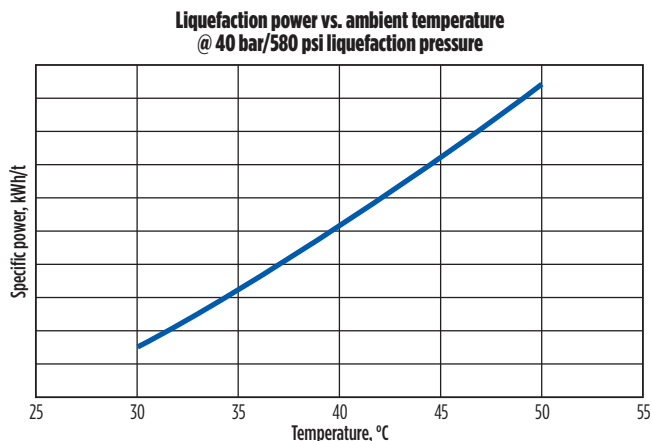


FIG. 3. Power vs. ambient design temperature.

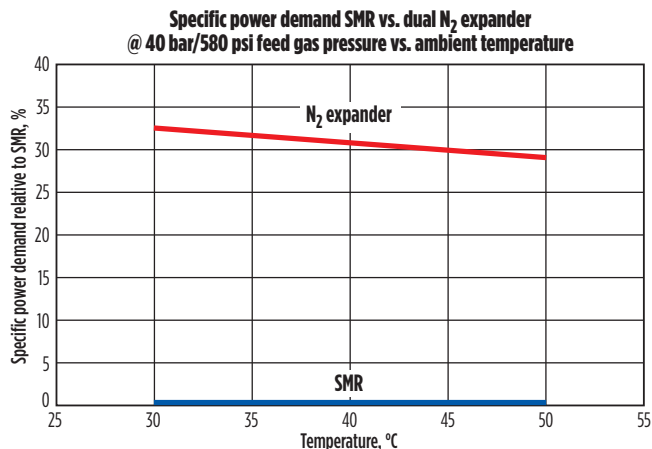


FIG. 4. Specific power demand for SMR vs. dual N<sub>2</sub> expander.

Based on exemplary calculations for a simple propane chiller, there appears to be improvement potential for the N<sub>2</sub> expander cycle of up to 15% compared to the stated values for the uncooled cycle. Feed gas precooling is technically simple, whereas refrigerant precooling is more complex, but also more rewarding.

In a best-case scenario, the power disadvantage of a pre-cooled N<sub>2</sub> expander cycle may be as low as 10% to 15% above a (non-precooled) SMR cycle.

**Additional observations.** Aside from power consumption, two other parameters with impact on investment cost are significantly different for the two refrigeration processes. Whereas the SMR cycle uses a two-phase refrigerant, the N<sub>2</sub> refrigerant in the N<sub>2</sub> expander cycle is always in the gas phase. It is not surprising that volumetric flows (and, therefore, pipe diameters) are larger in the N<sub>2</sub> expander cycle than in the SMR cycle at any given duty. Also, refrigerant pressures (and, therefore, pipe schedules) typically need to be significantly higher 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 (in.) for the SMR cycle and 24 in. for the N<sub>2</sub> expander cycle

- The high-pressure refrigerant operates at approximately 40 bar (600 psi) for the SMR cycle and 70 bar (1,000 psi) for the N<sub>2</sub> expander cycle, resulting in Class 300 piping for the SMR cycle and Class 600 piping for the N<sub>2</sub> expander cycle.

**Technical and operational pros and cons.** A number of additional aspects should be considered when comparing both technologies, as a thorough response requires more technical background information.

**Refrigerant use and makeup system.** Both the SMR and N<sub>2</sub> expander refrigeration cycles operate in closed loops; i.e., they do not “consume” refrigerant during operation. Typically, the compressors and seal systems used in these refrigeration cycles are not completely leak-tight, and, therefore, leakage must be replaced by “makeup.” A makeup system is required in every case. For the N<sub>2</sub> expander cycle, this system may consist of a liquid nitrogen (LN<sub>2</sub>) tank with an evaporator as the simplest solution. Additionally, for the SMR cycle, makeup storage of the hydrocarbon components C<sub>2</sub> to C<sub>5</sub> is also required. **Note:** C<sub>1</sub> makeup is sourced from the feed gas.

Refrigerant makeup rates are typically much higher for N<sub>2</sub> expander plants. This higher makeup rate is due to design differences between the SMR cycle and the N<sub>2</sub> expander cycle compressor seals:

- N<sub>2</sub> compressors and expanders/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<sub>2</sub> refrigerant compressors.
- SMR compressors are products of the oil and gas processing industry, where hydrocarbon leakage is considered a hazard and must be minimized. Dry gas seals (DGSs) 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, dry gas seals feature significantly higher complexity and come at a much higher cost (approximately \$250 thousand USD), which is why DGSs are not commonly used for N<sub>2</sub> compressors.

**Note:** Hermetically sealed compressors, exhibiting zero refrigerant loss, have also been reviewed to complete the picture. In the analyzed capacity range and at the assumed cost of makeup components, they do not seem to be an economical escape route, either for the mixed refrigerant or the N<sub>2</sub> compressor. Alternately, hermetically sealed expanders/boosters appear more attractive, despite only contributing a minor part of the total leakage rate in an N<sub>2</sub> expander cycle.

Although refrigerant leakages from the cycle are considered unavoidable, it does not automatically mean that those losses must be fully matched by external makeup 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<sub>2</sub> to C<sub>5</sub> makeup components from the fractionation process, in most cases, this is not an economical option for small-scale LNG plants, although it is technically feasible and has been success-

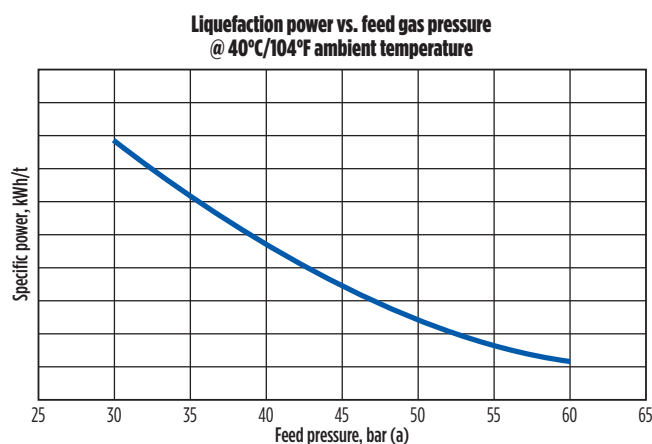


FIG. 5. Liquefaction power vs. feed gas pressure.

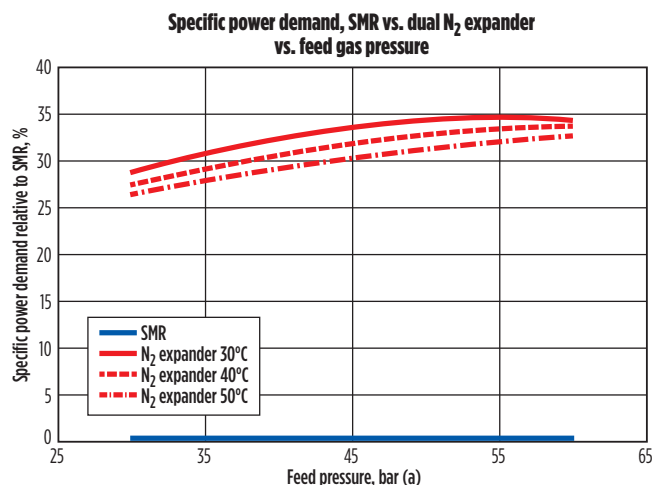


FIG. 6. Specific power demand for SMR vs. dual N<sub>2</sub> expander.

fully demonstrated. Therefore, makeup import from external sources is usually considered, and refrigerant components are limited to C<sub>2</sub> and C<sub>4</sub>. This comes at the expense of a small efficiency loss, which is considered in the efficiency comparison. This small efficiency loss helps to minimize both the investment cost for the makeup system and logistical/procurement efforts for the plant operator.

While an inexpensive/high-leak seal design is technically an option for N<sub>2</sub> expander cycle machinery, it is an economic question of which setup offers the best lifecycle cost, as will be discussed later.

**Makeup system operation.** In the N<sub>2</sub> expander cycle, the operator must monitor the cycle pressure and add N<sub>2</sub> when the pressure drops below certain limits. The machinery seal type and resulting leakage rate of the system determine the frequency for adding makeup. This frequency may range from a continuous operation to a weekly occurrence.

Operating efforts may be doubled in case a C<sub>3</sub> precooling cycle is added to the N<sub>2</sub> expander cycle (depending on C<sub>3</sub> compressor seal design). For the SMR cycle, leakage and resulting makeup rates are lowered by an order of magnitude. Nonetheless, the operator must monitor the refrigerant composition in addition to the cycle inventory. An online analyzer (i.e., a gas chromatograph) is provided to this end, and biweekly checking of inventory and composition is recommended. (Contrary to statements found in some literature, the authors' experience

has shown that SMR cycle efficiency is quite forgiving to off-spec MR composition and is sufficient to achieve close to the recommended component mix.) To add makeup 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.

**Operation at off-design conditions.** Liquefaction capacity can be adjusted for both refrigeration technologies. In principal, capacity is influenced by the refrigerant system inventory; i.e., reduced refrigerant system inventory will result in lower pressures, lower refrigerant mass flows and lower LNG production.

For the N<sub>2</sub> expander cycle, such inventory adjustment is a widely used method to achieve efficient partial-load operation. The operator must only release or add inventory to decrease or increase the plant load. By doing so, the refrigerant compressor antisurge 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 can be added for temporary storage. This can be quite a large and expensive vessel, depending on the plant capacity, but operation of such a system is relatively simple. The typical N<sub>2</sub> expander process can reach a partial load as low as 30%.

The SMR technology features the maintenance of a two-phase refrigerant of a certain composition. Releasing inventory is more complex and, therefore, is only done occasionally. Dumping of released refrigerant usually is not an option, so temporary storage is required. Without such optional extra equipment, partial-load operation is realized by reducing the compressor throughput (e.g., via inlet guide vanes) and, below a certain load, opening the recycle valves to protect the compressor from surge. Partial-load process efficiency will drop drastically when operating in recycle mode. To maintain correct two-phase flow patterns in the PFHE, partial-load operation is limited to approximately 50% in this setup.

In the frequent case where extended partial-load operation is expected—mostly during the initial operating period of an LNG plant—no extra equipment is needed. In that case, operations require the filling of the SMR cycle inventory up to the level corresponding to the desired plant load. This step-by-step procedure allows for highly efficient partial-load operation (as low as 30%) at no additional cost.

Additionally, SMR technology gives the option to vary the refrigerant design composition to improve process efficiency at off-design operating conditions (typically, ambient temperatures). This can be realized 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.

To avoid loss of refrigerant, such an adjustment should be made in the normal frequency of adding makeup, unless a refrigerant buffer is provided. Therefore, this method is only suitable for longer-term (typically, seasonal) adjustments, rather than daily adjustments, although it may still result in lower annual power consumption.

**Startup time.** Startup from a warm condition to a full load must be performed slowly with the SMR option. This is necessary to keep thermal stress in the PFHE within permissible limits, because liquid refrigerant has a far higher heat-

**TABLE 2. Differences in capital cost for SMR vs. N<sub>2</sub> expanders**

CAPEX difference, million USD	Dual N <sub>2</sub> expander		
	SMR	High CAPEX/ low OPEX	Low CAPEX/ high OPEX
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 labor	0	+1.4	+1.4
Refrigerant makeup system			
Static equipment	+0.6	0	0
Bulk materials and labor	+0.7	0	0
<b>Total</b>	<b>+1.75</b>	<b>+2.35</b>	<b>+1.55</b>

**TABLE 3. Differences in operating cost for SMR vs. N<sub>2</sub> expander**

OPEX difference, million USD per year	Dual N <sub>2</sub> expander		
	SMR	High CAPEX/ low OPEX	Low CAPEX/ high OPEX
Electric power (0.06 USD/kWh)	0	+0.7	+0.7
Refrigerant makeup/seal gas			
MR hydrocarbon components (0.4 USD/lb)	+0.15	0	0
Nitrogen (0.1 USD/lb)	+0.07	0	+0.75
<b>Total</b>	<b>+0.22</b>	<b>+0.70</b>	<b>+1.45</b>

transfer coefficient than does gas. With liquid refrigerants, the PFHE core temperature approaches refrigerant temperature faster. Typically, the startup of an N<sub>2</sub> expander process can be achieved in about half the time required for the startup of an SMR process.

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.

**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.

The N<sub>2</sub> expander cycle comprises two additional expander/booster sets. Therefore, three machines require regular maintenance, and three sets of capital spare parts must be procured. The typical seal systems used in this scenario have good operating records, and spare parts are a much lower matter of expense than for DGSs. Also, the likelihood of unscheduled maintenance issues is greater on three pieces of compression equipment vs. a single piece of compression equipment.

One possibility to achieve 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.

The N<sub>2</sub> expander cycle situation is more impacted when a precooling cycle is added to enhance process efficiency, as this configuration adds a fourth compressor.

**Environmental and process safety.** The handling and storage of LNG is key when it comes to safety and permits for LNG plants. There is no difference between the two refrigeration technologies in this regard. The methodology 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<sub>2</sub> expander plant may have is canceled when C<sub>3</sub> precooling or ammonia precooling is added. These considerations drive the novel CO<sub>2</sub> precooling system to appear on the agenda for floating LNG (FLNG).

To achieve the same compact layout at an 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 an FLNG plant.

While some publications suggest that the N<sub>2</sub> expander cycle is friendlier to the environment than the SMR due to its use of N<sub>2</sub> as the refrigerant, this is only a partial truth. 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, resulting in CO<sub>2</sub> emissions, or it may be recycled. In this case, the N<sub>2</sub> expander cycle has an environmental benefit, since its seals will release only harmless N<sub>2</sub>. However, when evaluating energy efficiency with a corresponding CO<sub>2</sub> footprint, this advantage is turned on its head, and the SMR cycle has more benefits.

**Economics.** Differences in investment and operating cost have been determined for some examples to ensure that evaluation of the different technologies is considered on an equal basis. The ex-

Having demonstrated only minor capital cost differences between the two refrigeration technologies, it can be concluded that a decision is best based on operating cost and operability issues. For applications with high annual operating hours near design load, the SMR technology has a strong advantage with respect to operating cost.

ample provided is deemed representative. It encompasses a typical LNG liquefier (i.e., liquefaction, refrigeration and makeup units) in a US Gulf Coast location with a capacity of 200,000 gpd. For the N<sub>2</sub> expander cycle, two options are shown in **TABLE 2**:

1. Process machinery, either seal-less or fitted with refrigerant recovery, resulting in higher investment cost but lower utility consumption and operating cost
2. Process machinery fitted with standard seal systems (C-rings on the refrigerant compressor and labyrinths elsewhere), resulting in lower investment cost but higher utility consumption and operating cost.

**Capital cost.** Capital expenditures (CAPEX) include engineering, procurement and construction (EPC) and 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 on this comparison include:

- SMR compressors are expensive equipment compared to the air separation unit machinery of the N<sub>2</sub> expander cycle
- Piping quantities are greater than 100% higher for the N<sub>2</sub> expander cycle compared to the SMR cycle, resulting in significantly higher materials and construction cost
- Total cost differences between the three alternatives are 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, greenfield LNG plant.

**Operating cost.** Operating expenditures (OPEX) assessed in **TABLE 3** account only for power and refrigerant makeup consumption and are based on 8,000 hours per year. The cost for operating personnel will be identical, whereas cost differences for equipment maintenance are difficult to assess precisely.

Observations on this comparison include:

- The SMR cycle shows the expected benefits with respect to power consumption
- For the N<sub>2</sub> expander cycle, the cost of LN<sub>2</sub> makeup reaches the same order as the cost of power

- When considering a 15-year lifecycle cost, the relative OPEX disadvantage of the N<sub>2</sub> expander cycle to the SMR reaches the same order of magnitude as the absolute cost of the exemplary liquefier system.

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

For applications with high annual operating hours near design load, such as baseload or peakshaving LNG plants, the SMR technology has a strong advantage with respect to operating cost. Its disadvantages, including longer startup time and reduced partial-load capability, are less relevant.

For applications with low annual operating hours and wide load-profile requirements, such as boiloff gas reliquefaction units, the N<sub>2</sub> expander cycle, with a refrigerant buffer system, offers significant advantages with short startup time, as well as wide partial-load capability and efficiency, while low operating hours compensate for higher specific operating cost.

Additionally, in remote areas where C<sub>2</sub> and C<sub>4</sub> makeup component delivery comes at high logistical effort and price, the OPEX gap between the SMR cycle and the N<sub>2</sub> expander cycle will be smaller. However, this situation will rarely arise in the US.

The extra investment in an N<sub>2</sub> expander cycle low-leakage system typically will have an attractive payback time of less than three years. **HP**

#### NOTES

<sup>1</sup> The SMR process used in this study is Linde's proprietary single-cycle, multistage mixed-refrigerant process LIMUM. The N<sub>2</sub> expander process is BHP Billiton's licensed dual-nitrogen expander process.

<sup>2</sup> SMR power consumption is used as a reference point for comparison and is, therefore, set to 100% throughout the temperature/pressure range.

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