LNG plant scale-up could cut costs further

The scale-up of Phillips' Optimised Cascade LNG Process to much larger train sizes is proving to be surprisingly easy, and offers the prospect of another significant reduction in the unit-cost of LNG. And scale-down to smaller plants is also possible, explain Amos Avidan and Frank Richardson, of Bechtel, and Kent Anderson and Bill Woodard, Phillips Petroleum

FOLLOWING record low unit-cost achieved on the Trinidad LNG project in 1999, further significant reductions may be achieved by scaling-up Phillips's Optimised Cascade LNG Process (OCLP) to much larger train sizes. Similarly, scale-down to allow economic smaller plants is also possible. Indeed, the "two-trains-in-one" design provides very-high reliability in a single-train plant of any size.

Base-load natural gas liquefaction plants have always been designed along the train concept. While some plants consist of a single train, most LNG facilities have several parallel process trains. The train concept has evolved because of market demand, delivery and shipping logistics, and mechanical limitations on the size of critical equipment, such as mechanical drivers, compressors, and heat exchangers.

Early on, small trains matched smaller market demands, fitted well within available equipment capabilities, and allowed for back-up in case of mechanical malfunction. Each train usually includes gas-treating, dehydration, mercury removal, refrigeration, heavy hydrocarbon removal and LNG production and transfer equipment. While the trains are supplied by outside utilities (such as electric power, cooling water, instrument air), each is, in effect, an independent process plant. A single train can be shut down for a period of months without affecting the operations of adjacent trains.

Single-train plants

One of the most successful early LNG plants is Phillips's Kenai plant, which pioneered the Pacific LNG trade. This single-train plant was built by Bechtel and commissioned in 1969. Subsequent debottlenecking has increased capacity to 1.5m tonnes a year (t/y).

Like today's Phillips and Bechtel LNG plant designs, this plant features the "two-trains-in-one" reliability concept. Two identical parallel compressor strings are utilised for each refrigeration service. The rest of the plant consists of a single train of gas treating, heat exchangers, and liquefaction equipment.

With this concept, the loss of any refrigeration compressor string does not shut down the train, it only necessitates a reduction in plant feed. By adjusting loads between the remaining refrigerant compressors, LNG production can be maintained at 70-80% of full capacity. The success of Atlantic LNG's (ALNG) Trinidad plant is recent reconfirmation of this design philosophy.

The historical trend in LNG plant design has been showing accelerating growth in train size (Figure 1). Single-train size increased from the 0.5m-1.0m t/y range, in the industry's early days, to 1.0m-1.5m t/y during the 1970s and 1980s. Typical train size then grew quickly, from 2m t/y in 1990 to 3.0m-3.5m t/y and trains with capacities of over 4.0m t/y are being considered by several projects.

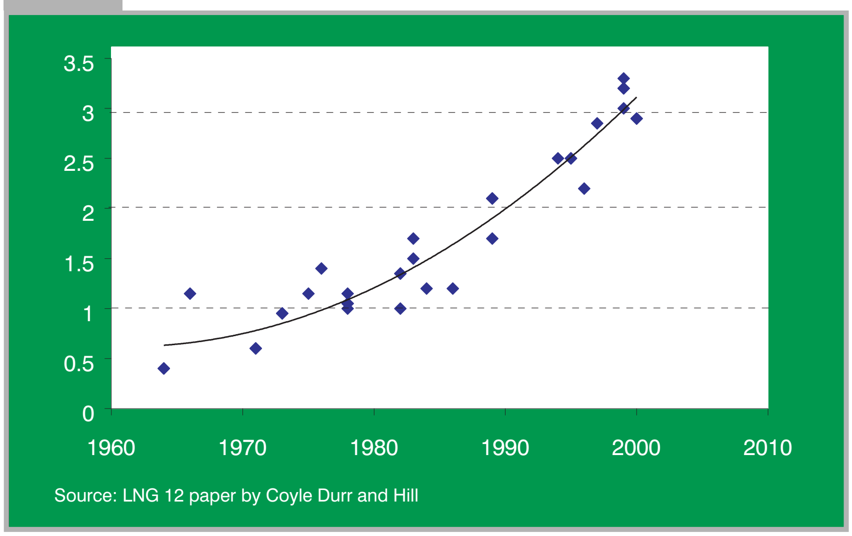
Many factors should be considered when choosing optimal train size for an LNG project:

- Gas deliverability from the field;
- Market demand, and LNG delivery build-up profile;
- Overall optimisation of production, storage and shipping logistics;
- Available proven equipment size;
- Potential capital cost savings; and
- Operational flexibility, reliability and maintenance.

Gas deliverability from the field includes the optimisation of factors such as proven reserves, the costs of developing different areas of the field, pressure maintenance policy (for example, the need for compression addition), and the size and type of pipelines from field to plant.

Market demand and the required delivery build-up schedule dictate plant size, train size, and the spacing between train completions. There is also an optimal low-cost execution delay between trains that must be taken into consideration. LNG plants have traditionally been built to satisfy exclusive long-term contracts,

Figure 1 LNG single train sizes (m t/y)



Source: LNG 12 paper by Coyle Durr and Hill

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which, in turn, limited the amount of gas that could be sold at one time. A typical single-gas contract may vary between 2m and 5m t/y, but an LNG project developer can combine several such commitments to create larger blocks of demand.

There has been a gradually-increasing trend of acceptance of larger equipment sizes for LNG trains. This has been matched by a gradual increase in LNG storage-tank size. Early tank designs were usually smaller than 40,000 cubic metres (cm). Tanks ranging in size from 100,000 cm to 140,000 cm were common in new plants in the 1990s, while, more recently, tanks with capacities of 160,000-200,000 cm have been built. Future designs may involve larger tanks still. The critical components of an LNG train that may be limited in size are: mechanical drivers; compressors; heat exchangers; vessels; valves; and piping.

Gas turbines

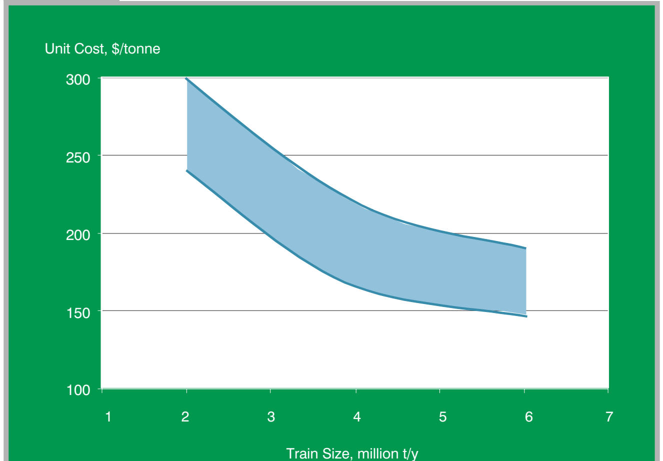
Gas turbines are commonly used as mechanical drivers in LNG plants, although steam turbines were used in some earlier designs. Some of the most common gas turbines considered for LNG use are shown in Table 1. They can be broadly categorised as heavy-duty industrial types (Frame turbines) and industrial aero-derivatives, characterised by their light weight and higher efficiency. To date, no aero-derivative types have been used in a base load LNG plant.

Relative cost is ratio of the bare equipment cost for the turbine relative to the cost for a Frame-5C. The relative specific cost is the ratio of bare equipment cost per kilowatt of power generated relative to the Frame-5C. It becomes clear that the larger turbines are much lower in specific cost. These larger turbines, however, are single-shaft designs originally meant for electrical generation service rather than mechanical drive. They have very limited, if any, speed flexibility. This makes them more difficult to operate, less efficient at turn-down conditions and they require more complex controls and auxiliary equipment, which adds to the installed cost.

The Frame-9 size is greater than any proven compressor power so it requires multiple compressors and/or generators to be placed on the same string, which introduces new mechanical design issues.

Table 1 shows how competitive the aero-derivative machines have become in terms of cost per unit of power, considering their markedly-better efficiency. LNG plant project developers are beginning to assign hard economic criteria (such as higher fuel values), which may result in the use of aero-derivatives in the near future. So far, most developers have not assigned hard criteria for reducing carbon dioxide emissions, but this will come soon, increasing the demand for this type of turbine.

Figure 2 **Unit cost against train size**



Source: DOE/authors' calculations

Large trains

A typical large-train design is the 3m-t/y ALNG plant train 1. ALNG was a milestone because it was the:

- First single-train plant built in almost 30 years;
- Lowest unit-cost plant (capital expenditure per tonne of LNG produced);
- Most aggressive expansion on record: original train started up 1999, train 2 will start up 2002, and train 3 will start up 2003; and
- Largest single-train plant in the world (at start-up).

In the two years following the ALNG start-up, LNG train sizes under design have increased dramatically. For more than one client, Phillips and Bechtel engineers have proposed single-train sizes of more that 4m t/y. These designs have been put forward with a great deal of confidence, as the basic design of the Phillips OCLP is very straightforward to scale up or down.

These larger train designs offer potential cost savings. Figure 2 shows unit cost (capital expenditure per million t/y of LNG capacity) as a function of LNG train size. The cost indicated in Figure 2 represents a complete grass-roots single-train LNG manufacturing complex. It includes what is typically within the general engineering, procurement and construction contractor's turn-key scope. It does not include gasfield facilities, pipelines, LNG ships or owners' project-development or project-management costs. It does include all the facilities needed to receive pipeline gas, and produce, store and load LNG onto ships, and support facilities, such as offices, shops and warehouses.

There is, of course, a very significant variation in plant costs for a given LNG capacity because of three broad items:

- The nature of the gas supply, composition and supply pressure;
- The nature of the site and site specific design requirements; and
- The owners' standards and specific requirements.

Figure 2 shows a range of unit costs as a function of train size, and this range is intended to account for variations such as those above. Most projects are expected to fall into this range. All costs represent a complete single-train plant with an appropriate amount of LNG storage. All train sizes at or above 3m t/y are "two-trains-in-one" concept, providing two-train reliability.

Compressors and drivers

The base design of the Phillips OCLP uses two identical, parallel driver/compressor sets for each of the three refrigerant circuits. This has been perceived by some as a disadvantage to LNG processes that utilise only two driver/compressor sets. But the Trinidad experience demonstrates that parallel driver/compressor sets are a cost-effective solution. The six drivers are identical, minimising the required spare parts inventory.

And by splitting the compressor load between two compressors (in each service) the resulting

Table 1 Gas turbine comparison

Frame turbines					
Model:	**GE 5C**	**GE 5D**	**GE 6**	**GE 7**	**GE 9E**
ISO power, MW	28.3	32.6	43.5	85.4	123.4
Relative cost	1.0	1.2	1.3	2.7	3.0
Relative specific cost	1.0	1.04	0.85	0.89	0.69
No. of shafts	2	2	1	1	1
Efficiency %	29.3	30.3	33.2	32.7	33.8
Aero-derivatives					
Model:	**GE LM2500+**	**GE LM6000**	**RR Coberra 6761**	**RR Trent**	
ISO power, MW	30.0	44.6	33.4	52.55	
Relative cost	1.2	1.7	1.2	1.9	
Relative specific cost	1.13	1.08	1.02	1.02	
Number of shafts	2	3	2	3	
Efficiency %	40.3	42.6	40.5	42.5	

Source : authors calculations

units are in the more proven ranges of multiple manufacturers, encouraging competition among vendors for the compressors and also for valves and other system components.

The Phillips and Bechtel experience with parallel compressors also provided a natural segue for larger train sizes. It has been proven that six driver/compressor sets can be an effective solution, so why not add driver/compressor sets to achieve even greater capacity? Phillips and Bechtel have developed designs utilising seven or eight turbine/compressor sets capable of producing up to 4.5m t/y of LNG.

This is possible because the process refrigeration duties can be distributed among the three refrigeration circuits. In addition, the dependable and economic General Electric (GE) Frame-5C gas turbine has now been up-rated by 15% in power (GE Frame-5D). Utilising eight of the new Frame-5D machines it is possible to build a single train with a capacity of 4.5m-5m t/y.

Cold boxes

The Phillips OCLP utilises two “cold boxes” in the heart of the liquefaction section. Cold boxes for ALNG train 1 were designed by Phillips and Bechtel engineers. All the equipment housed in the cold boxes is sized specifically for this process and is available from several manufacturers. Various fabricators are also capable of constructing the cold boxes. Both of these ensure competition among vendors and help to keep the cost down.

Extensive optimisation studies and updated heat-exchanger technologies since the Trinidad LNG project have made significant throughput increases possible for a typical cold box. For example, a recent design included cold boxes with a capacity of 4.5m t/y. Yet, the size and weight of the boxes were practically the same as those provided for ALNG train 1.

Typical heat exchangers utilised most heavily in the Phillips OCLP are air-cooled exchangers and brazed aluminum plate fin-heat exchangers. Shell and tube exchangers are used in only a few applications. Air-cooled exchangers are used for the inter-stage and after-cooling of the refrigerants, as well as for condensing the propane.

The brazed aluminium plate-fin heat exchangers (BahxPF) are used for condensing ethylene and cooling the feed gas. These BahxPF exchangers are utilised in two configurations – traditional and “core-in-kettle”. The traditional application of these exchanges is free-standing Bahx units which may have multiple streams (two, three, four, five, six) being heat exchanged. The core-in-kettle application comprises one or more Bahx units in a shell (kettle), usually with an evaporating, single-component refrigerant on the shell side. The Bahx unit or units in the kettle may have multiple streams being cooled.

Air-cooled exchangers have been utilised in the gas processing and refining and petrochemicals industries for many years. Designs of these units are proven and there are a number of manufacturers capable of providing quality units.

As the demands on the required duty for these heat exchangers increases, it is a common practice to add additional bays in parallel. For example, the propane condenser for ALNG train 1 consists of 43 air-cooled exchangers (or bays) in parallel. Large banks of air-cooled exchangers to meet specific requirements have been designed many times, in many different applications. There is virtually no scale-up risk with these heat exchangers.

Bahx have been utilised in the cryogenic gas processing plants since the 1950s. The Phillips Kenai LNG plant, commissioned in 1969, also makes use of these exchangers. These exchangers have a good performance record in cryogenic applications. The Kenai plant has never had a problem with the Bahx exchangers.

Exchanger volume

Advantages of the Bahx exchanger include compact size and expandability. Bahx exchangers typically provide over 300-400 square feet of surface area per cubic-foot of exchanger volume. This is six to eight times the surface density of comparable shell and tube exchangers.

Although different manufacturers have different size limitations for a single core exchanger, manufacturers are well versed in manifolding two or more cores into batteries to achieve the required surface area. These batteries may be as simple as a single row of cores with a distribution header, much like stringing air-fin exchangers together for parallel service, or they may be complicated arrangements with multiple rows of multiple cores.

Their use in core-in-kettle designs, with single-component refrigerants, ensures excellent refrigerant flow through all units and eliminates thermal shock when plant feed-gas-flow is started or stopped. Use of multi-component refrigerants with Bahx exchangers is more difficult.

The design of the Phillips OCLP provides complete turn-down of the liquefaction section. This has been demonstrated in Kenai and Trinidad. The operability and flexibility have proved outstanding. The OCLP plant can run idle for long periods, processing only enough gas to fuel the gas turbines. This was demonstrated many times during the commissioning of the Trinidad plant. For example, the plant was operated smoothly to produce LNG for storage-tank cool-down at just over 1% capacity or 8 cm an hour. There was no flaring or burning of LNG during this period.

Two shaft gas turbines, while limited in size, allow more efficient turn-down operation in the range of 60-100% of design capacity. The compressor speeds are simply reduced. Two shaft turbines also allow a fast restart, without need to depressure compressor cases or engage special starting equipment. Turn-down methods for fixed-speed machines are less efficient, but the process can still be turned down.

Plant restart is very easy because of the nature of the core-in-kettle exchangers and the well-insulated cold boxes. No venting of refrigerants is necessary in the event of a plant shut-down. The cold boxes allow the containment of the refrigerant for hours or even days, if necessary, without venting.

Similarly, the plant size can be scaled down by several means: selecting smaller drivers, such as the aero-derivative LM2500; using only five or four compressor strings per process train instead of six; and using one compressor train per refrigerant circuit instead of two.

Because almost all items have parallel components, the scale-down to about 40% of Trinidad capacity, or 1.2m t/y, can be done without a great increase in unit cost. This cannot be said of the present versions of the propane, precooled MR processes.

For optimum flexibility, larger train sizes can be designed utilising electric motor drives for the refrigeration compressors. As an example, using three GE Frame-9E units (or using two units in a combined-cycle power plant), a 6m t/y LNG train can be achieved. The required power for each refrigerant section would be around 80-100 megawatts. Compression for each of the refrigerant loops can be split between two or more compressors, depending on the capabilities of the compressor manufacturer. With electric motor drivers and the load-shifting capabilities of the Phillips OCLP, design engineers have the ability to optimise the motor/compressor combinations for the specific site and all refrigeration compressor strings can be kept within the range of proven components.

An N+1 sparing philosophy is not required for the Frame-9E power plant because of the two-trains-in-one compressor string philosophy. As with the gas-turbine drive option, loss of any power generator will not necessitate a plant shut-down. It will only require a reduction in feed. For example, if three Frame-9Es are supplying power to the train and one of these units shuts down, the feed to the plant would have to be reduced to around 50%. But if the refrigeration load is been split between more than six compressors, plant feed can be maintained at up to 66% of capacity. This compares favourably with other large multi-train LNG complexes.

Environmental benefits

A Frame-9E (or similar) combined-cycle power plant with all electric process drives may well be the LNG plant of the future. This is due primarily to the efficiency and environmental benefits of combined-cycle power generation. Gas turbine manufacturers are expected to focus their efficiency and emission-improvement efforts on the larger turbine sizes.

The ease of operability and the ability to scale-up the Phillips OCLP economically should compare favorably with other LNG processes in this scenario. The Phillips OCLP can also achieve a combined cycle by using gas turbines with waste-heat recovery on two-thirds of the compressor drivers and steam turbines on the other third. This feature will allow cost-effective down-sizing.

LNG plant designs using one of these processes have been proposed for train capacities in the range of 4.2m-4.4m t/y. These designs followed the Shell-pioneered breakthrough in using a Frame-6 turbine for propane and a Frame-7 for MR processes, and using an efficient and operationally-flexible axial flow compressor for the first stage of the MR process. These designs are based on utilising the full available power from two Frame-7 gas turbines and other capacity enhancements, also pioneered by Shell, such as liquid expanders.

This is not simple, as the process refrigeration duties naturally incur a power split. Furthermore, a significant scale-up in the spiral-wound cryogenic heat exchanger, the heart of such processes, is required. The engineering design for such a scale-up is not obvious. Shell has proposed using two spiral-wound units in parallel for Train 4 at the Woodside LNG facility in Australia. This should have an impact on plot area and associated bulk material costs.

Beyond trains

The ease of scale-up and the use of multiple parallel units of key equipment in the OCLP will allow designers abandon the traditional concept of production trains. There is no single equipment item now setting train size. This may allow some pre-investment schemes to become a reality.

Looking to the Trinidad example, where a decision to triple capacity was made when the plant was only a year old, it is feasible that soon major new complexes will be envisioned with a steady but aggressive capacity build-up. In this scenario, equipment could be installed in the steps most economic for the future high capacity of the facility and not necessarily as unified consistent capacity increments. Refrigeration at various levels, for example, may become available as utilities.

Similarly, liquefaction may, in the future, be only a part of a huge gas monetisation complex comprising gas treating, NGLs extraction, power production, ethylene production, gas-to-liquids plants, fertiliser plants and various other related fuels and petrochemical units. The refrigeration sections of the LNG plant using the OCLP may easily be designed to serve some of these other processes. The gas treating and electric power sections would, of course, serve many of the other facilities. □