SECTION THREE: LIQUEFACTION

As you learned in the last Section, the LNG delivery chain (liquefaction, shipping and regasification) replaces the transportation function generally attributed to interstate pipelines. In the first step, liquefaction, natural gas is converted from its gaseous state to a liquid state so that it can be transported via tanker. In the simplest of terms, the liquefaction process takes raw feed gas, removes impurities and other components, cools the gas until it liquefies, and finally moves the liquid into storage tanks. The LNG is then loaded onto tankers for transportation to market. While this sounds reasonably simple, the actual process is quite a bit more complex. In this Section we will explore the technology and costs associated with the liquefaction process. We will also discuss both existing and planned liquefaction infrastructure around the world as well as the key issues affecting the future of liquefaction.

Liquefaction Technology

The three basic steps of the liquefaction process are as follows:

1. Removal of impurities and recovery of natural gas liquids (NGLs)
2. Refrigeration of the gas until it liquefies
3. Movement of the LNG to storage and ultimately into the tanker

Removal of Impurities and Recovery of NGLs

The gas supply that comes from the production field is called raw feed gas. This is typically made up of methane, other hydrocarbons such as ethane, propane, butane, and/or pentane, and substances such as water, sulfur, mercury, and other impurities. The raw feed gas is delivered via pipeline to a processing plant. Here the gas is processed to remove impurities as well as valuable NGLs. The first step is pretreatment, which includes the removal of acid gas such as carbon dioxide and sulfur, as well as mercury and other substances. All of these must be removed either because their freezing points are well above the temperature of the final LNG product (and
they could freeze and damage equipment during the cooling process), or because they are impurities that must be removed to meet pipeline specifications at the delivery point. Next water is removed.

After the above steps, the NGLs such as ethane, propane, butane, and pentanes (also known as heavy hydrocarbons) are removed and collected. In many cases the gas is processed upstream of the liquefaction unit, using traditional gas processing technology (i.e., the same processing that is done to any gas entering an interstate pipeline system). In other cases, the NGLs recovery may be done as an integral step in the liquefaction process. The NGLs collected are valuable products in their own right, and may also be used as refrigerants for the liquefaction process or may be reinjected into the
LNG stream at a later point to adjust the Btu content and flammability characteristics of the LNG. Pentanes and other heavy hydrocarbons are generally exported as a gasoline product. Butane and propane are often also exported as separate products and/or used as refrigerants. Ethane is often reinjected into the LNG stream and may also be used as a refrigerant.

**Liquefaction of the Methane**

Next, the methane along with any reinjected components, is further cooled to -260 degrees Fahrenheit using LNG liquefaction technology. In this step, the methane mixture liquefies into the final cryogenic liquid state. Although slightly different processes are used in various liquefaction facilities, the basic cooling and liquefaction principles of each process are the same. The key technology is heat exchange. Here, a cold liquid refrigerant is passed through cooling coils and the natural gas stream is allowed to flow over them, resulting in cooling of the gas stream. As the temperature drops to about -260 degrees Fahrenheit, the gas becomes liquid and can then be pumped into a storage tank.

Different liquefaction processes include the APCI MCR Process, the Phillips Optimized Cascade Process, and the Linde/Shell Fluid Cascade Process. The process chosen is a design decision and depends on various factors including the composition of the feed gas, the availability of refrigerants, whether the NGLs are being removed upstream, the size of the facility, requirements for operational flexibility, and the cost/availability of power for compressors.

Liquefaction facilities are generally constructed in modular units called trains. A train is a complete stand-alone processing unit, but often multiple trains are built side-by-
side. Train sizes currently range from less than 1 to 5 mtpa. Future designs may extend sizes to as large as 8 mtpa as engineers attempt to take advantage of economies of scale.

Storage and Pumping the LNG into Tankers

After the liquefaction process, the LNG is pumped into a cryogenic storage tank. These tanks are typically double-walled, with an outer wall of reinforced concrete lined with carbon steel and an inner wall of nickel steel. Between the two walls is insulation to prevent ambient air from warming the LNG. The LNG is stored in these tanks until a tanker is available to take the LNG to market. After an empty tanker docks at the berth (which is located as close to the liquefaction facility as possible), the LNG is loaded onto the tanker through insulated pipes that are attached to the tanker by rigid loading arms. Once the tanker is filled, the pipes are disconnected, the loading arms are swung away from the ship, and the tanker is ready to sail.

Liquefaction Plant Costs

Capital Costs

The capital cost of a liquefaction plant is a critical component of the overall cost of an LNG delivery chain. In fact, total costs of a facility can run as high as $2 billion. While this is certainly a huge expenditure, costs on a per unit basis have dropped significantly in the last 26 years. The initial liquefaction plants were small in size compared to...
those in the planning stages today, with no trains over 2 mtpa built until the 1990s. As the LNG trade became more than a small niche market, plant owners began looking for ways to lower costs. One key was to take advantage of economies of scale by building larger facilities. As you can see from the chart on page 26, the cost of liquefaction has fallen significantly – from over $500 a tonne in 1988 to below $200 a tonne today.

This drastic reduction in costs is due to a number of influences. Certainly, technology was pushed to gain economies of scale. But in addition, organizational learning, research and development, project management, and technology supplier competition had a hand in reducing the cost of liquefaction. And we may still see future cost reductions. Gains are not likely to come from component prices since steel and concrete have experienced 100% to 400% price increases during the last two years. Construction time, however, is actually more expensive than the materials required to build the asset. For example, the facility recently built by Oman LNG at Qalhat involved 10,000 tons of steel, 40 million man hours of construction time and over 100,000 cubic meters of concrete for the foundations alone. Even though the steel and concrete numbers are impressive, the cost of steel represents less than 3% of total capital costs. But streamlining the 40 million manhours spent on construction could result in considerable cost reductions.

Economies of scale are also a significant factor in obtaining reductions in liquefaction unit costs. Many of the new plants being considered will include trains in the 4 mtpa, 5 mtpa, and 8 mtpa range. While larger trains can accomplish a substantial reduction in costs, there are concerns. One of the major hurdles is the significant reduction in LNG production that occurs when one of these super-size compressor trains goes out of service unexpectedly or for planned maintenance. Thus operational flexibility can be an important factor in design decisions. The future costs and reliability of mega trains remain to be seen, and at this point the jury is still out on their feasibility, especially given cost and reliability concerns.
Variable Costs

Ongoing costs to operate a liquefaction unit are also an important factor in the overall cost of liquefaction. Important factors include use of natural gas as fuel in the liquefaction plant, taxes paid to the local government and general operating and maintenance (O & M) costs. A typical liquefaction unit might use 11% of the plant’s input gas as fuel. If we assume a fuel cost of $0.75/Mcf (current supply costs range from $0.55 to about $1/Mcf) then the operating cost associated with use of fuel is approximately $0.08/Mcf. Taxes will vary depending on where the facility is located but might be on the order of $0.15/Mcf and O & M costs are typically about $0.20/Mcf. The resulting overall variable cost of liquefaction is then about $0.43/Mcf, which is more than half the original cost of the gas from the field.

Liquefaction Infrastructure

Existing Plants

With the commissioning of the Damietta, Egypt plant in late 2004, liquefaction plants are now operating in 13 different countries at 16 different sites. A total of 70 trains have been built worldwide, with several others under construction and additional facilities in planning. Total production capacity is approximately 150 mtpa worldwide, with actual production estimated at 90% for year end 2004. The table on page 29 lists the exporting countries along with their market share at the end of 2004.

Historically, a typical LNG liquefaction plant has consisted of between one and three process trains, though some plants have used as many as six. In simple terms, a train can be viewed as a standalone liquefaction unit (i.e., it is possible to shut down one train without impacting the operation of other trains). Multiple trains add flexibility to plant design by allowing the operator to match the number of trains online to the amount of available gas. Today some facilities are being designed for greater flexibility within a single train, allowing for a reduction in the number of trains commonly required for new or expanded facilities.

The initial liquefaction plants built in the 1960s and 1970s consisted of multiple trains with lower capacities. For example, the first commercial LNG plant was constructed with three trains, each with a capacity of .37 mtpa. Five years later, the Kenai, Alaska plant came online with two trains, each with a capacity of .70 mtpa.

1 The Kenai plant is sometimes referred to as a single train facility. Its design is actually a “two-in-one” configuration, making both a single train and a two train label correct.
The initial liquefaction design, which featured smaller and multiple trains per plant, was probably necessitated by a market whose primary focus was supply security – even at additional capital cost. The older projects were built with generous capacity margins and redundant design features to assure security of supply with the ability to meet contractual supply obligations. But beginning in the late 1990s, train size began to increase dramatically, and the common number of trains dropped to one or two per plant. The latest plant to be commissioned was a single train 5 mtpa facility. Experience has allowed plant owners to decrease the design redundancy of their facilities which in turn has reduced the capital costs per train.

Although demand for new liquefaction slowed in the mid-80s through the first half of the 1990s, a new boom in demand began in the late 1990s and continues today. In the period from 2000 to 2004, approximately 28.5 mtpa of new liquefaction capacity was commissioned, representing a 25% increase over existing facilities. The associated capital cost for these new plants was some $7.7 billion. It is anticipated that expenditures for liquefaction will more than triple over the next four-year period.

**Proposed and Future Plants**

The overall trend in the LNG industry points to strong market growth. In the next five years, over $65 billion is likely to be spent in new LNG facilities, with almost half of this spent on a massive increase in global LNG liquefaction output.

Africa and the Middle East have announced projects requiring a dramatic growth in capital spending. These projects will add around 75 mtpa of liquefaction and account for 61% of forecast liquefaction spending. In Africa, key developments include the Idka facility in Egypt as well as further development of the Damietta plant. Other developments include the Gassi Touil project in Algeria, the Bioko Island project in

<table>
<thead>
<tr>
<th>Country</th>
<th>Volume (in million tonnes)</th>
<th>Market Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indonesia</td>
<td>24,817</td>
<td>19.0%</td>
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<tr>
<td>Malaysia</td>
<td>20,128</td>
<td>15.1%</td>
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<td>Qatar</td>
<td>18,220</td>
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<tr>
<td>Algeria</td>
<td>18,017</td>
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<tr>
<td>Trinidad and Tobago</td>
<td>9,712</td>
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<td>Nigeria</td>
<td>9,489</td>
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</tr>
<tr>
<td>Libya</td>
<td>489</td>
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</tr>
</tbody>
</table>

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Equatorial Guinea and the continuing expansion of the Nigerian Bonny Island plant. In the Middle East, the RasGas II and Qatargas II developments will be the most significant. In addition, the third train added to the existing Oman plant as well as the Pars LNG development in Iran will also be significant.

Western Europe (Norway) and Russia should see their first LNG export facilities operational during the 2005 to 2009 timeframe. There are also a variety of plants in the planning phase in Angola, Algeria, Australia, Brazil, Indonesia, Nigeria, Peru, Qatar, Trinidad, Venezuela, and Yemen. North America is the only region with no new liquefaction facilities forecast for this period of time.

Key Issues

Key issues to watch are the development of new technology needed to accommodate offshore liquefaction terminals and market changes impacting the cost of liquefaction. Throughout the world, much of the stranded gas under development exists offshore. Yet to date, all liquefaction facilities have been built onshore with close proximity to a safe harbor. Because large gas reserves exist offshore, liquefaction technology is currently being developed for offshore application. Initially, the capital unit costs may be higher since train size will be smaller. In addition, equipment and loading facilities will have to be certified for LNG application. However, offshore facilities eliminate land purchase, jetty facilities and the need for compression and pipeline to move gas to shore, offsetting a large portion of the additional costs.

The LNG marketplace is beginning to demand more flexibility in timing and amount of gas taken from liquefaction facilities. To accommodate these contractual terms, LNG liquefaction plants have to be able to reduce their output to match market demand, or find a ship and market available to purchase the spot load. This production flexibility is dependent upon plant design as discussed previously in this Section. While growth in this market is unquestionably favorable for the asset owner, the flexibility now required makes the business significantly more complicated.

In addition to volume flexibility, the evolving marketplace for spot sales impacts the quality requirements of gas produced from liquefaction. If a liquefaction facility has the ability to adjust the Btu content of the LNG as needed, more markets are available to that product. Thus facilities with quality adjustment capability will be more profitable in today’s buyer’s market.