Natural gas liquefaction process designers look for larger, more efficient liquefaction plants

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The international Liquefied Natural Gas (LNG) trade continues to expand rapidly. While there were only two new grass roots LNG plants in the 1980's, the 1990's saw the startup of six new grass roots projects in Malaysia, Oman, Qatar, Nigeria, and Trinidad. In addition, existing facilities were revamped and expanded. Seven additional grass roots plants are currently in, or about to enter engineering and construction: two projects in Egypt, one at Idku and one at Damietta, and one project in each of the following countries: Australia, Equatorial Guinea, Indonesia, Norway, and Russia. Expansion continues in newly built plants (such as Trinidad and Nigeria), and additional new projects are being proposed in Nigeria, Angola, Qatar, and other locations.

The total capacity of LNG currently in engineering and construction is about 60 million tonnes per annum (mta), or about 50% of existing worldwide base-load LNG capacity (Table 1). If all of these projects come on stream in the coming years, the LNG trade will be well on its way to reach a projected worldwide volume of over 180 mta by the end of the decade. Additionally, there are many more projects that could enter engineering and construction shortly, but are constrained by market availability, partner alignment, or other issues (Table 2). These projects total more than 100 mta of LNG, and in all likelihood some will have to wait for 10 years or more for the market to catch up with potential supply.

Table 1: LNG base-load projects in EPC, or about to start EPC in early 2003

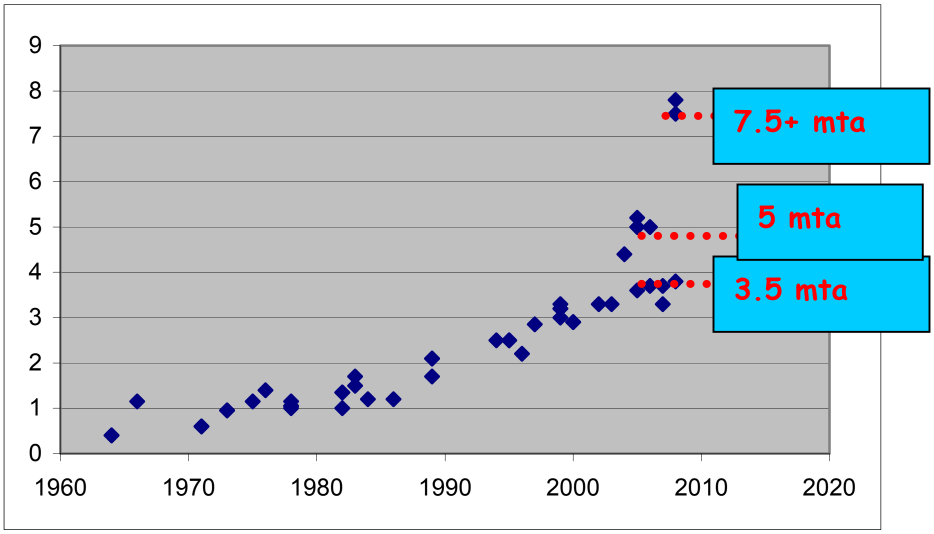
Project	Startup	mta
Atlantic market		
Atlantic LNG Trains 3/4	2003/5	8.5
Egypt LNG Trains 1,2	2005/6	7.2
Egypt Damietta	2004	5
NLNG Plus train 4/5	2005/6	8
Snohvit	2006	4
RasGas Train 4	2006	4.7
Pacific market:		
Malaysia Tiga	2003	7
Oman Train 3	2003	3
RasGas Train 3	2004	4.7
NWS Train 4	2004	4.2
Darwin LNG	2005	3.7
Total, mta		***60***

Table 2: Additional LNG projects in various stages of development

Project	Projected capacity mta
Atlantic market:	
Equatorial Guinea	3.5
Brass (Nigeria)	5
Atlantic LNG expansion	5+
Angola LNG	4
Egypt LNG expansion	3.6+
Egypt Damietta train 2	5
NLNG Train 6	4
Algeria	3+
Amazon	3
Venezuela	4+
Qatar	7.5+
Pacific market	
Tangguh	7
NWS 5	4.5
Bontang Train I	3
Sakhalin	8
Pacific LNG	7
Camisea	4
Gorgon	7
Sunrise	5
Yemen	3
Iran	5+
Total, mta	***100+***

As LNG facilities get larger, owners keep looking for ways to lower costs by benefiting from economies of scale. As export capacity grows, owners tend to have fewer concerns over maximal LNG train size, especially when the design includes a “two-trains-in-one” reliability concept that allows the LNG train to operate at about 60 to 80% capacity even with one of the gas turbine drivers down. The outstanding safety, reliability, and high operating factors of the LNG industry build up confidence in larger trains. Last year, we showed acceleration in train size for projects in Engineering Procurement and Construction (EPC) with capacities of up to about 5 million tons per annum (mta) (Figure 1, ref 1). Figure 1 has now been updated with new potential prospective LNG trains, including two with nominal capacities of between seven and eight mta, which could come on stream before the end of the decade.

Figure 1: Trends in LNG train size



Recent discussions within the industry have focused on train sizes from 3 to 8 mta and in some instances, 10 mta. Notwithstanding shipping and market acceptability, LNG train designs in the coming decade appear to fall within three groups having nominal capacities of approximately:

Nominal Capacity, mta	***Typical drivers for train capacity***
3 to 4	Expansion trains – copy design; limited gas supply or sales;
5	Expansion or grass-roots trains – lower $/ton; higher gas supply and sales
8+	Expansion train at a large existing complex; targeting a large, distant market, Lower $/ton; higher gas supply and sales potential

These three LNG train design capacities may co-exist in the coming years, as different projects find it advantageous to choose one vs. another. A major question facing developers and designers of large-capacity trains will be: "How does a single large LNG train (i.e., 8+ mta) train compare in cost and operational flexibility to that of two smaller 50% trains (i.e., 2x4-mta)?"

Scheduled engineering and construction for the Trinidad Atlantic LNG train 4, which at a nominal capacity of 5.2 mta is the largest LNG train in consideration in the world (Figure 2) today. A similar capacity (about 5 mta) LNG train is also in construction at Damietta, Egypt.

Figure 2: Construction continues on additional LNG capacity at the Atlantic LNG complex in Trinidad. Train 1 (on the right) has been operating successfully since July 1999. Train 2 was started up in August, 2002, 3 months ahead of schedule. Trains 3 schedule has also been accelerated as well and it was started up in May 2003.

A recent study by BP using a newly developed liquefaction technology, called Liquefin is described in reference 3. The new process uses dual mixed refrigerants, and aluminum plate fin heat exchangers. The authors of this study evaluated several cases, including a case using two Frame 7 or Frame 9 gas turbines, each driving a refrigerant compressor, with waste heat recovery. The generated steam is used to generate plant electricity. Another case study used four LM 6000 gas turbines, with inlet air cooling, driving the compressors. Yet another case study utilized large (up to 100 mW) electric drives for the refrigeration compressors. The authors have concluded that there are indeed opportunities to lower costs and reduce emissions of CO_2 from larger train LNG plants.

Air Products and Chemicals Inc. has developed the AP-X™ process by adding a nitrogen expansion cycle to the propane pre-cooled, mixed refrigerant process (reference 4). The addition of the nitrogen cycle reduces the load on the limiting mixed refrigerant service to about 60%, hence making capacities of up to 8 mta possible.

The ConocoPhillips-Bechtel LNG Product Development Center (or PDC) has developed large LNG train designs using the proven Phillips Optimized Cascade LNG Process (POCLP). Operating LNG trains that use POCLP have so far utilized the Frame 5 series gas turbines as compressor drivers. Recently, the LM2500+ aeroderivative gas turbine was chosen for the Darwin LNG project in Australia. A POCLP design proposed for the Tangguh LNG project in Indonesia in 2002 was based on the use of two Frame 7 gas turbines with waste heat recovery and steam turbines driving the methane compressors.

While the POCLP dual-shaft Frame 5 series driver configurations have provided robust LNG producing facilities with some of the highest on-stream factors in the world, there are cases where they may not be the optimal drivers. In some cases, the use of Frame

7EA and Frame 9E industrial gas turbines, in concert with steam turbines and electric motors can provide attractive alternatives for large liquefaction plants.

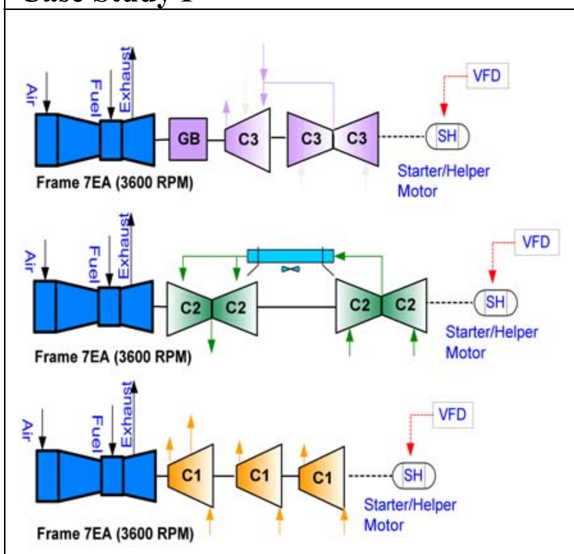
The Frame 7EA industrial gas turbine is a 115,330hp (85.9MW) ISO rated, single-shaft turbine that operates at 3600 rpm. The Frame 7EA was originally designed for electrical generation service rather than for mechanical drive service and has limited rotating speed flexibility. This somewhat reduces the operating flexibility of the LNG process, but not enough to warrant a multiple split-shaft turbine design. For instance, the ConocoPhillips Kenai LNG facility was the first to utilize single-shaft industrial gas turbines and it has been operating for over 33 years with an availability, production efficiency, and turbine reliability of 98+, 95+, and 99+ percent, respectively.

Driver/Compressor Case Study Configurations

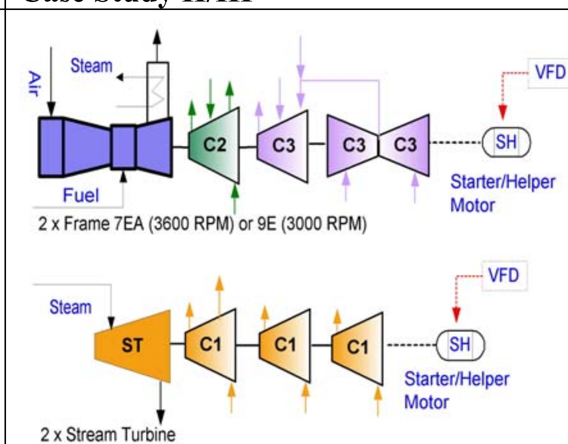
Three of the case studies evaluated by the ConocoPhillips-Bechtel LNG PDC are discussed in this report. In Case-I the study used three Frame 7EA's for the refrigerant cycles, while in Case II we used two Frame 7EA gas turbines equipped with waste heat recovery and two parallel steam turbines. Case III was similar to Case II, but Frame 9 gas turbines were used instead of Frame 7's. These configurations are shown in Figure 3. The driver/compressor arrangement in Case I required a gearbox between the gas turbine and the propane compressor to reduce the nominal speed from 3600 rpm to about 2400. Further optimization of these configurations continues as part of the PDC ongoing efforts.

Figure 3 – Driver Compressor Configurations

Case Study I



Case Study II/III



C1 = Methane, C2 = Ethylene, C3 = Propane

Unlike the split-shaft gas turbines, single-shaft turbines such as the Frame 7EA series turbines require starting assistance beyond what is typically provided by the vendor. For the driver/compressor configurations presented it was necessary to equip the Frame 7EA with a starting motor that would in turn be utilized as helper motor to achieve the desired LNG production rate. The motor size rating is dependent upon the refrigerant pressure within the piping and compressor system and their respective isolation valves, and the incremental power required to achieve target LNG production rate. Depending on the design premise of the respective facility, the starter/helper motors can range from 5 to 30 MW.

System Dynamics

The ConocoPhillips-Bechtel LNG PDC hired an independent third party dynamic modeling expert to simulate start-up capabilities of the proposed configurations. Several scenarios were tested with the use of a full-scale plant dynamic simulation. The goals were not only to demonstrate start-up, but also controllability and operability of the LNG plant during upset conditions.

Unlike the Frame 5D gas turbine, the Frame 7EA requires external assistance during start up especially, if the respective compressor is to remain pressurized. There are two primary methods for starting large single shaft-frame type industrial gas turbines coupled to compressors. Of these two, an electric motor in concert with a variable frequency drive (VFD) for low speed high torque starting is the primary mechanism for starting single shaft gas turbines. The other, as equally effective but not as common is the steam turbine. The motor starter was chosen for these studies.

Studies conducted in the ConocoPhillips-Bechtel LNG PDC confirmed starting motor and recycle valve sizing relative to system starting pressures and cooling mechanism for both the propane and ethylene refrigerant cycles of the POCLP Process. Dynamic simulations of the plant process were also performed. Trip scenarios such as a blocked outlet valve, loss of refrigerant cooling, plant emergency trips, etc. were performed. The results provided insight toward optimization of the control scheme for such operating upset conditions.

Economies of Scale

Over the past couple of years, "economy of scale" has been an area of focus within the LNG community. Generally, plant capital costs increase to the 0.65 power as capacity is increased. There have been indications that this is also the case for LNG, but there has been much debate as to whether this cost reduction reaches a plateau somewhere around 5 mta. The reasons would be factors such as reaching maximal capacities in critical equipment such as gas compressors, largest possible control valves, etc. As part of the study, the PDC examined the availability, cost and projected reliability of these critical pieces of equipment.

Compressors

The ConocoPhillips-Bechtel PDC solicited the help of GE Power Systems - Nuovo Pignone and Elliott for suitable compressor suggestions and designs. The designs submitted by both manufacturers were thoroughly evaluated, especially with regard to flow coefficients, rotor dynamics and relative mach numbers. We have found that compressor size is not expected to be a limiting factor for LNG trains utilizing the POCLP for the range of capacities evaluated (5.0 to over 7.5 mta).

Piping

For the two cases shown in this report the largest gas pipe size ranged from 72 to 84 inch in diameter for velocities of 30 m/s for both the low-pressure propane and ethylene compressor inlets. These gas velocities were considered acceptable in terms of erosion, vibration, and noise considerations. Piping in these sizes was determined to be readily available.

Fittings and Valves

We considered cryogenic and carbon steel butterfly valves of up to 84" ID in this study. Maximal pipe diameter considered was 120". Figures 4 & 5 demonstrate the increased cost for both carbon steel and cryogenic valves relative to size.

Figure 4: Cryogenic Butterfly Valves

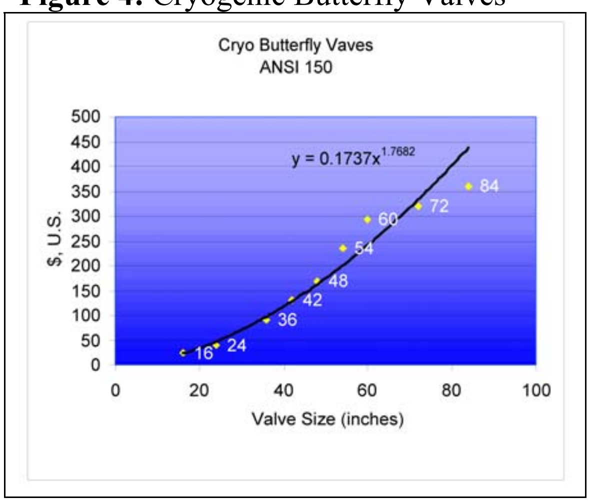
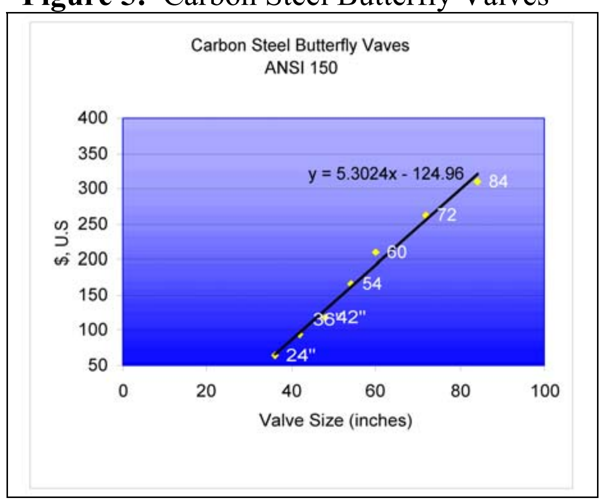


Figure 5: Carbon Steel Butterfly Valves



Vessels and Exchangers

Process equipment sizes increase as production increases. We found no technical constraints for vessel size, fabrication, or wall thickness, but transportation could be an issue for the larger vessels and exchangers especially if rail or highway transportation is required. The economics of a particular plant location would ultimately be the deciding factor for selection of vendors or transportation method.

Cold Box

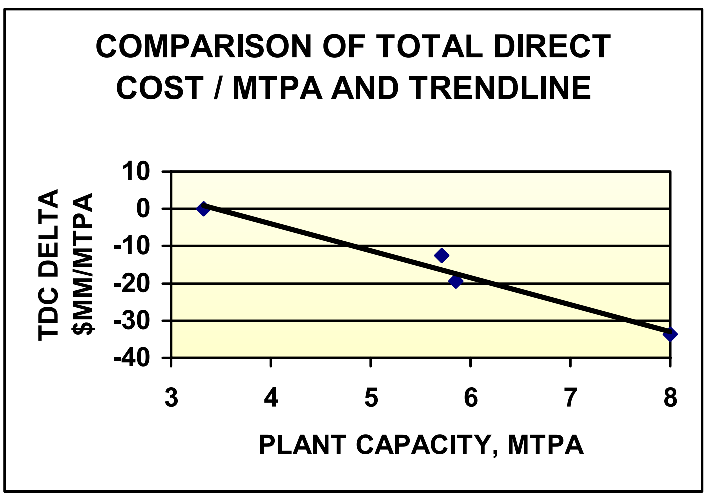
Cold box sizes, fabrication and shipping were also evaluated. One limit appears to be the size of the brazing furnace used to fabricate brazed aluminum heat exchangers. This limit can be resolved by using multiple, smaller units to achieve the required duty. As with vessels, the size of the cold box for the larger LNG plant could result in transportation issues for the weights and dimensions of the large boxes. Additional studies are underway by the PDC to address these issues.

Capital cost comparison

A cost estimate was developed for each of the configurations. We used a detailed takeoff for most bulks, a combination of in-house pricing from recent projects or quotes for major equipment, and budgetary pricing for the combustion turbine generators and process compressors. The Total Direct Costs (TDC) for each configuration were developed and compared for consistency.

The results showed that unit cost keeps decreasing with increasing LNG production capacity:

Figure 6: Total direct cost comparison



Efficiency

Table 3 provides a summary of refrigeration power required for the respective case studies plant overall thermal efficiencies.

Table 3: Refrigeration Power Summary & Thermal Efficiency

	Units	**Frame 5D Base**	**Frame 7EA Case I**	**Frame 7EA Case II**	**Frame 9E Case III**
LNG Production	mta	3.3	5.9	5.7	8
[1]Overall Thermal Efficiency	%	91	92	93+	93+
Turbine Speed	rpm	4670	3600	3600	3000
Heat Rate	BTU/KWH	11278	10420	10420	10,100
Iso Rated Power	KW	32600	86200	86200	123,400
1. Overall thermal efficiency includes, fuel, heater, acid gas incinerator, flares, etc.					

Emissions

The differences in heat rate between the gas turbine drivers and addition of waste heat recovery provide for higher thermal efficiencies. Table 4 compares emission data to that of a Frame 5D Phillips Optimized Cascade LNG Process facility.

Table 4: Emission data comparison to that of a Frame 5D LNG facility

FUEL USAGE	**PERCENT CHANGE (%)**		
FUEL USAGE	**Frame 7EA Case I**	[1] **Frame 7EA Case II**	[1]**Frame 9E Case III**
Btu/hr/mta	-16.3	-39.7	-45.1
Heat rate, [2]BTU/KWH	-8.2	-8.2	-11.7
EMISSIONS[4]			
CO_2,total	33.6	18.6	32.6
NO_X, total	33.5	12.8	30.6
CO, total	33.8	18.5	32.3
Unburned Hydrocarbon, total	32.0	19.0	32.0
Total tonnes/yr	33.6	18.6	32.6
Tonnes/mta[3]	-17.8	-40.8	-47.0

1. The Frame 7EA and 9E gas turbines are equipped with waste heat recovery. The methane compressors are driven by steam turbines.
2. The fuels presented in this table are based on the gas turbines with supplemental firing and hot oil heater where appropriate. For example, the base case has both the gas turbines and hot oil heater but no waste heat supplemental firing. However, the Frame 7EA case studies consider supplemental firing of the waste heat recovery units and hot oil heater where applicable.
3. The environmental data considers the following emissions release points: refrigeration gas turbines, power generation, regeneration gas heater, hot oil heater (process), supplemental waste heat firing where applicable, acid gas incinerator, wet gas flare, dry gas flare and marine flare.
4. Percent change equals lbs/hr of the base case less the case study result divided by the base case multiplied by 100.

Selection criteria for LNG plant owners and designers

1. **Capital and Operating Costs**
   Capital costs keep decreasing as LNG production capacity increases. Single train configuration with direct driver and no waste heat recovery will give the lowest capital cost plant per mta at a specific capacity. However the, operating costs for a similar size plant that includes waste heat recovery will be lower. Each facility will need to evaluate their own priorities and economic data to determine which best meets their objectives.

2. **Emissions**
   Larger industrial gas turbines tend more efficient and will have lower emissions. The use of waste heat recovery to produce steam to drive one or more refrigeration trains reduces both the gas consumed for fuel, and the emissions for a given size mta rating. Aeroderivative gas turbines (which were also studied by the PDC but not reported in this paper) are known to have higher efficiencies than industrial frame machines. Recently, GE has announced a new version of the Frame 5 gas turbine (5E), which will have a higher efficiency than the 5D machine. The use of electric drives, using electricity produced by a combined cycle power plant, can also result in higher efficiency and lower emissions. These configurations are currently being studied by the PDC.

3. **Operability**
   We found no significant issues regarding operability with the larger drivers and compressors. The Frame 7EA drivers have a narrow band of speed control, and therefore, the system design has to compensate for this. Dynamic simulations were performed in order to assure there were no operability issues.

4. **"Two-trains-in-one" concept**
   The ConocoPhillips-Bechtel LNG designs have typically used the "two trains in one" concept. This allows the LNG plant to operate at about 70% capacity even when one of the gas turbine drivers trips.

Acknowledgments:

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