

LNG: LARGER IS GREENER

Robert P. Saunderson, Joseph M. Petrowski, James C. Bronfenbrenner

Air Products and Chemicals, Inc., September 2003

Introduction

As economy of scale has driven baseload LNG trains to larger capacities, innovative process technologies and equipment advancements have resulted in lower operating expenses and reduced the capital cost per unit of production. Natural gas is the cleanest burning fossil fuel and emits less CO₂ per unit of energy than oil or coal. Air Products and Chemicals, Inc. is the leading liquefaction process licensor in the LNG industry and is a company with a strong environmental commitment as evidenced by our adoption of the American Chemistry Council's Responsible Care[®] initiative. Air Products' recently introduced AP-X[™] Hybrid LNG Process has the ability to drive the baseload LNG industry to lower CO₂ emissions and reduce the unit cost of product.

The MCR[®] Process Era

Air Products' MCR[®] processes are the most widely used liquefaction cycles in the baseload LNG industry. The C₃-MR version of the MCR[®] process was first used in the early 1970's. It remained the liquefaction process cycle of choice as train capacity more than tripled over the past thirty years. In **Table 1**, a comparison of Net LNG to Fuel Gas Consumed demonstrates a 13% advantage in overall plant fuel efficiency for the C₃-MR cycle over the second most commonly used cycle.

Table 1 – Overall Plant Fuel Efficiency

Process	Net LNG Production MMBtu/day	Fuel Gas Consumed MMBtu/day	Net LNG / Fuel Consumed
C ₃ -MR	438,838	50,573	8.7
Cascade [2]	425,239	55,419	7.7

Similar site ambient condition

Another strength of Air Products' MCR[®] processes is their flexibility. They can maintain high efficiency through feed composition changes and daily/seasonal temperature variations.

Equipment Evolution - Rotating Machinery

Over the past 30 years power generation turbines and refrigerant compressors have evolved to provide better efficiency at a lower unit cost (\$/kW). Also, the time between scheduled maintenance outages has increased substantially, yielding a higher onstream factor. Early C₃-MR cycle LNG trains used steam turbines to generate refrigeration power. During the 1970's gas turbines gained acceptance as main refrigerant compressor drivers due to improved reliability. As a result, the capital investment in steam generating equipment was reduced.

In the 1990's, the transition from dual-shaft to large single-shaft gas turbines increased fuel efficiency by 10-15% [7]. For example, as shown in **Table 2**, the Frame 7EA is 13% more fuel-efficient (kWhr/kg) than the Frame 5C.

Table 2 – Gas Turbine Fuel Efficiency

Gas Turbine	Fuel Efficiency* kWhr/kg of fuel**
Frame 5C	2.32
Frame 5D	2.41
Frame 6B	2.55
Frame 7EA	2.62

* provided by General Electric, based on ISO heat rate

** Fuel is 70% methane, 30% nitrogen

Certain single-shaft turbines could be directly connected to the refrigerant compressor shaft eliminating the need for a speed altering gear and its associated power losses. The power output of large-frame single-shaft gas turbines more than doubled the power output of existing dual-shaft turbines. ISO Power for commonly used dual-shaft (Frame 5C, 5D) and single-shaft (Frame 6B, 7EA) gas turbines is shown in **Table 3**.

Table 3 – Gas Turbine Power

Gas Turbine	ISO Power* Megawatts
Frame 5C	28.3
Frame 5D	32.6
Frame 6B	41.5
Frame 7EA	87.4

* provided by General Electric

Instead of the 1-to-1 turbine to compressor casing relationship, two mixed refrigerant compressor casings could be connected to one single-shaft gas turbine. The resulting capital cost reduction (\$/kW) associated with the shift to single-shaft turbines was in the range of 15-25% [7].

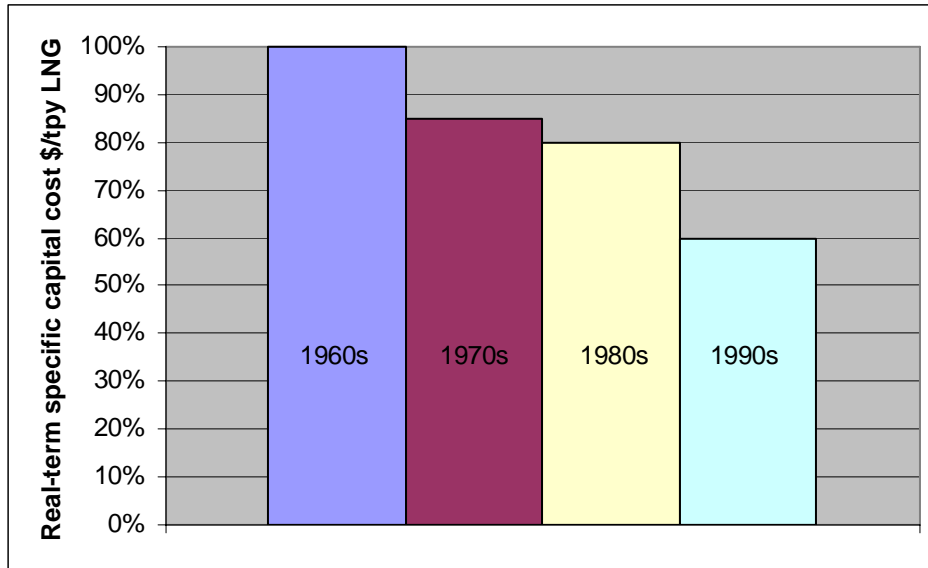
In the late 1990's Air Products introduced the SplitMR™ machinery configuration permitting two large-frame, equal-power, single-shaft gas turbines to be fully utilized, thereby making more efficient use of the capital invested in refrigeration power generation. Two MR compressor casings are connected to one turbine, and a third MR compressor casing is on the same shaft with the propane compressor connected to the second turbine.

During this same time period, improved compressor technology resulted in higher polytropic efficiencies and therefore lowered the required refrigeration power per unit of production. Also, compressor seal leakage losses were reduced substantially due to the use of dry face seal technology resulting in decreased hydrocarbon emissions to the atmosphere.

LNG – Economics and the Environment

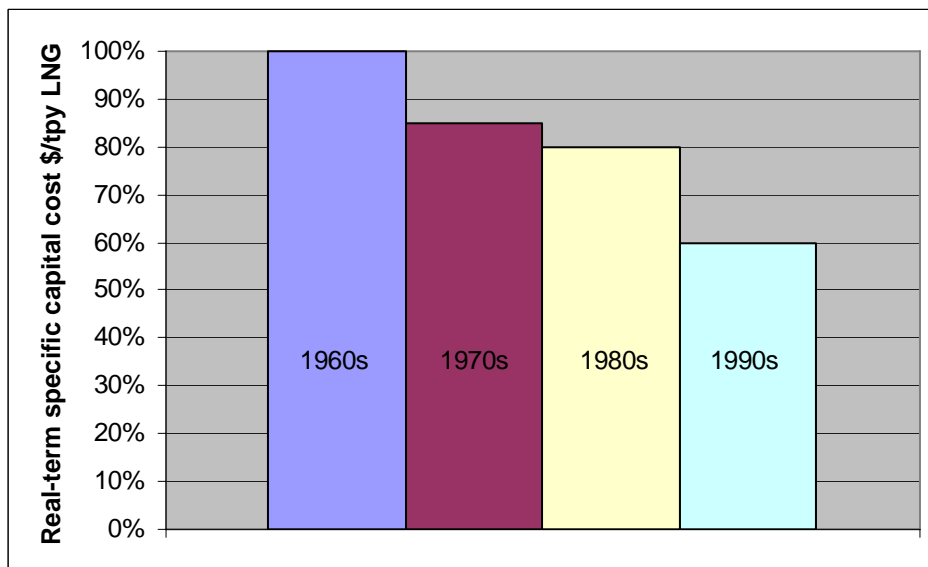
The innovations and evolutions in the LNG industry during the C₃-MR process era resulted in a 40% decrease in the real term specific capital cost of producing LNG in \$/tpy [7].

Figure 1 – Real Term Capital Cost per Train [7]
(Averaged by decade)



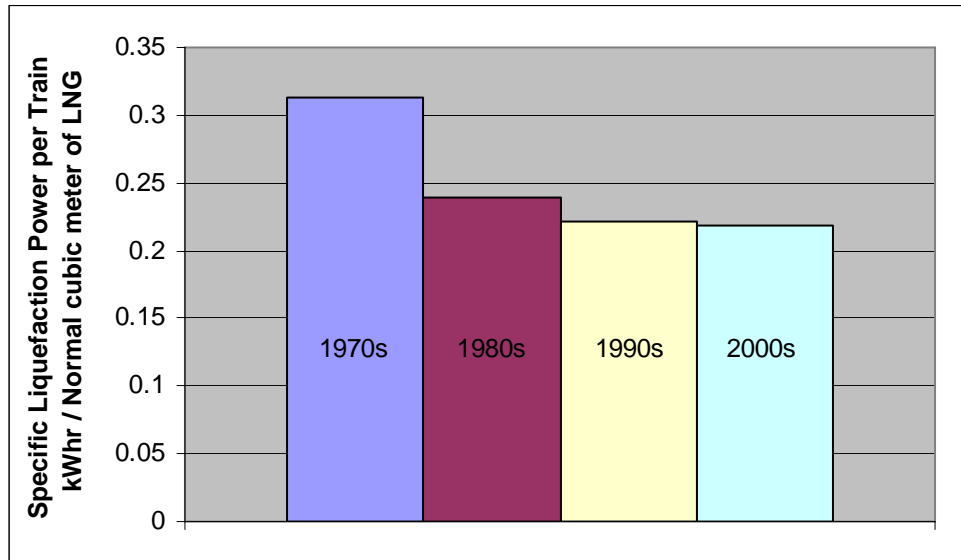
During the same time period LNG production capacity per train increased more than 300%.

Figure 2 – Typical LNG Production per Train using C₃-MR Process
(Averaged by decade)



Also, the typical specific refrigeration power requirements of trains using the C₃-MR cycle fell about 30% in kWhr/Normal cubic meter of LNG.

Figure 3 – Typical Specific Liquefaction Power per Train using C₃-MR Process
(Averaged by decade)



LNG has become more affordable to purchase due to the decrease in capital cost and the reduction in operating expenses resulting from the improvements described above. This increased economic viability of LNG has enabled nations without indigenous supplies of natural gas to import LNG for use in power generating plants and gradually displace less environmentally friendly fossil fuels. Natural gas is the cleanest burning fossil fuel and emits less CO₂ per unit of energy than oil or coal. For example, switching from coal to natural gas reduces CO₂ emissions per unit of energy by more than 40%. Emission factors for various fuel types are shown in **Table 4**.

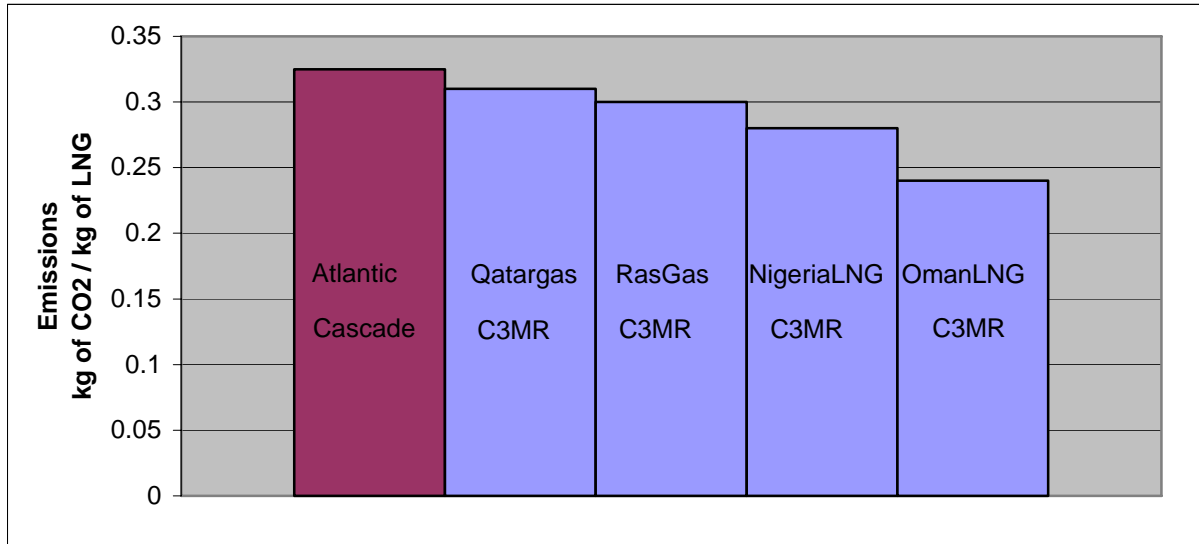
Table 4 – Emission Factors [4]

Fuel	Emission Factor (kg of CO ₂ /gigajoule)
Natural gas	55
Petroleum	68
Black Coal	91
Brown Coal	95

LNG is being produced in a manner that has reduced the fuel requirements necessary to drive the refrigeration system used to liquefy natural gas. This means less specific CO₂ emissions on the LNG production side as well. For example, the 30% reduction in specific refrigeration power shown above in **Table 3** translates to a reduction of CO₂ emissions per unit of LNG product.

Also, the 13% advantage in overall plant fuel efficiency previously shown in **Table 1** for the C₃-MR process provides the benefit of reduced CO₂ emissions compared to the facility not using the C₃-MR process. This difference is illustrated in **Figure 4**.

Figure 4 – Carbon Dioxide Emissions from Fuel [9]



The selection of gas turbines to provide power for liquefaction is just as important as the choice of process cycle. To achieve a train capacity of 4.5 to 5.0 Mta, the preferred adaptation of the cascade process uses eight Frame 5D gas turbines [3]. The C₃-MR cycle with the SplitMRTM machinery configuration achieves the same production range with two Frame 7EA gas turbines plus additional power approximately equivalent to a Frame 5D gas turbine. Carbon dioxide emission factors and year 2003 price information for these gas turbines are shown in **Table 5**.

Table 5 – Gas Turbine CO₂ Emissions and Economics

Gas Turbine	CO ₂ Exhaust Emissions at 30°C* (kg-mole/hr)**	2003 Turbine Capital Cost Factor* (Normalized dollars)
8 × Frame 5D	8 × 463 = 3704	8 × 1.0 = 8.0
2 × Frame 7EA + Frame 5D	2 × 1112 + 463 = 2687	2 × 2.78 + 1.0 = 6.56

* provided by General Electric

** Fuel is 70% methane, 30% nitrogen

The two Frame 7EA plus one Frame 5D combination has a distinct advantage over the eight Frame 5D configuration in both capital cost and CO₂ emissions. For similar LNG production, using two Frame 7EA plus one Frame 5D gas turbines costs 18% less and reduces CO₂ emissions 27%.

A New Era – The AP-X™ Hybrid LNG Process

To increase LNG train capacities beyond 5 Mta using the existing MCR® cycles would require the addition of compressor casings to the propane and/or MR refrigeration systems. In 2001, Air Products' patented AP-X™ Hybrid LNG Process [5] was introduced to the LNG industry. It will enable the production capacity of a single LNG train to leap from 5 Mta to 8 Mta without adding propane or MR compressor casings in parallel service. The MR and propane compressor casings can also remain within reasonable extensions of proven vendor frame sizes, and the dimensions of the MCHE will not need to increase beyond the size currently being manufactured. The AP-X™ cycle also retains the major strength of the previously existing MCR® cycles, namely the flexibility to maintain high efficiency through changes in feed composition and daily/seasonal temperature variations.

The AP-X™ cycle enhances LNG production capacity by augmenting the C₃-MR cycle with a nitrogen-expander refrigeration system to accomplish LNG subcooling. The refrigeration load absorbed by the nitrogen-expander system alleviates the need to increase the size and quantity of the propane and MR system equipment. Air Products has extensive experience in nitrogen refrigeration systems used for air separation, nitrogen liquefaction, and LNG peak shaving cycles worldwide. The manner in which the C₃-MR cycle is enhanced to form the AP-X™ cycle is analogous to the way the C₃-MR cycle was originally invented more than 30 years ago. At that time, the single-MR (SMR) cycle used in an early LNG train was augmented with a propane refrigeration system used for feed gas and MR precooling. The AP-X™ process patent also has an embodiment where a dual-MR system is similarly enhanced with a nitrogen system for LNG subcooling.

The AP-X™ Hybrid LNG Process - Economic and Environmental Impact

The Kyoto Protocol calls for nations to reduce greenhouse gas emissions by an average of 5% from 1990 levels by 2010. This is one factor that will drive the natural gas market to expand from the roughly 25% share of the world energy market it currently occupies. Economy of scale has favored increasing train sizes for baseload LNG plants in order to drive down the unit cost of LNG.

The AP-X™ cycle can use Frame 9E gas turbines to increase LNG production capacity per train to 8 Mta. A comparison between the Frame 9E and the Frame 7EA gas turbine is shown in **Table 6**.

Table 6 – Gas Turbine CO₂ Emissions and Economics

Gas Turbine	Power at 30°C* Megawatts	CO ₂ Exhaust Emissions at 30°C* (kg-mole/hr)**	Specific CO ₂ Exhaust Emissions at 30°C* (kg-mole/MWhr)**	2003 Turbine Capital Cost Factor* (Normalized dollars)
Frame 7EA	79.4	1112	14.0	1.0
Frame 9E	120.8	1598	13.2	1.16

* provided by General Electric

** Fuel is 70% methane, 30% nitrogen

Using a Frame 9E gas turbine provides about 50% more power at only 16% higher capital cost than a Frame 7EA. CO₂ emissions from the Frame 9E turbine are about 6% less than the Frame 7EA's per unit of power generated.

This unprecedented increase in LNG train size, coupled with the specific cost (\$/MW) advantage of the Frame 9E gas turbine, has the potential to drive another major step change in LNG facilities, namely the introduction of combined cycle power generation. In combined cycle power generation, the waste heat from the gas turbines is used to generate steam to drive a steam turbine. The turbines provide power to electric motors that are connected to the refrigerant compressors. Combined cycle power generation can be 55-60% efficient compared with 30-34% for gas turbines [1]. Also, the combined cycle is approximately 20% less CO₂ intensive than gas turbines or steam turbines alone [8].

Combined cycle power generation requires a larger initial capital investment than gas turbines alone, but the higher efficiency and better on-stream availability of the combined cycle reduce operating costs. When the substantial increase in train capacity provided by the AP-XTM cycle is also factored into the long-term economic evaluation, a major step toward crossing the threshold where combined cycle power generation will become standard at baseload LNG facilities has been achieved.

Conclusion

Viable LNG train size will increase to 8 Mta with the introduction of the AP-XTM Hybrid LNG Process. With this step change in production capacity comes the opportunity to simultaneously realize economic and environmental benefits. Specifically, lower capital cost per unit of production, better refrigeration power generation efficiency, and reduced CO₂ emissions per unit of production.

References

1. Knott, Terry 2001. 'Cool Future for Gas'. Frontiers. December 2001. www.bp.com/company_overview/technology/frontiers/fr02dec01/fr02lng.asp
2. Richardson, 2000. 'Passing the Baton Cleanly – Commissioning and Start-Up of the Atlantic LNG Project in Trinidad', F.W. Richardson, P.Hunter, T.Diocee, J. Fisher. Presented at Gastech 2000, 14-17 November, Houston, TX.
3. Richardson. 'Compressor and Driver Enhancements for Large LNG Plants – Look Again at Combined Cycle Options' F.W. Richardson, N.P. Naudat, W.E. Schmidt, D.E. Yates
4. Roarty, M. 1998. 'Natural Gas Energy for the New Millenium' Parliamentary Library Research Paper 5 1998-99, Parliament of Australia.
5. Roberts et al. 2001. 'Hybrid Cycle for the Production of Liquefied Natural Gas'. M.J. Roberts, R. Agrawal. US Patent 6,308,521.
6. Roberts, 2002. 'Large Capacity LNG Process – the AP-XTM Cycle'. M.J. Roberts, Y.N. Liu, J.M. Petrowski, J.C. Bronfenbrenner. Presented at GasTech2002.
7. Ryan, R.G. 2001. 'Special Report: Technology, Commercial Developments, Speed Changes in the World LNG Industry' Robert Ryan, Colin Bowkley, and Peter Baruch, published in the Oil and Gas Journal, July 16, 2001, Vol. 99 No. 29.
8. Scott, Gary 2001. 'Greenhouse Implications of Natural Gas Development in Australia' Environmental Center NT, September 2001 www.ecnt.org/pdf/natural_gas_discuss.pdf
9. Yost, C. 2003. 'Benchmarking Study Compares LNG Plant Costs' Chuck Yost, Robert DiNapoli, published in the Oil and Gas Journal, April 14, 2003.