Aeroderivative Gas Turbines for LNG Liquefaction Plants –
Part 1: The Importance of Thermal Efficiency
Part 2: World's First Application and Operating Experience

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AERODERIVATIVE GAS TURBINES FOR LNG LIQUEFACTION PLANTS – PART 1: THE IMPORTANCE OF THERMAL EFFICIENCY

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ABSTRACT

The trade in Liquefied Natural Gas (LNG) is expanding rapidly with projects being proposed worldwide to meet the industry forecasted growth rate of 12% by the end of the decade. This paper will cover the importance of thermal efficiency in base load LNG liquefaction facilities and delineate the underlying factors as to why it is becoming more important today. Advantages of the use of aeroderivative engines include lower greenhouse gas emissions, enhanced LNG production and the ability to startup without the use of helper motors. This paper presents for the first time, a comprehensive overview of the thermal efficiency considerations for LNG liquefaction plants and the value of the use of aeroderivative engines. Part 2 of this paper covers the world's first implementation and operational experience of aeroderivative engines in a LNG liquefaction plant.

1.0 INTRODUCTION

The international trade in Liquefied Natural Gas (LNG) is expanding at a rapid pace. The estimated consumption of natural gas in 2006 was over 100 trillion cubic feet (Tcf) which represents a 60% increase over the past 20 years. By 2025 it is estimated that this consumption will be around 156 Tcf and account for 25% of the predicted world demand. Natural gas is brought to market either by traditional pipeline or by a LNG supply chain.

Natural gas is converted to LNG by chilling and liquefying the gas to a temperature of -160°C (-256°F). When liquefied, the volume of natural gas is reduced to 1/600 th of its standard condition volume. This allows for the efficient transportation of gas using specialized LNG tankers at a competitive cost. The size of a liquefaction facility is usually stated in millions of tons per annum (MTPA)[1].

1.1 Overview of the LNG Liquefaction Process.

LNG liquefaction process in common use have been described by Shukri, [1]. The ConocoPhillips *Optimized Cascade*^{SM} LNG Process uses three refrigerants - propane, ethylene and methane. Each refrigerant has a parallel compression train. While the focus of this paper is the ConocoPhillips Optimized Cascade process, the concepts relating to thermal efficiency would apply to any LNG process. This technology was first used in the Kenai LNG Plant in Alaska and more recently at the Atlantic LNG facility in Trinidad (four trains), Egypt LNG (two trains), Darwin LNG in Australia, and a train in Equatorial Guinea, which started up in early 2007. A simplified process flow diagram of the Optimized Cascade process is shown in Figure 1. The standard design for this process incorporates a "two trains in one" concept. Each compressor is driven by a gas turbine of appropriate size. Each refrigerant cycle (propane, ethylene, and methane) includes a minimum of two compressors operating in parallel. This parallel configuration allows the plant to operate at production rates of around 60% when any single gas turbine compressor is off-line. Avidan et al [2] and Redding et al [3] have demonstrated that this operating flexibility, equipment reliability, and overall design lead to production efficiencies[2] greater than 95%. The ConocoPhillips Optimized Cascade process has been used in nine plants with capacities of 1.5 to 5.2 MTPA.

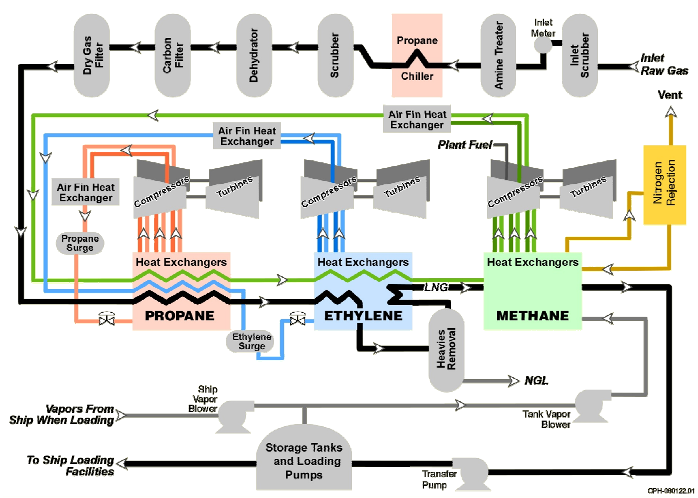


Figure 1. Simplified process flow diagram of the Optimized Cascade Process.

[1] One metric ton of LNG is equivalent to 52 million BTUs of gas (54.8 GJ).

[2] The production efficiency is defined as actual annual LNG Production divided by the required annual LNG production.

1.2 Growth and Structure of the LNG Industry

As described by Houston [4], the LNG industry has entered a transformational phase where in recent years; the rate of growth has increased with a growth of 13% per annum expected through 2015. The LNG industry evolution and projections to 2015 are shown in Figure 2 (Houston, [4]). A detailed review of the LNG industry can be found in Harris and Law [5], and Houston [4]. An overview of the industry from 1989 to 2007 has been made by Glass and Lowe [6]. Details on the evolution of the LNG market may be found in Avidan et al [2,7] and Wood and Mokhatab [8]. LNG train size has been increasing from a typical 1.5 MTPA in the 1970's to a typical 2.5-3 MTPA design in the mid 1990s as shown in Figure 3.

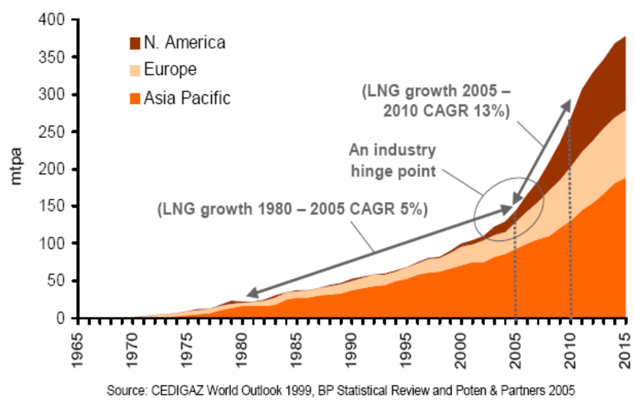


Figure 2. LNG industry evolution over time and future trends[4].

Today, plant sizes are typically around 3 MTPA, and 5 MTPA with a few "super trains being built sized at 8 MTPA. A recent article by Wood and Mokhtab [9] has indicated that the future market demand will be for plants of approximately 4 MTPA.

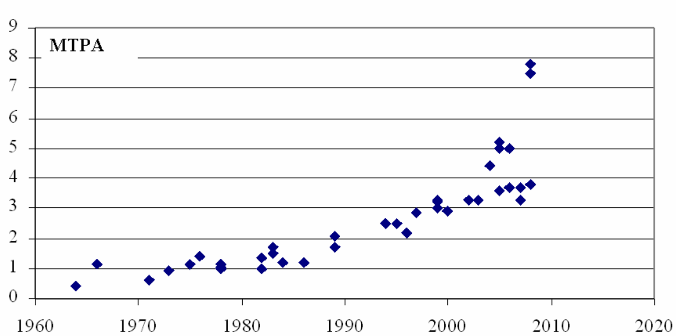


Figure 3. Growth in LNG Plant Size (MTPA) over Time.

1.3 Compressor Drivers Used for LNG Liquefaction.

The general evolution of the industry is depicted in Figure 4. The first LNG plant to utilize a gas turbine driver was the ConocoPhillips Kenai Alaska plant which used Frame 5 gas turbines. This plant was started in 1969 and is still in operation today. After this installation, all LNG plants have used gas turbines ranging from Frame 5Ds, Frame 7EA, Frame 6B and recently, the Frame 9E[3]. The world's first aeroderivative driven LNG liquefaction plant at Darwin LNG was started up in 2006. Details of this plant and operating experience are described in Part 2 of this paper.

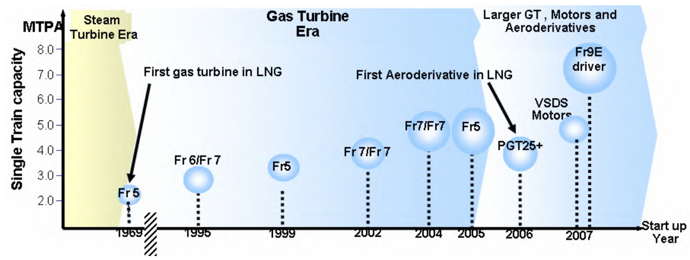


Figure 4. Drivers used in LNG Plant service. The world's first application of aeroderivative engines was implemented in 2006.

2.0 AERODERIVATIVE ENGINES AS LNG LIQUEFACTION DRIVERS

In any natural gas liquefaction facility, the economics are primarily driven by the quantity and price of the LNG sold, and the quantity and price of the feed gas purchased, EPC cost, and life-cycle operational cost. The ratio of LNG price to feed gas cost have the highest impact on profitability, and are usually driven by market conditions of supply and demand which are normally beyond the direct control of the project company. LNG operators can greatly improve profitability by focusing on plant thermal efficiency.

Thermal efficiency is an important benchmark that is used to compare various liquefaction technologies, but can be misleading if all the energy entering and exiting the plant boundary is not clearly defined. Higher thermal efficiency can significantly lower lifecycle operating costs and improve plant economics. The thermal efficiency of a LNG facility is defined as the total energy that can be sold from the facility divided by the total energy that is delivered to the facility.

There are several fundamental issues in today's market place that make aeroderivative engines an excellent fit.

- Sizes of available aeroderivative engines ideally fit the two trains in one concept of the ConocoPhillips LNG process.
- Aeroderivative engines are variable speed drivers which aids the flexibility of the process and allow startup without the use of large VFD starter motors as are commonly used on single shaft gas turbines. Aeroderivative engines also allow startup under settle out pressure conditions, with no need to depressurize the compressor as is common for single shaft drivers.
- High efficiency results in a greener train with a significant reduction in greenhouse gas emissions.
- Lack of availability of gas supplies. Several projects are gas constrained. This situation occurs both on new projects being considered and also at existing LNG facilities. In these situations, any fuel reduction due to higher thermal efficiency of the gas turbines means that this can be converted to LNG.
- Gas supplies are constrained due to greater NOC (National Oil Company) control of the sources. Gas supplies are no longer available "free" or at low costs to LNG plants and the notion that "fuel is free" is now a thing of the past. Several current projects and FEED studies prove this point with fuel being valued much higher than a decade ago. Host governments are requiring more gas for domestic gas use, accentuating shortfalls for LNG plants.

[3] There is one exception of a recent all electric plant driven by VFD motors. Power is supplied by 5 x LM6000 gas turbine generator sets.

Given the above (i.e., a gas constrained situation), and the fact that fuel *not* consumed can be converted to LNG there are significant benefits of the order of hundreds of millions of present value of by the use of high efficiency aeroderivative engines. Given that the NPV is a strong function of feed gas costs and LNG sales price, the present value is highly affected by the plants thermal efficiency especially when the FOB LNG costs are high as is the current market situation. The overall situation is indicated in Figure 5 below.

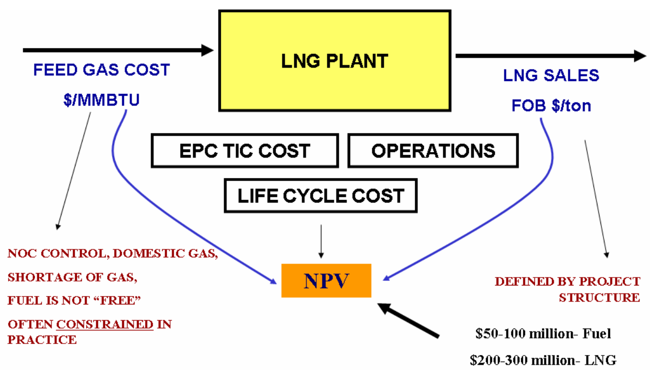


Figure 5. Overview of project and importance of thermal efficiency.

3.0 THERMAL EFFICIENCY CONSIDERATIONS

The thermal efficiency of a LNG facility depends on numerous factors such as gas composition, inlet pressure and temperature, and even more obscure factors such as the location of the loading dock relative to the liquefaction process[4]. Gas turbine selection, the use of waste heat recovery, ship vapor recovery, and self-generation versus purchased power all have a significant effect on the overall thermal efficiency of the process. Process flexibility and stability of operation are issues of paramount importance and must be incorporated into the considerations regarding thermal efficiency as the value of a highly efficient process is diminished if plant reliability and availability are sacrificed.

Yates [10] has provided a detailed treatment of the design lifecycle and environmental factors that impact plant thermal efficiency, such as feed gas characteristics, feed gas conditioning, and the LNG liquefaction cycle itself. Some of the key elements of this discussion are provided below as it leads into the discussion of the selection of high efficiency aeroderivative engines.

A common consideration in evaluating competing LNG technologies is the difference in thermal efficiency. The evaluation of thermal efficiency tends to be elusive and subjective in that each project introduces its own unique characteristics that determine its optimum thermal efficiency based on the strongest economic and environmental merits for the project. Different technologies or plant designs cannot be compared on thermal efficiency without understanding and compensating for the unique differences of each project.

The definition of thermal efficiency also has proven to be subjective depending on whether an entire plant, an isolated system, or item of equipment is being compared. Thermal efficiency, or train efficiency, has been expressed as the ratio of the total HHV (higher heating value) of the products to the total HHV of the feed. The use of this definition fails to recognize the other forms of thermodynamic work or energy actually consumed by the process. For example, if purchased power and electric motors are used for refrigeration and flashed gas compression, this definition would not account for the work done by these motors. When evaluating the benefits of achieving a high thermal efficiency with a specific LNG plant design, a true accounting of all of the energy being consumed in the process must be considered.

Turndown capabilities of an LNG process also need to be considered when thermal efficiency and lifecycle comparisons are being made. Thermal efficiency comparisons are typically based on the process operating at design conditions. In an actual plant environment, this design point is elusive and an operator is always trying to attain a "optimal spot" where the plant will operate at its peak performance under prevailing conditions. As the temperature changes during the day, impacting the performance of the air coolers, the turbines, or the process fluid and equipment, the operator needs to continually adjust plant parameters to achieve optimal performance. Designing a plant to allow an operator to continually achieve this optimum performance point will impact the overall thermal efficiency of the plant and lifecycle costs.

The efficiency of a LNG process is dependent on many features. The two most significant ones are the efficiency of heat exchange and the turbomachinery efficiency. The heat exchange efficiency is a function of the process configuration and selection of the individual heat exchangers, which sets temperature approaches. The turbomachinery efficiency depends on the compressor and turbine efficiencies.

3.1 Cooling Curve Performance

The liquefaction cooling curve performance[5] is another benchmark that is reviewed in LNG technology comparisons and is often misunderstood or incorrectly applied. Recent analysis by Ransbarger [11] has comprehensively evaluated the issue of cooling curve performance with respect to overall thermal efficiency.

A liquefaction cooling curve plot depicts the temperature change of the heat sink and the heat source as a function of the heat transferred. Frequently, cooling curves are shown with only the feed gas as a heat source and then used as a means to compare different liquefaction processes. Cooling curves should include all duty that is transferred at a given temperature, which includes cooling and condensing of the refrigerants as well as the feed gas. The composite cooling curve analysis seeks to optimize the area or temperature difference between the heat source and the heat sink in a cost effective manner. Each of the available liquefaction processes attempts to optimize this temperature difference in a different way.

Very often process efficiencies of LNG technologies have been compared with the *Classical* Cascade process. It is important to note that the ConocoPhillips Optimized Cascade process encompasses two major modifications which include:

- The addition and optimization of heat recovery schemes
- Where appropriate, the conversion of the traditional closed loop methane refrigeration system to an open loop system

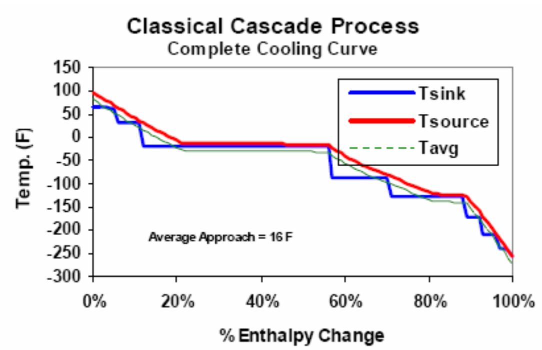
The plate fin heat exchangers used in this process are also recognized for their ability to achieve an exceptionally close temperature approach. The use of pure refrigerants allows accurate prediction of refrigerant performance continually during plant operation without the need for on-line refrigerant monitoring. Therefore, for a given feed

[4] The length of the jetty impacts costs and issues relating to boil off gas etc.

[5] Also known as a temperature- duty curve

gas composition range, the cascade liquefaction technology provides the plant designer with flexibility in cooling stage locations, heat exchanger area, and operating pressure ranges in each stage resulting in a process that can achieve high thermal efficiency throughout a wide range of feed conditions.

When utilizing cooling curves, incorrect conclusions can be drawn if only the feed gas is used as a heat source. It is imperative that heat transfer associated with cooling and condensing refrigerants be included[6]. When this is done, a "complete cooling curve" can be derived. Complete cooling curves of the Classical Cascade Process and the Optimized Cascade process are depicted in Figure 6. The average temperature approach of the classic cascade is 16°F (8.89°C) for this example while the average approach temperature of the optimized cascade is 12°F (6.67°C) i.e., a reduction of 25% which represents a 10-15% reduction in power**.**



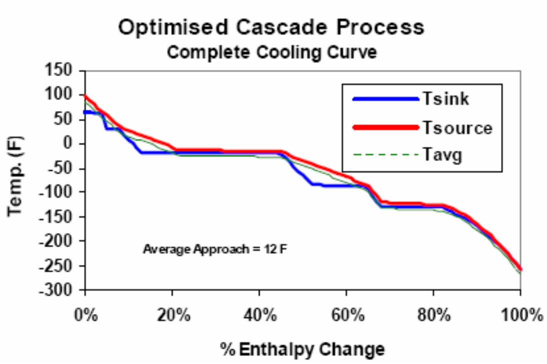


Figure 6: Comparison of Cooling Curves- for Classical Cascade Process and the ConocoPhillips Optimized Cascade Process. [11]

The maturity of the liquefaction processes has now approached a point *where changes in duty curve no longer represent the greatest impact.* Two developments that have a significant impact on efficiency are the improvement in liquefaction compressor efficiency[7] and the availability of high efficiency gas turbine drivers.

A comparison of LNG technologies at a single design condition does not address plant performance during variations in operating conditions. A two-shaft gas turbine, with its ability to control compressor performance without the need for recycle, can deliver significant improvements in thermal efficiency during turndown operations. Due to significant production swings during the day as a result of changes in ambient temperature, the performance of the gas turbine and compressor package needs to be considered in any comparison of plant thermal efficiency.

4.0 AERODERIVATIVE ENGINE SELECTION

A wide range of factors go into the selection of a gas turbine driver.

4.1 Advantages of Aeroderivative Engines over Heavy Duty Gas Turbines

As was mentioned ahead, aeroderivative engines are a unique fit into the CoP Optimized Cascade Process. The reasons for this include:

- Sizes of available aeroderivatives (30-50 MW) ideally fits the two trains in one concept
- Aeroderivative engines are variable speed drivers which aids the flexibility of the process
- Excellent starting torque capacity- aeroderivative engines have excellent torque- speed characteristics allowing large trains to start up under settle out pressure conditions.
- Higher thermal efficiency- greener train- lower CO2 production (approximately 30% less than with heavy duty gas turbines.)
- Easier installation due to lighter weight
- Modular maintenance possible- this is a particular benefit in remote regions where local manpower or repair facilities are not available. A full engine change out can be affected in approximately 24-48 hours.
- Higher production efficiency (1-2 points higher)
- Better NPV compared to heavy duty GTs
- Excellent for Arctic LNG Projects due to its very high power at low temperatures and modularity of maintenance.
- DLE technology available and proven on several engines.

4.2 Multiple Shaft vs. Single Shaft Gas Turbines

Gas turbines that have been traditionally used for power generation application are typically single shaft machines with a very limited speed range[8]. Drivers such as the Frame 6, Frame 7 and Frame 9 fall into this category. These machines are incapable of starting up a large compressor string without the help of large variable speed drive starter motors. Split shaft machines may be heavy duty (such as the Frame 5D) or aeroderivative engines such as the LM2500+ that have free power turbines which allow very high startup torques. Some larger aeroderivative drivers such as the LM6000 are multispool machines but with no free power turbine, that still exhibit a large speed range and excellent start up torque capability. A generalized map showing specific work and thermal efficiency and the parameters of typical heavy frame engines and aeroderivative engines is shown in Figure 7. Aeroderivative engines operate at higher turbine inlet temperatures and pressure ratios than heavy duty engines.

[6] In the Optimized Cascade process this would include the propane refrigerant loads necessary to cool and condense ethylene and the ethylene refrigeration loads necessary to cool and condense methane flash vapors.

[7] Compressor polytropic efficiencies are now in excess of 80% and high efficiency gas turbines are available with simple cycle thermal efficiencies above 40%

[8] Speed ranges are typically 95-102%.

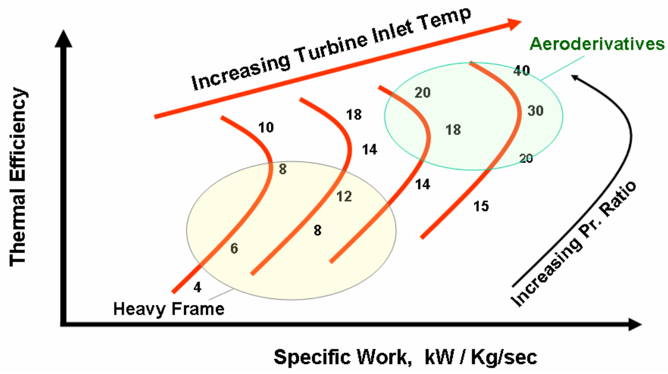


Figure 7. Heavy duty and aeroderivative engines

While a perception exists that heavy duty machines are more rugged, extensive mechanical drive experience with aeroderivatives (both offshore and onshore) have shown that good availabilities have been obtained even under hostile operating conditions. Maintenance of aeroderivatives is more complex with engines typically being shipped to an authorized repair depot for service. On the other hand, heavy duty units can be maintained in situ, though the time required to remove the engine and perform the overhaul is considerably longer than that of an aeroderivative engine. The high power to weight ratio of an aeroderivative engine can also be of importance for floating LNG facilities. Details on aeroderivative engines including design and operating features may be found in Badeer [12, 13]. Performance details of the differences between aeroderivative and single shaft engines are provided in Kurz and Brun [14]. A treatment of the interaction of efficiency and greenhouse emissions is made by Peterson et al [15].

4.3 Thermal Efficiency and Greenhouse Gas Considerations

From the above discussion, one can see that the selection of the gas turbine plays an important role in the efficiency, greenhouse gas emissions, and flexibility under various operating conditions. Where high fuel costs are expected, the selection of a high efficiency driver becomes a strong criterion in the lifecycle cost evaluation. In the past, LNG projects were developed to monetize stranded gas reserves, where the low cost fuel favored industrial gas turbines. This situation is however changing and the value of gas is now growing. Further, in situations where the gas is pipeline or otherwise constrained, there is a clear benefit in consuming less fuel for a given amount of refrigeration power. In such cases, a high efficiency gas turbine solution where the saved fuel can be converted into LNG production can result in large benefits.

Aeroderivative gas turbines achieve significantly higher thermal efficiencies than industrial gas turbines as shown in Figure 8[9]. This figure shows the engines' thermal efficiency vs. specific work (kW per unit air mass flow). The higher efficiency of an aeroderivative can result in a 3% or greater increase in overall plant thermal efficiency. Further, there is a significant improvement in plant availability as a result of the ability to completely change out a gas turbine gas generator (or even a complete turbine) within 24-48 hours versus fourteen or more days that would be required for a major overhaul of a heavy duty gas turbine.

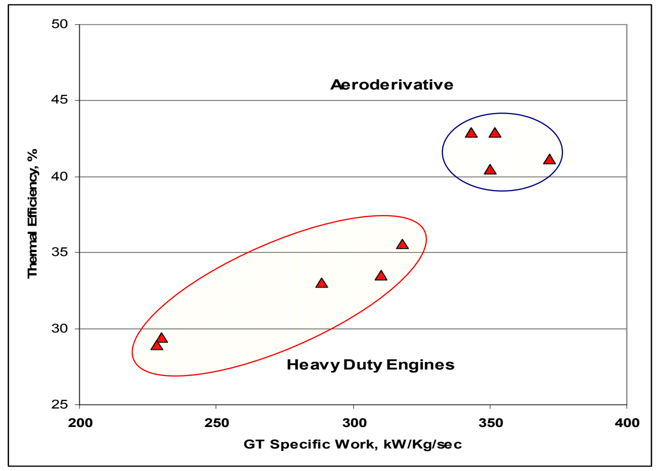


Figure 8. Map of ISO thermal efficiency vs. specific work of commonly used Frame drivers and aeroderivative engines.

An example of an aeroderivative engine that has been implemented at the Darwin LNG Plant is the GE PGT25+ aeroderivative gas turbine. The PGT25+ is comparable in power output to the GE Frame 5D but has a significantly higher thermal efficiency of 41.1%. This improvement in thermal efficiency results directly in a reduction of fuel required per unit of LNG production. This reduction in fuel consumption results in a reduction in CO_2 emissions as shown in Figure 9.

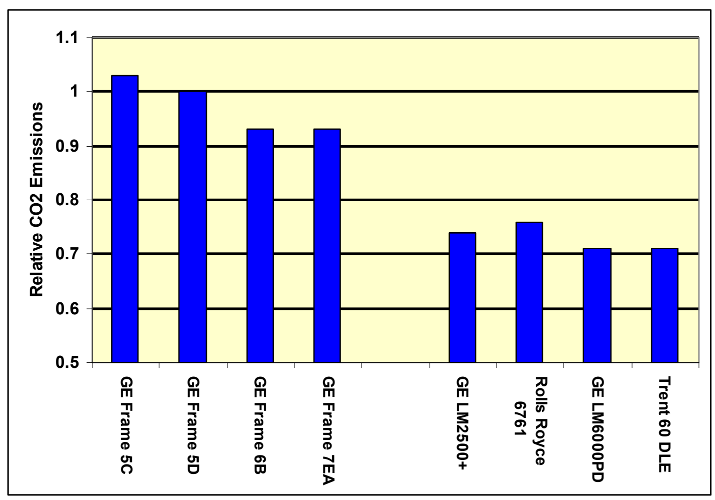


Figure 9. Relative CO_2 Emissions from different classes of gas turbines.

A similar beneficial greenhouse gas reduction comes from the use of waste heat recovery on the PGT25+ turbine exhaust that is used for various heating requirements within the Darwin LNG plant (discussed in Part 2 of this paper) The use of this heat recovery eliminates greenhouse gas emissions that would have been released had gas fired equipment been used. The result of using waste heat recovery equipment is a reduction in greenhouse gases by approximately 9.3% of the total emissions compared to the use of direct fired heaters.

[9] Based on Frame 5C, 5D, 7EA, and 9E frame type drivers and GE PGT25+, LM6000, RR 6761, and RR Trent aeroderivative units.

4.4 Influence of Ambient Temperature

Ambient temperature is a major factor affecting LNG production as production is linked to refrigeration driver power. Unless a gas turbine inlet cooling technique is used, there is little that can be done regarding the ambient temperature. Inlet cooling techniques might include traditional refrigeration chilling, inlet evaporative cooling by use media, or inlet fogging. Turbine output is a strong function of the ambient air temperature with power output dropping by 0.5 -0.9% for every 1°C rise in ambient temperature (0.3-0.5 % per 1°F). Gas turbines can experience, power output drops of around 14-20% when ambient temperatures increase from 15°C (59°F) to 35°C (95°F). There is also a concurrent heat rate increase of about 5%.

Aeroderivative gas turbines exhibit even a greater sensitivity to ambient temperature conditions. A representation of the power boost capability for given inlet cooling potential for different types of gas turbines is shown in Figure 10. The drop in performance due to high ambient temperatures can be further aggravated with gas turbine recoverable and unrecoverable performance deterioration due to several factors as presented in Meher-Homji et al [16, 17, 18]

An analysis and simulation of 91 gas turbines was conducted to evaluate the sensitivity to ambient temperature in terms of the net work ratio of the engines. The net work ratio is defined as the output of the gas turbine divided by the total turbine work (i.e., the output + axial compressor work). Results of these simulations are shown in Figure 11 (Chaker and Meher-Homji[19]). This graph shows that units with lower net work ratios (such as the aeroderivatives) tend to have a greater sensitivity to ambient temperature. Details relating to climatic analyses as it applies to inlet cooling may be found in Chaker and Meher-Homji [20].

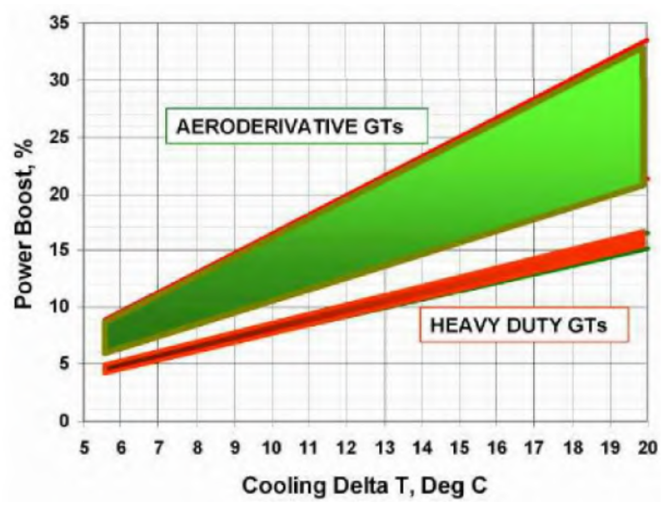


Figure 10. Power boost for different inlet temperature drop for typical aeroderivative and heavy duty gas turbines.

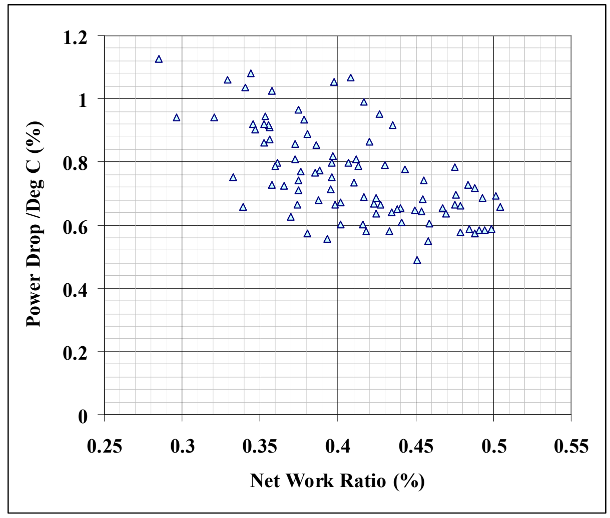


Figure 11. Net Work Ratio Vs. Power drop/Deg C., aeroderivatives tend to be lower Net Work Ratio machines.

5.0 LNG PLANT NPV BENEFITS WITH HIGH EFFICIENCY AERODERIVATIVES

In an LNG Plant, fuel consumption is typically approximately 10 % of the feed. In feed constrained situations, reducing the consumption of the drivers by the use of high efficiency aeroderivative engines, results in the ability to produce more LNG. An economic analysis of the NPV of gross margin increase, derived by increasing the driver efficiency and converting fuel gas savings into LNG for a 5.0 MTPA plant is shown in Figure 12. The figure compares a low efficiency driver with a thermal efficiency of 30% to a range of drivers including aeroderivative with efficiencies of 40% and a combined cycle configuration with a thermal efficiency of 50%. A combined cycle configuration may include gas turbine drivers for the propane and ethylene compressors each with HRSGs, and then two steam turbines driving the methane compressors. Combined cycle drivers provide an attractive design alternative for a LNG plant and have been studied but not yet implemented. A study of the application of combined cycles is provided in Tekumalla et al [21]. Qualls and Hunter [22] described how a combined cycle successfully reduces capital costs and increases thermal efficiency. The thermal efficiency of this approach is superior to most simple cycle plants

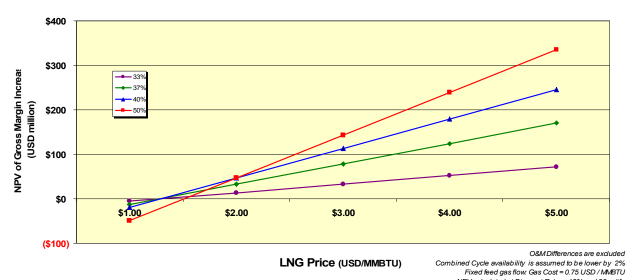


Figure 12. NPV value of gross margin- converting fuel savings into LNG for a 5 MTPA LNG Plant for varying LNG FOB prices, and with varying cycle efficiencies.

As can be seen from this figure, the NPV value of changing from a low efficiency heavy duty gas turbine to a high efficiency gas turbine can be in the order of several hundred million dollars. The model assumes a discount rate of 12% and a project life cycle of 20 years.

This model excludes the impact of improved production efficiency with the aeroderivative engines due to the reduced downtimes but the combined cycle production efficiency was reduced by 2%.

6.0 FUTURE POTENTIAL OF AERODERIVATIVE ENGINES WITHIN THE OPTIMIZED CASCADE LNG PROCESS

There are several factors that must be considered in choosing an optimal train size including:

- Gas availability from the field
- Market demand and LNG growth profile (this would also define the buildup and timing between subsequent trains)
- Overall optimization of production, storage and shipping logistics
- Operational flexibility, reliability and maintenance of the refrigeration block.

As the Optimized Cascade process utilizes a "two train in one" concept, in which two parallel compressor strings are utilized for each refrigeration service, the application of larger aeroderivative engines is an ideal fit. With this concept, the loss of any refrigeration string does not shut down the train but only necessitates a reduction in plant feed, with overall LNG production remaining at around 60% of full capacity[10].

The significant benefits of aeroderivative engines as opposed to large single shaft gas turbine make large aeroderivative units a very attractive proposition for high efficiency high output LNG plants. By adding gas turbines, larger LNG plant sizes can be derived as shown in Table 1. While the output with one driver down in a 2+2+2 configuration is approximately 60%, the percentage would be even higher with configurations having a larger number of drivers.

Table 1. Configuration/ Size of LNG plants using Aeroderivative Engines.

Aeroderivative Engine	Configuration Propane/Ethylene/Methane	Approx. Plant Size, MTPA
6 X LM2500+ DLE	2+2+2	3.5
8 X LM2500+ DLE	3+3+2	5
6 X LM6000 DLE	2+2+2	5
9 X LM6000 DLE	3+3+2	7.5

As split shaft industrial gas turbines are not available in the power class of large aeroderivative gas turbines, the application of aeroderivative engines offers the significant advantage of not requiring costly and complex large VFD starter motors and their associated power generation costs.

For example, the LM6000 depicted in Figure 13 is a 44 MW driver[11], operating at a pressure ratio of 30:1, with an exhaust mass flow rate of 124 kg/sec. This engine is a two-spool gas turbine with the load driven by the low speed spool. The low speed spool is mounted inside the high speed spool enabling the two spools to turn at different speeds. The output speed of this machine is 3400 rpm.

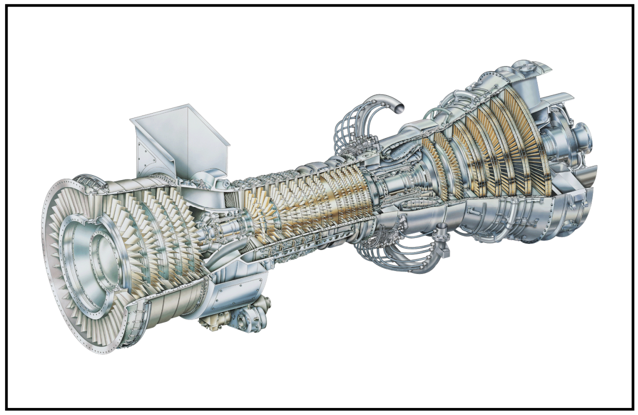


Figure 13. The LM6000 gas turbine, rated at 44 MW, and a thermal efficiency of 42% (Courtesy GE Energy)

The LM6000 gas turbine makes extensive use of variable geometry to achieve a large operating envelope. The variable geometry includes the variable inlet guide vanes, variable bypass valves and the variable stator vanes in the engine compressor with each system independently controlled. The gas turbine consists of five major components- a five stage low pressure compressor, a fourteen stage high pressure compressor, an annular combustor, a two stage high pressure turbine, and five stage low pressure turbine. The low pressure turbine drives the low pressure compressor and the load. The engine is available in both a water injected and DLE configuration. Details on this engine are provided in Montgomery [23].

CLOSURE

Market forces and a move toward greener trains has made the use of high efficiency aeroderivative engines important for LNG plants. The ConocoPhillips process which uses a two train in one concept, is ideally suited to the sizes of aeroderivative engines available on the market today. The aeroderivative engines variable speed capability and ability to start without the use of VFD motors (as is needed for large single shaft gas turbines) along with the ability to rapidly change out engines, has made this an extremely attractive option. Further, gas constrained projects, and situations where the cost of feed gas is no longer low (as was the case in the past) makes the aeroderivative engine an excellent fit. In gas constrained situations, the NPV benefits can be in the hundreds of millions of dollars.

This paper has comprehensively covers the importance of high efficiency turbomachinery in the design of an LNG liquefaction plant. Part 2 of this paper [24] covers the implementation of the world's first LNG plant utilizing aeroderivative engines at the Darwin LNG facility.

[10] This is obtained by shifting refrigerant loads to the other refrigeration services.

[11] To provide a comparison of the power to weight ratio, the LM6000 core engine weighs 7.2 tons compared to 67 tons for a 32 MW Frame 5D engine (core engine only).

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GT 2008-50840

AERODERIVATIVE GAS TURBINES FOR LNG LIQUEFACTION PLANTS – PART 2: WORLD'S FIRST APPLICATION AND OPERATING EXPERIENCE

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ABSTRACT

LNG market pressures for thermally efficient and environmentally friendly LNG plants coupled with the need for high plant availability have resulted in the world's first application of high performance aeroderivative gas turbines for a 3.7 MTPA LNG plant in Darwin. The six engines utilized are GE PGT25+ engines rated at 32 MW ISO driving propane, ethylene and methane compressors. The paper describes the design, manufacture, testing, and implementation of these units focusing on both the gas turbine and the centrifugal compressors. Power augmentation utilized on these units is also discussed. An overview of operating experience and lessons learned are provided. Part 1 of this paper provides a detailed analysis of why high thermal efficiency is important for LNG plants from an economic and greenhouse gas perspective.

1.0 INTRODUCTION

Market pressures for new thermally efficient and environmentally friendly LNG plants and the need for high plant availability have resulted in the world's first application of high performance PGT25+ aeroderivative gas turbines for the 3.7 MTPA Darwin LNG plant. The plant was operational several months ahead of contract schedule and has exceeded its production targets. This paper will describe the philosophy leading to the world's first aeroderivative based gas turbine plant and future potential for the application of larger aeroderivative drivers which are an excellent fit for the ConocoPhillips *Optimized Cascade*SM LNG Process.

Aeroderivative engines fit the Optimized Cascade process because of the "two trains in one" design concept[1] that facilitates the use of available aeroderivative engines. The plant is able to operate at reduced rates of 50-70% in the event that one refrigeration compressor is down. The wide range of large aeroderivative engines allow flexibility in plant capacities using the Optimized Cascade process. Benefits of aeroderivative engines over large heavy duty single and two shaft engines include significantly higher thermal efficiency and lower greenhouse gas emissions, the ability to start without the use of large helper motors, and improved production efficiency[2] due to modular engine change outs. This paper covers several practical aspects relating to the application of aeroderivative gas turbines as refrigeration drivers and discusses design and implementation considerations.

2.0 OVERVIEW OF THE DARWIN LNG PROJECT

The Darwin LNG plant was successfully commissioned and the first LNG cargo was supplied to the buyers, Tokyo Electric and Tokyo Gas, on February 14, 2006. The Darwin plant represents an innovative benchmark in the LNG industry as the first to use aeroderivative gas turbine drivers. This follows another landmark innovation by ConocoPhillips - being the first to apply gas turbine drivers at the Kenai Alaska LNG plant built in 1969.

The Darwin plant is a nominal 3.7 million tonne per annum (MTPA) capacity LNG plant at Wickham Point, located in Darwin Harbor, Northern Territory, Australia, and is connected via a 500-km, 26" subsea pipeline to the Bayu-Undan offshore facilities. The Bayu-Undan Field was discovered in 1995 approximately 500 kilometers northwest of Darwin, Australia in the Timor Sea. (See Figure 1). Delineation drilling over the next two years determined the Bayu-Undan Field to be of world-class quality with 3.4 TCF gas and 400 MMbbls of recoverable condensate and LPG. In February of 2004, the Bayu-Undan offshore facility commenced operation with current production averaging 70,000 bbls of condensate and 40,000 bbls of LPG per day.

[1] Each refrigeration service is accomplished by at least two parallel trains.

[2] The production efficiency is defined as actual annual LNG production divided by the required annual LNG production.

The shareholders of the Darwin LNG project are ConocoPhillips (plant operator), with 56.72%, ENI with 12.04%, Santos with 10.64%, INPEX with 10.52%, and Tokyo Electric and Tokyo Gas with a combined 10.08%.

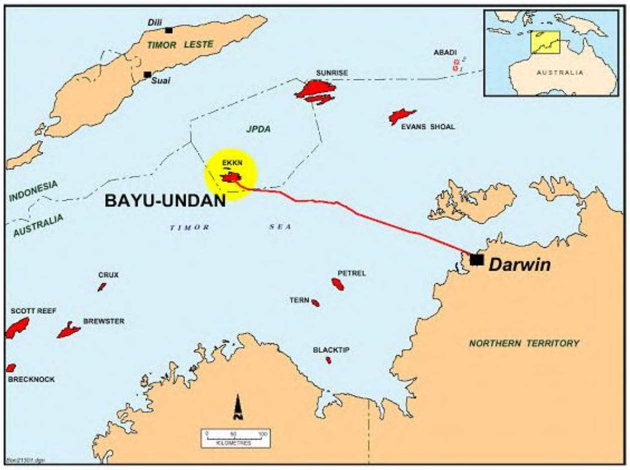

Figure 1. Bayu-Undan field location and the Darwin LNG plant.

The Darwin plant has established a new benchmark in the LNG industry by being the first LNG plant to use an aeroderivative gas turbine as refrigerant compressor drivers and also the first to use evaporative coolers. The GE PGT25+[3] is comparable in power output to the GE Frame 5D gas turbine but has an ISO thermal efficiency of 41% compared to 29% for the Frame 5D. This improvement in thermal efficiency results in a reduction of fuel consumption which reduces greenhouse gas in two ways. First, there is a reduction in CO_2 emissions due to a lower quantum of fuel burned. The second greenhouse gas benefit results from a reduction in the total feed gas required for the same LNG production. The feed gas coming to the Darwin LNG facility contains carbon dioxide, which is removed in an amine system prior to LNG liquefaction and is released to the atmosphere. The reduction in the feed gas (due to the lower fuel gas requirement) results in a reduction of carbon dioxide emissions from the unit.

The Darwin plant incorporates several other design features to reduce greenhouse gas emissions. These include the use of waste heat recovery on the PGT25+ turbine exhaust. The waste heat is used for a variety of heating requirements within the plant. The facility also includes the installation of ship vapor recovery equipment. The addition of waste heat and ship vapor recovery equipment not only reduces emissions that would have been produced from fired equipment and flares, but also result in a reduction in plant fuel requirements. This reduction in fuel gas results in a lowering of carbon dioxide released to the atmosphere.

The Darwin LNG plant has been designed to control nitrogen oxide emissions from the gas turbines by utilizing water injection into the combustor. Water injection allows the plant to control nitrogen oxide emissions while maintaining the flexibility to accommodate fuel gas compositions needed for various plant operating conditions, without costly fuel treatment facilities that may be needed for dry low NO_x combustors.

The Darwin plant uses a single LNG storage tank, with a working capacity of 188,000-m^3 which is one of the largest above ground LNG tanks constructed to date. A ground flare is used instead of a conventional stack to minimize visual effects from the facility and any intrusion on aviation traffic in the Darwin area. The plant uses vacuum jacketed piping in the storage and loading system to improve thermal efficiency and reduce insulation costs. MDEA with a proprietary activator is used for acid gas removal. This amine selection lowers the regeneration heat load required, and for an inlet gas stream containing over 6% carbon dioxide, this lower heat load results in a reduction in equipment size and a corresponding reduction in equipment cost.

The Darwin LNG Project was developed through a lump sum turn-key (LSTK) contract with Bechtel Corporation that was signed in April 2003 with notice to proceed for construction issued in June 2003. An aerial photo of the completed plant is shown in Figure 2. Details regarding the development of the Darwin LNG project have been provided by Yates [1, 2].

Figure 2. Aerial view of the 3.7 MTPA Darwin LNG plant– the world's first liquefaction facility to use high efficiency aeroderivative engines. The 188,000 m^3 storage tank and the 1350-meter jetty and loading dock can also be seen.

3.0 PLANT DESIGN

The Darwin LNG Plant utilizes the ConocoPhillips *Optimized Cascade*[SM] LNG Process. This technology was first used in the Kenai LNG Plant in Alaska and more recently at the Atlantic LNG in Trinidad (four trains), Egypt LNG (two trains), and a train in Equatorial Guinea, started up in 2007. A simplified process flow diagram of LNG plant was presented in Part 1 of this paper [3].

3.1 Implementation of the PGT25+ GT & Compressor Configurations.

The Darwin LNG compressor configuration encompasses the hallmark two-in-one design of the Optimized Cascade process, with a total of six refrigeration compressors configured as shown in Figure 3 in a 2+2+2 configuration (2 x propane compressor drivers, + 2 x ethylene compressor drivers and 2 x methane compressor drivers). All of the turbomachinery was supplied by GE Oil and Gas (Nuovo Pignone). Both the propane and ethylene trains had speed reduction gearboxes, with the methane being a direct drive. The high speed power turbine design speed is 6100 rpm.

[3] This engine utilizes a LM2500+ gas generator, coupled with a two stage high speed (6100 rpm) power turbine developed by GE Oil and Gas. The complete unit is designated a PGT25+

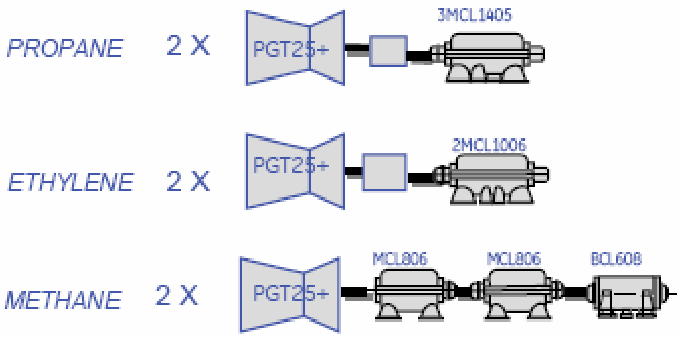

Figure 3. Overview of GT- Compressor configurations.

A view of the gas turbines inlet systems is shown in Figure 4. As can be seen, four of the gas turbines have once through steam generators located on their stacks to capture heat and produce steam which is used for process needs. All six gas turbines utilize pulse type filters and media type evaporative coolers fitted with mist eliminators.

Figure 4. Photograph of compressor trains at Darwin LNG. View of the inlet filter ducts and once through steam generators (heat recovery units) on four gas turbines on the left.

4.0 IMPLEMENTATION OF THE PGT25+ AERODERIVATIVE ENGINE

The PGT25+ engine used at the Darwin plant has a long heritage starting from the TF-39 GE aeroengine as shown in Figure 5. This highly successful aeroengine resulted in the industrial LM2500 engine which was then upgraded to the LM2500+. The PGT25+ is essentially the LM2500+ gas generator coupled to a 6100 RPM high speed power turbine (HSPT). The latest variant of this engine is the G4, rated at 34 MW.

The LM2500+ was originally rated at 27.6 MW, and a nominal 37.5% ISO thermal efficiency. Since that time, its ratings have grown to its current level of 31.3 MW and a thermal efficiency of 41%.

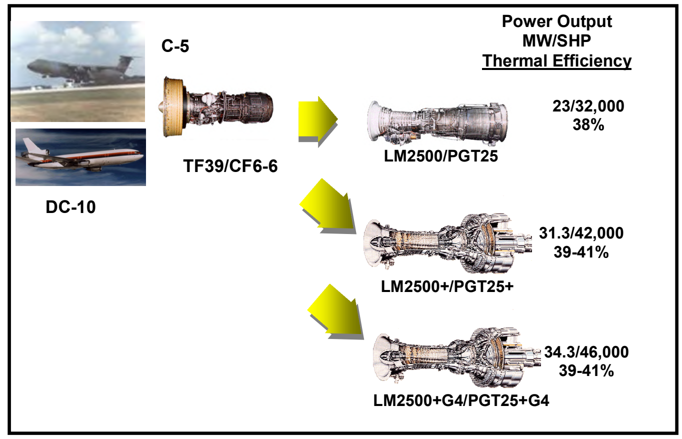

Figure 5. LM2500 engine evolution.

The LM2500+ has a revised and upgraded compressor section with an added zero stage for increased air flow and pressure ratio by 23%, and revised materials and design in the high pressure and power turbines. Details may be found in Wadia et. al [4]. A view of the gas generator is shown in Figure 6.

Figure 6. LM2500+ Gas generator being installed at Darwin LNG.

4.1 Description of the PGT25+ Gas Turbine

The PGT25+ consists of the following components:

4.1.1 Axial Flow Compressor

The compressor is a 17 stage axial flow design with variable-geometry compressor inlet guide vanes that direct air at the optimum flow angle, and variable stator vanes to ensure ease of starting and smooth, efficient operation over the entire engine operating range. The axial flow compressor operates at a pressure ratio of 23:1 and has a transonic blisk as the zero stage[4]. As reported by Wadia et al [4] the airflow rate is 84.5 kg/sec at a gas generator speed of 9586 RPM. The axial compressor has a polytropic efficiency of 91%.

[4] The zero stage operates at a stage pressure ratio of 1.43:1 and an inlet tip relative mach number of 1.19.

4.1.2 Annular Combustor

The engine is provided with a single annular combustor (SAC) with coated combustor dome and liner similar to those used in flight applications. The single annular combustor features a through-flow, venturi swirler to provide a uniform exit temperature profile and distribution. This combustor configuration features individually replaceable fuel nozzles, a full-machined-ring liner for long life, and an yttrium stabilized zirconium thermal barrier coating to improve hot corrosive resistance. The engine is equipped with water injection for NO_x control.

4.1.3 High Pressure Turbine (HPT)

The PGT25+ HPT is a high efficiency air-cooled, two-stage design. The HPT section consists of the rotor and the first and second stage HPT nozzle assemblies. The HPT nozzles direct the hot gas from the combustor onto the turbine blades at the optimum angle and velocity. The high pressure turbine extracts energy from the gas stream to drive the axial flow compressor to which it is mechanically coupled.

4.1.4 High Speed Power Turbine

The PGT25+ gas generator is aerodynamically coupled to a high efficiency high speed power turbine. The high speed power turbine (HSPT) is a cantilever-supported two stage rotor design. The power turbine is attached to the gas generator by a transition duct that also serves to direct the exhaust gases from the gas generator into the stage one turbine nozzles. Output power is transmitted to the load by means of a coupling adapter on the aft end of the power turbine rotor shaft. The HSPT operates at a speed of 6100 RPM with an operating speed range of 3050 to 6400 rpm. The high speed two-stage power turbine can be operated over a cubic load curve for mechanical drive applications.

4.1.5 Engine-mounted accessory gearbox driven by a radial drive shaft

The PGT25+ has an engine-mounted accessory drive gearbox for starting the unit and supplying power for critical accessories. Power is extracted through a radial drive shaft at the forward end of the compressor. Drive pads are provided for accessories, including the lube and scavenge pump, the starter, and the variable- geometry control. An overview of the engine including the HSPT is shown in Figure 7.

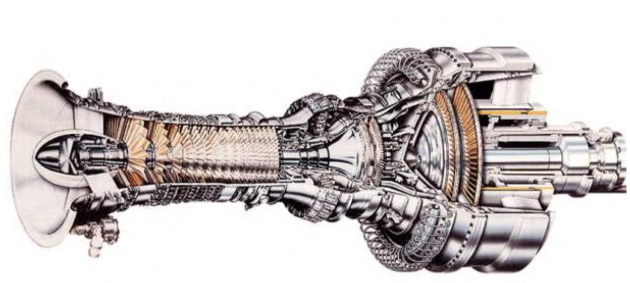

Figure 7. Overview of the PGT25+ gas turbine (Courtesy GE Energy).

4.2 Maintenance Plans and Experience

A critical factor in any LNG operation is the life cycle cost that is impacted in part by the maintenance cycle and engine availability. Aeroderivative engines have several features that facilitate “on condition” maintenance. Numerous boroscope ports allow on-station, internal inspections to determine the condition of internal components, thereby increasing the interval between scheduled, periodic removal of engines. When the condition of the internal components of the affected module has deteriorated to such an extent that continued operation is not practical, the maintenance program calls for exchange of that module. This allows “on condition maintenance”, rather than strict time based maintenance.

The PGT25+ is designed to allow for on-site, rapid exchange of major modules within the gas turbine. On-site component removal and replacement can be accomplished in less than 100 man hours. The complete gas generator unit can be replaced and be back on-line within 48 hours. The hot-section repair interval for the aeroderivative is 25,000 hours on natural gas however, water injection for NO_x control shortens this interval to 16,000 hours to 20,000 hours depending on the NO_x target level[5].

4.3 Performance Deterioration and Recovery

Gas turbine performance deterioration is of great importance to any LNG operation. Total performance loss is attributable to a combination of “recoverable” (by washing) and “non-recoverable” (recoverable only by component replacement or repair) losses. Recoverable performance loss is caused by fouling of airfoil surfaces by airborne contaminants. The magnitude of recoverable performance loss and the frequency of washing are determined by site environment and operational profile. Generally, compressor fouling is the predominant cause of this type of loss. Periodic washing of the gas turbine, by on-line wash and crank-soak wash procedures will recover 98% to 100% of these losses. The best approach to follow is to couple on line and off line washing. The objective of on line washing is to increase the time interval between crank washes. It should be noted that the cool down time for an aeroderivative is much less than that for a frame machine due to the lower casing mass. Crank washes can therefore be done with less downtime than heavy duty frame gas turbines. Gas turbine performance deterioration is covered in references [5,6].

4.4 Potential Upgrades of the PGT25+

A general advantage of using aeroderivative engines for LNG service is that they can be uprated to newer variants, generally within the same space constraints, and this might be useful feature for future debottlenecking.

The LM2500+G4 is the newest member of GE’s LM2500 family of aeroderivative engines. The engine retains the basic design of the LM2500+ but increases the power capability by approximately 10% without sacrificing hot section life. The modification increases the power capability of the engine by increasing the air flow, improving the materials and increasing the internal cooling. The number of compressor and turbine stages, the majority of the airfoils and the combustor designs remain unchanged from the LM2500. The LM2500+ G4 engine is shown in Figure 8. Details of this variant may be found in [7].

[5] The level of water injection is a function of the NOx target level.

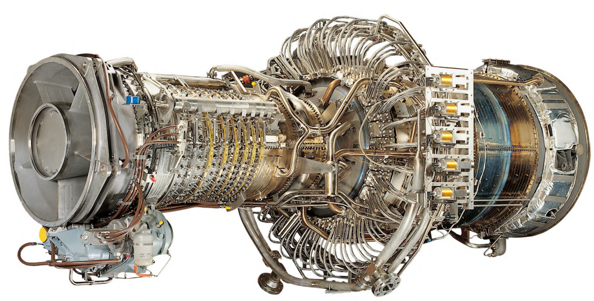

Figure 8. The uprated LM2500+ G4 engine -DLE variant (Courtesy GE Energy).

The growth in power of this variant compared to the base engine is shown in Figure 9.

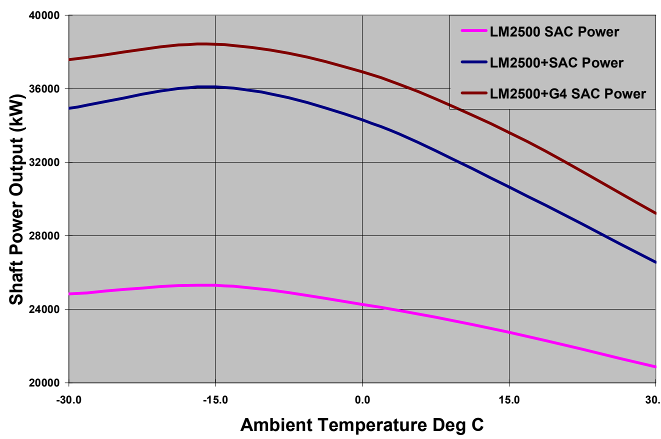

Figure 9. Growth of the LM2500+G4 variant (Courtesy GE Energy)

4.4 Power Augmentation by Evaporative Cooling

LNG production is highly dependent on the power capability of the gas turbine drivers of the propane, ethylene and methane compressors. Industrial gas turbines lose approximately 0.7% of their power for every 1°C rise in ambient temperature. This effect is more pronounced in aeroderivative gas turbines due to their higher specific work where the sensitivity can increase to well over 1% per °C. The impact of ambient temperature on the PGT25+ power and air flow is depicted in Figure 10.

As aeroderivative machines are more sensitive to ambient temperature, they benefit significantly from inlet air cooling. Darwin LNG utilizes media type evaporative coolers - another first for LNG refrigeration drivers. Details on media based evaporative cooling may be found in Johnson [8].

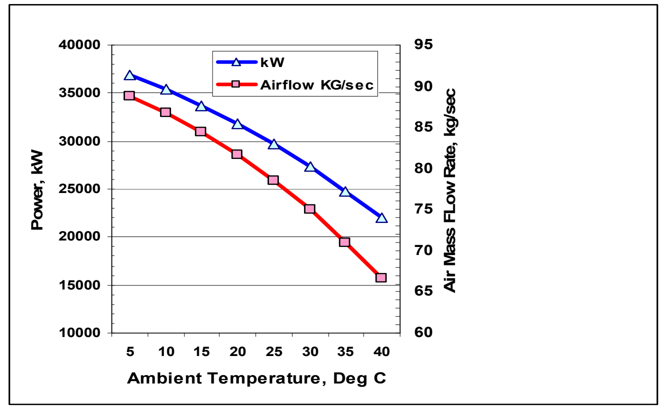

Figure 10. Variations in power output and air flow rate for the PGT25+ gas turbine.

Key advantages of power augmentation include:

- Boosts LNG production by lowering the gas turbine compressor inlet air temperature, increasing the air mass flow rate and power
- Improves the thermal efficiency of the gas turbine and results in lower CO_2 emissions

There is considerable evaporative cooling potential available in Darwin especially during the periods of high ambient temperatures as the relative humidity tends to drop as the temperature increases. The average daily temperature profile at Darwin is shown in Figure 11. The relationship of relative humidity and dry bulb temperature is shown in Figure 12[6]. Details regarding the climatic analysis of evaporative cooling potential may be found in [9].

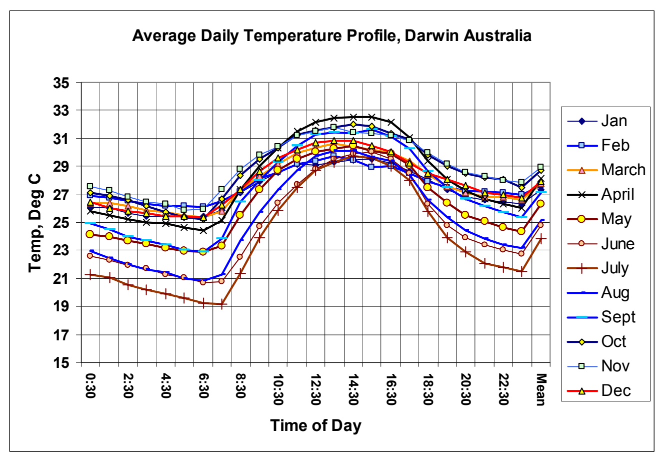

Figure 11. Temperature profile over time of day for 12 months in Darwin.

[6] Data is from the TMY2 database, for Darwin Airport

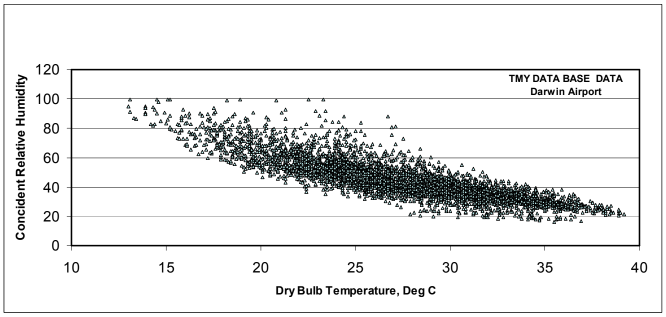

Figure 12. Relative Humidity vs. Dry Bulb Temperature, Darwin.

Media based evaporative coolers use a corrugated media over which water is passed. The media material is placed in the gas turbine air flow path within the air filter house and is wetted via water distribution headers. The construction of the media allows water to penetrate through it and any non-evaporated water returns to a catch basin. The media provides sufficient airflow channels for efficient heat transfer and minimal pressure drop. As the gas turbine airflow passes over the media, the air stream absorbs moisture (evaporated water) and heat content in the air stream is given up to the wetted media resulting in a lower compressor inlet temperature. A typical evaporative cooler effectiveness range is 85% to 90%, and is defined as follows:

Effectiveness = (T1DB – T2DB) / (T1DB – T2WB)

Where,

T1DB = Entering Air Dry Bulb Temperature
T2DB = Leaving Air Dry Bulb Temperature
T2WB = Leaving Air Wet Bulb Temperature

Effectiveness is the measure of how close the evaporative cooler is capable of lowering the inlet air dry bulb temperature to the coincident wet bulb temperature. Drift eliminators are utilized to protect the downstream inlet system components from water damage, caused by carry-over of large water droplets.

The presence of a media type evaporative cooler inherently creates a pressure drop which reduces turbine output. For most gas turbines, media thickness of 12 inches will result in a pressure drop of approximately 0.5 -1” water. Increases in inlet duct differential pressure will cause a reduction of compressor mass flow and engine operating pressure. The large inlet temperature drop derived from evaporative cooling, more than compensates for the small drop in performance due to the additional pressure drop.

Inlet temperature drops of around 10°C have been achieved at Darwin LNG which results in a power boost of around 8-10 %. A graph showing calculated compressor inlet temperatures (CITs) with the evaporative cooler for a typical summer month of January is shown in Figure 13.

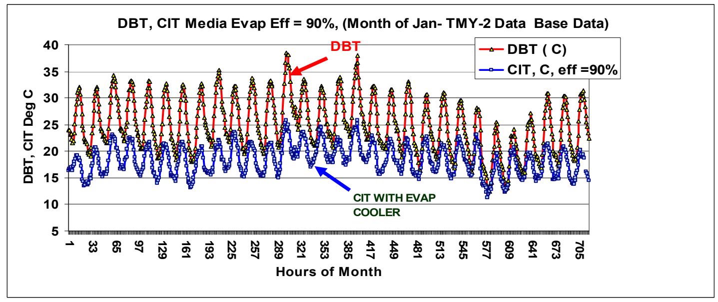

Figure 13. Calculated compressor inlet temperature (CIT) due to evaporative cooling over a summer month.

5.0 REFRIGERATION COMPRESSORS

5.1 Description of LNG Refrigeration Compressors- Design Process.

The design of LNG compressors involving large casing sizes, optimized impeller designs, high inlet relative Mach numbers, 3D flows, and the complexities of sidestream mixing, requires that a careful evaluation of the specific design and experience be made. The propane compressor is the most challenging machine in terms of flow coefficient and inlet relative Mach number. The design complexities, and compromises involved in the selection and design of refrigeration compressors will be covered in this section. Because of the complexity of the compressor designs, process optimization has to be done in cooperation with the compressor designer to ensure that compressor selections are aerodynamically and mechanically robust while meeting process performance and operability requirements. This is an iterative process involving the compressor designer the process licensors and the EPC team.

Design fundamentals and terminology for centrifugal compressors can be found in Aungier [10], Japikse [11]. Details on LNG Compressor design may be found in Meher-Homji, et al [12].

The design complexities, risks and compromises involved in the selection and design of large refrigeration compressors include aerodynamic and mechanical issues and constraints. The final compressor design involves several interrelated tradeoffs between aerodynamics, rotordynamics, impeller stress, efficiency and operating range. Understanding the complexities requires an appreciation of these interactions. Issues that are to be examined for each compressor selection include:

- Machine Mach number and inlet relative Mach number
- Selection of 2D and 3D impellers
- Impeller head per stage
- Range vs. Efficiency tradeoffs
- Head rise to surge and operating range
- Aerodynamic mismatching of stages
- Complexities of sidestream mixing
- Rotordynamic lateral behavior and stability.
- Casing stresses and designs.
- Need for model testing/ CFD analysis.

It is not advisable to set absolute limits on certain parameters as one might do for more traditional compressors and therefore a case by case study has to be made of each compressor service. A valuable discussion of the tradeoffs involved in compressor design is provided by Sorokes [13]. Another excellent reference is Japikse [11] which provides a qualitative graphical representation of design parameters on the performance, operating range and stress for centrifugal compressors. Both these references are valuable in helping engineers who are not aerodynamic specialists understand the design compromises that are needed.

From the perspective of compressor selection, design, and testing, close designer- user interaction and good communication is important to derive a robust compressor solution that will operate under varied operating conditions. Imposition of simple and rigid rules of thumb and specifications by the user that do not recognize that design compromises are inherent in compressor design will often result in non optimal designs. Recognition should exist that turbocompressor aeromechanical design is a complex area where several advanced tools are available to optimize design. The design of LNG turbomachinery must be considered in an integrated manner so that all components including auxiliaries work well.

5.2 Compressor Selections

The configurations for the Darwin LNG Plant are as follows:

- Propane: 2 X PGT25+ Gas Turbine + Speed reduction GB + 3MCL1405 Compressor
- Ethylene: 2 X PGT25+ Gas Turbine + Speed reduction GB + 2MCL1006 Compressor (Back to back design)
- Methane: 2 X PGT25 + Gas Turbine + MCL806 + MCL 806 + BCL608 (i.e., three casing compressor)

Both the propane and ethylene trains have speed reduction gearboxes. All compressors are horizontally split except for the last casing of the methane string which is a barrel design. The gas turbines and compressors are mezzanine mounted as shown in Figure 14, which facilitates a down nozzle configuration for the compressors. This aids in the maintenance of the components as piping may be left in place during compressor dismantling

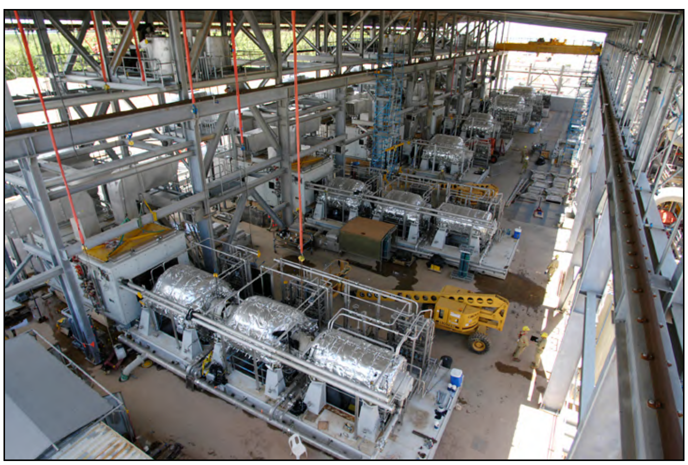

Figure 14. Photograph of compressor deck showing the six compressor strings. From front to back- 2 x methane compressors, 2 x ethylene compressors and 2 x propane compressors.

5.3 Compressor Testing

All of the compressor casings and spare rotors received API 617 mechanical run tests. Gearboxes were tested per API 613, and each kind of compressor was given a Class 2 ASME PTC 10 Test. All the testing was concluded successfully.

5.3.1 Special Testing and Analysis on Ethylene Compressor

The ethylene compressor rotor, when hung from the drive end for modal testing is shown in Figure 15. The compressors have two sections in a back-to-back configuration, with five impellers, and 220 mm dry gas seals. The rotors each weigh 5800 Kg, and are mounted in 200-mm tilting pad bearings with a length to diameter ratio (L/D) of 0.7. The maximum rotor diameter under the impellers is 420 mm, and the bearing span is 3.521 meters. The range from minimum to maximum continuous speed (MCS) is 4118 to 5087 rpm, with a trip speed of 5314 rpm. Shop (mechanical running) tests were performed on all three rotors

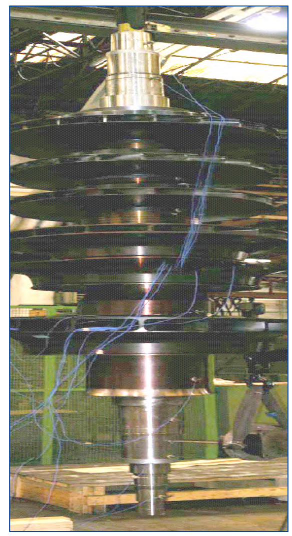

Figure 15.
Ethylene rotor undergoing modal testing.

During the mechanical run test the ethylene rotor ran exceedingly smoothly, with vibration levels in the 5-11 micron pk-pk range. The acceptance level is 25.4 microns pk-pk. However as the rotor reached the maximum continuous speed of 5087, a phase change of approximately 180 degrees was noted at the non-drive end and the vibration amplitudes on the non-drive end bearing, increased**.** The combination of the large phase change, with the rapid vector change in vibration near MCS, raised concerns that the second critical speed, which had been predicted to satisfy API 617 margins, might in fact be much closer than predicted.

The full shop test runs involved acceleration to maximum continuous speed, then a further acceleration to trip speed, followed by four hours at maximum continuous speed, with some variation of inlet oil temperature.

A series of run-up and run-down data on the same bode plot, obtained during the mechanical running test for the first rotor is shown in Figure 16. The first critical speed is around 2250 rpm and some probes exhibit a distinct split (double peak) in this first critical speed, particularly the non-drive end horizontal probe (shown in the bottom frame of Figure 16). In addition to the first critical speed characteristics, a large phase shift approaching 180 degrees occurs near maximum continuous speed (MCS) at both non-drive end bearings. The direction of this phase change reverses for an immediately successive pair of accelerations and decelerations to trip speed (run-up, run-down). The rapid vector change in vibration near MCS can be observed, together with relatively high vibration, exceeding 20 microns at trip speed.

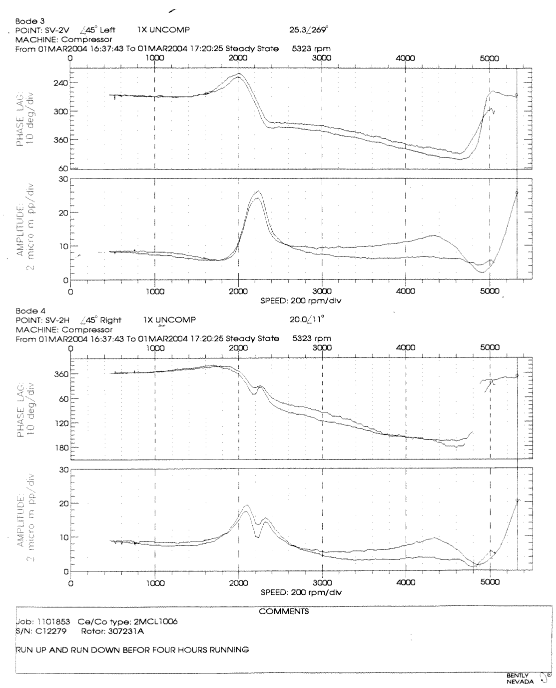

Figure 16. Ethylene rotor Bode plot showing growth in amplitude and phase shift when operating at MCS..

Extensive testing and rotor dynamic modeling was done with the help of South West Research Institute working in conjunction with the OEM. Details are provide in Vannini et al [14]. The tests included:

- **Detailed rotordynamic modeling** including modeling of rotor bending and shear flexibility, shaft distributed mass and rotary/polar inertia discretized at each station, with mass, polar, and transverse inertias of mounted components such as impellers, sleeves, thrust disk, couplings, and nuts lumped at the station corresponding to the component's center of gravity. The model accounts for the rotor stiffening caused by all interference fits, using the method of Smalley, et al. [15].
- **Free-Free modal testing** of the rotor for calibration purposes. To help validate the model, free-free response to shaker excitation was obtained for one of the rotors. In this testing, the rotor was supported in a vertical orientation from a hook attached to the drive end of the rotor, as shown previously in Figure 15. Accelerometers are arrayed at 10 points along the rotor, and shaker excitation is applied near the bottom. The freely mounted rotor has very little internal damping, so the resonant response at natural frequencies of the rotor is very distinct and sharp.
- **Experimental determination of the support stiffness**. To optimize accuracy of a model for predicting rotor-bearing system dynamics, flexibility of the structure, which supports the bearings, can become important. The casing for these compressors is horizontally split, and the bearing support structure is outboard from the casing. This structural configuration can contribute to support flexibility, particularly in the vertical direction.

Figure 17 shows a photograph of the casing under test with loads applied by a dynamic shaker to help identify likely casing flexibility. This photograph illustrates the outboard bearing support. Figure 17 also shows schematically the different orientations of the shaker during these tests. Accelerometers were mounted at various points on the casing and, in combination with a load cell between the shaker and the casing, provided a basis for calculating impedances

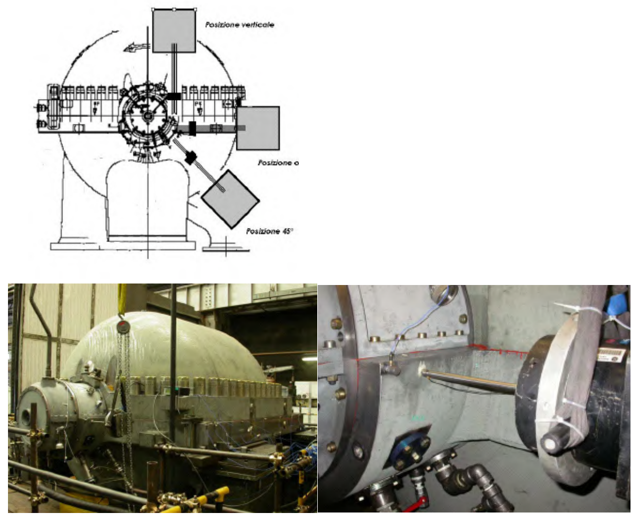

Figure 17. Support stiffness checks.

The analyses described above set to rest concerns about the second critical speed and the associated threat to integrity of two compressors for a critical application. Subsequent operation in the field has proved that the unit operates trouble free.

6.0 OPERATING EXPERIENCE

6.1 Overall Results

Looking at the performance of the LNG plant over approximately two years of operation, all expectations have been met and exceeded. LNG production has exceeded predictions. The aeroderivative gas turbines that were the first application in a LNG plant have been successful. Issues relating to integrations and some lessons learned are provided below.

In terms of reliability and availability, the planned targets have been met and exceeded. One engine had to be removed during an inspection due to a combustor crack that was noticed, however this was not an underlying problem and a recent inspection at 16000 hours have indicated that all machines are operating within tolerances.

6.2 Issues of Integration to the Process with Respect to LM2500+ Trips / Lock out issues.

Some issues were identified relating to integration of aeroderivative engine operation with the plant DCS system.

There are three types of trips:

- **TYPE [a] Normal Shutdown-** in this the GG comes to core idle (approx 6800 rpm) where it is held for 5 minutes. The LPT is at approximately 1600 rpm at this stage. After this period, the unit is tripped and the GG and PT speeds come to zero. The Turning gear (TG) is then energized at this point.

- **TYPE [b] Full Load Emergency Trip**.- this is a trip based on a certain set of engine parameters that are deemed critical. In this trip the fuel is cut off and the turbine comes down and a 4 hour lock out is imposed (on a timer) unless the trip can be reset within 10 minutes and the starter motor engaged to initiate a 5 minute cooldown
- **TYPE [c] Motor Trip (Crank Trip)** – In this trip, the GG and power turbine speeds drop and the hydraulic starter motor is engaged at approximately 200 rpm GG speed which accelerates the GG to around 2000 rpm. After a 5 minute cool down, the starter motor deenergizes and after the GG comes to a standstill, the turning gear is energized. This must be done within a 10 minute timeframe else a 4 hour lock out results. The turning gear (TG) is not energized until the GG speed equals zero. The reason for this is that there is not enough gas energy to break away the PT, but if the TG is energized, then the load compressor speed will attain 80-200 rpm which may be damaging to the dry gas seals. Consequently, in this mode, there may be as long as 25 minutes between the trip and the time when the TG is energized, which could allow a bow to occur in the load compressor rotor.

Consequently, future projects will include:

- Joint evaluation of engine trip by the OEM, EPC and Process Licencor.
- Development / Evaluate a cause- effect diagram to understand and categorize trip parameters to minimize Type B trips.
- Try to move trip parameters from type C to A, as the logic of type B trips defeats the use of turning gears.

6.3 Operator Training System (OTS) and Dynamic Simulation

As reported by Valappil et al (16, 17] dynamic simulation has established itself as a valuable technology in the chemical process industries. It is useful for a variety of purposes, including engineering and process studies, control system studies and applications in day-to-day operations and also for the development of dynamic Operator Training Systems (OTS). Process modeling, either steady state or dynamic can be carried out in the various stages of the LNG process lifecycle. The benefits of integrating these modeling activities have been realized in recent years. The dynamic model, evolving with the various stages of a plant lifecycle can be tailored for various applications within the project lifecycle as shown in Figure 18. The operability and profitability of the plant during its life depends on good process and control system design. Dynamic simulation helps to ensure that these aspects are considered early in the plant design stage. This eliminates or reduces any costly rework that may be needed later. The operator training system was implemented at Darwin LNG and has proved to be a very valuable training tool allowing operators to examine and train for dynamic plant operation.

There are several benefits to be realized by using the dynamic simulation in the various stages of an LNG project. On the process side, dynamic simulation is an important tool for evaluating the anti-surge control system for the refrigeration compressors. The reliable protection of this equipment is critical for long-term smooth operation of the LNG plant. Also, dynamic simulation can be pivotal in the support of sizing of specific key relief valves, and the overall relief system and optimum selection of equipment sizes. LNG plants are also characterized by extensive heat integration, the operational implications (stability and startup) of which can be studied by simulation. Further, the effect of external factors like ambient

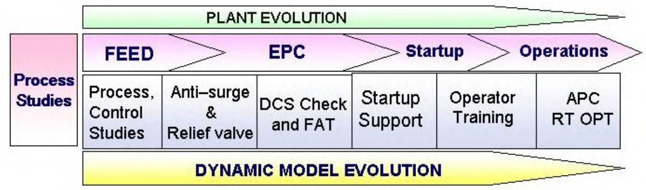

Figure 18. The use of dynamic simulation models used for Darwin LNG throughout the plant evolution process [16].

conditions and compositional changes on the future plant operation can be analyzed to further optimize the design.
Dynamic simulations are also fundamental to understand compressor behavior during operation and during transient conditions such as trips, and startup. Figure 19 shows the trip scenario on a centrifugal compressor.

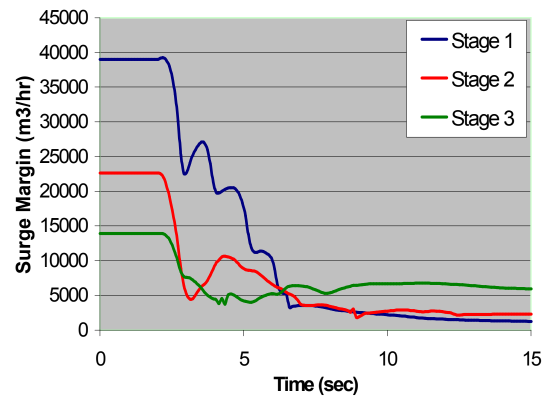

Figure 19. Response of a refrigeration compressor in a trip. Surge Margins for the three stages are shown as the machine speed drops. (Valappil et al, [17]).

7.0 CLOSURE

This paper has provided an overview of the application and operating experience of the world's first aeroderivative driven LNG Liquefaction facility. Part 1 of this paper described the underlying need for high thermal efficiency in the LNG market. The plant has been successfully operated for over two years and has met and exceeded its production goals.

Nomenclature

DLE	**Dry Low Emission**
GG	**Gas Generator**
GT	**Gas Turbine**
HPT	**High Pressure Turbine (GG Turbine)**
HSPT	**High Speed Power Turbine**
MCS	**Maximum Continuous Speed**
OTS	**Operator Training System**
RH	**Relative Humidity**
SAC	**Standard Annular Combustor**
TG	**Turning Gear**

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