REFRIGERATION COMPRESSOR DRIVER SELECTION AND TECHNOLOGY QUALIFICATION ENHANCES VALUE FOR THE WHEATSTONE PROJECT

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ABSTRACT

Chevron Australia, as part of the Wheatstone Project, is constructing a two-train liquefied natural gas (LNG) facility and domestic gas plant at the Ashburton North Strategic Industrial Area, 12 kilometres west of Onslow on the Pilbara coast of Western Australia. The initial two-train facility design capacity is 8.9 million tonnes per annum (MTPA). Eventually, the facility could expand to produce up to 25 MTPA of LNG. During the early stages of project development, a driver selection study was performed based on the ConocoPhillips Optimized Cascade® natural gas liquefaction process. This driver study evaluated a variety of project-specific parameters and resulted in the selection of a General Electric LM6000 PF aeroderivative gas turbine based on overall value to the shareholders considering production rates, production efficiency, fuel costs, greenhouse gas emissions, installed cost, operational and maintenance cost.

The selection of the LM6000 gas turbine results in the first commercial use of the LM6000 engine in a mechanical drive application. The final decision to use the LM6000 engine was based on a detailed technology qualification. A collaborative qualification was performed with representatives from the EPC contractor, process licensor, end user/operator, and the equipment manufacturer. The technology qualification followed a systematic approach to identify the risks and novelties within the application. Risk items identified were analyzed with a combination of detailed studies, computer-based modelling and full-scale engine testing.

Following the completion of the technology qualification, a detailed risk mitigation plan was developed. The plan was incorporated into the purchase order of the equipment and subsequently incorporated into the equipment manufacturer's Failure Mode Effects Analysis (FMEA) process. Finally, detailed analysis and testing requirements were selected to address all risks that were highlighted in the risk mitigation plan.

INTRODUCTION

The Wheatstone Project is one of Australia's largest resource projects—providing both LNG export and greater security of supply for domestic gas production. The project will provide significant benefits to the people of Australia, including significant employment opportunities during the construction and operational phases, government revenue and local business opportunities. The project includes offshore development wells and associated facilities as well as the onshore LNG and domestic gas plants located within the Ashburton North Strategic Industrial Area (ANSIA), 12 kilometres west of Onslow in Western Australia's Pilbara region.

The Wheatstone Project is a joint venture between Australian subsidiaries of Chevron (64.14%), Apache (13%), Kuwait Foreign Petroleum Exploration Company (KUFPEC, 7%), Shell (6.4%), and Kyushu Electric Power Company (1.46%), together with PE Wheatstone Pty. Ltd. (partly owned by TEPCO, 8%).

The Wheatstone Foundation Project will process gas from various fields located 145 km offshore in the West Carnarvon Basin. Eighty percent of the Wheatstone Foundation Project capacity will be fed with natural gas from the Wheatstone and Iago Field operations, which are operated by Chevron in joint venture with Australian subsidiaries of Shell and Kyushu Electric Power Company, together with PE Wheatstone Pty. Ltd. The remaining 20% of gas will be supplied from the Apache and KUFPEC’s Julimar and Brunello fields. The Foundation Project will consist of two LNG processing trains, each with a capacity of approximately 4.45 (MTPA), as well as a Domgas plant with a nominal capacity of 190 MMSCFD. The overall project is expected to consist of at least five LNG trains and additional Domgas facilities with a nominal LNG production capacity of up to 25 MTPA.
A final investment decision to proceed with the Wheatstone Project was made on September 26, 2011, with construction beginning soon after in December 2011.

LIQUEFACTION TECHNOLOGY

The Wheatstone LNG Plant will utilize the ConocoPhillips Optimized Cascade® process. This technology was first used in the Kenai LNG plant in Alaska in 1969, and since then ConocoPhillips has licensed 22 LNG liquefaction trains with over 90 MTPA of liquefaction capacity in the world. A simplified process flow diagram of the Optimized Cascade® process for Wheatstone LNG shown in Figure 1.

The Optimized Cascade® technology offers the following benefits for the Wheatstone Project:

- Commercially proven technology that can process natural gas of varying composition which is well suited to the development of a number of separate gas fields and the Wheatstone Project’s ‘hub’ concept; the technology has been used around the world, starting with Kenai in 1969.
- Operational flexibility enabling plant throughput to be tuned to market demand and available gas supply.
- Benchmarks favorably with alternative processes and existing LNG plants in terms of its process efficiency and reliability.
- Uses multiple, parallel compressor circuits within each liquefaction train that allow continued operation (at reduced rates) during periods of planned and unplanned gas turbine maintenance, reducing the number of full plant shutdowns and startups.
- Use of parallel compressors allows the opportunity to use smaller compressor process drivers for a given LNG throughput, which complements the use of high-efficiency aeroderivative gas turbines.

The ConocoPhillips-Bechtel LNG collaboration has provided constant innovation, specifically in the design and implementation of LNG driver configurations. The world’s first application of gas turbines in LNG service was implemented in 1969 at Kenai. The plant was built with six GE Frame 5 gas turbines and has operated for 43 years, never missing an LNG shipment. In 2006, ConocoPhillips and Bechtel designed and constructed the Darwin plant in Australia, which is still the only operating LNG facility to utilize high efficiency aeroderivative gas turbines (LM2500+G4) in LNG refrigeration service. Since then, eleven LNG liquefaction trains have implemented the LM2500+ for the primary refrigeration driver. This constant innovation and thirst for efficiency improvement has led to the development of the LM6000 PF gas turbine in LNG service. Wheatstone LNG will be the first LNG facility utilizing the LM6000 to drive its refrigeration compressors.

DRIVER ALTERNATIVES
The selection of the driver for the refrigeration compressors within an LNG plant has a key impact on the overall LNG plant efficiency and capacity of the plant. Natural gas liquefaction plants are generally designed to the limits of the available refrigeration compressor drivers to maximize train capacities. It is therefore critical that an adequate amount of effort is put into the evaluation of driver options. Figure 2 shows the evolution of the LNG process technology since the early years from steam turbine to gas turbines as the driver of choice for the refrigeration compressors.

![Figure 2: Evolution of Refrigeration Compressor Drivers in the LNG Industry](image)

There are three major types of drivers used in the baseload LNG industry as described below.

- **Steam Turbine Drivers**
  
  Most of the earlier LNG baseload plants used steam driven refrigeration compressors. However, their use has become less common over the past 25 years. The steam turbine driver can be customized to the precise desired power requirement for the compression system, has high equipment reliability and provides the ability to vary operating speed over a wide range. However, the use of the steam turbine driver requires an elaborate steam, water treatment and cooling system, making it relatively complex to operate and high in initial capital cost. While the equipment reliability of the steam turbine is high, this benefit has to be balanced against the reliability as well as thermal efficiency of the total system.

- **Gas Turbine Drivers**
  
  The gas turbines come in a variety of discrete sizes with ISO ratings varying from approximately 27 MW (for a Frame 5 gas turbine) to 130 MW (for a Frame 9E gas turbine). The first use of gas turbines in an LNG plant was at the ConocoPhillips LNG plant in Kenai, which started up in 1969. This plant, with an LNG production capacity of 1.5 MTPA, used Frame 5 gas turbines to drive the refrigeration compressors. Initially, smaller gas turbines were used resulting in plant sizes ranging from 1 to 3 MTPA. As the LNG industry matured and focused on efficiency and cost reduction, the single train capacities grew to 5 MTPA or more. The higher capacity trains offered the opportunity to use large-size gas turbines.

- **Electric Drivers**
In recent years, there has been increasing interest in using electric motors as drivers for the refrigeration compressors. Some in the industry have proposed that high availability of electric motors can increase the overall plant production efficiency (availability). While the extent of increase in production efficiency is debatable, this option typically requires significant additional investment for power plants and systems. The Snohvit project in Norway is the only LNG plant to use motors as primary refrigeration drivers. To improve the overall thermal efficiency of electric driver arrangements, combined cycle power generation would be required with similar pros and cons of the steam systems mentioned previously.

**AERODERIVATIVE VS. INDUSTRIAL GAS TURBINES**

There are two broad categories of gas turbine drivers used as mechanical drivers in the LNG facilities:

**Industrial Gas Turbines**

Industrial gas turbines such as Frame 5, 6, 7 and 9 have been used in the LNG liquefaction industry as mechanical drivers for refrigeration compressors since the late 1960s. The first application was at the Kenai plant in 1969. Since the mid 1980s, most LNG plants have used industrial gas turbines as mechanical drivers for refrigeration systems. The thermal efficiencies, at ISO conditions, of these gas turbines range from 29% to 34% (based on lower heating value). Industrial gas turbines can be either a single shaft or dual shaft design. Most industrial gas turbines used in power generation application, such as Frame 6, 7 and 9, are single shaft machines and have a limited range of speed variation. Typical speed ranges for single-shaft gas turbines are on the order of 95% to 101%. These machines, when used in mechanical drive application, also require a variable speed startup motor for starting up the compression strings. Unlike the large industrial gas turbines, the Frame 5 gas turbines have a two-shaft design that allows high startup torques, making it possible to start the compression strings under refrigeration compressor settle out pressure conditions and without a large starter motor.

**Aeroderivative Gas Turbines**

The use of aeroderivative gas turbines for mechanical drive dates back to the 1950s. They are attractive as mechanical drives because of their small size, fuel efficiency and ease of maintenance. Aeroderivative gas turbines, such as LM2500 and LM6000, have been developed from aircraft engines. They are relatively compact, light weight and have thermal efficiencies, at ISO conditions, ranging from 39% to 43% based on LHV.

Aeroderivative and industrial gas turbines have inherent technical differences, some of which may impact which type is selected for a particular LNG project. Both turbine types are available in a wide range of sizes that provide flexibility in the selection of the appropriate size for a given application. The sizes are finite and are not adjusted to fit the application, as are motors, steam turbines and the compressors they drive. Aeroderivative units are “multi-shaft” designs, whereas most large industrial units are single-shaft design. This feature gives the aeroderivatives advantages in part load efficiency and speed variation over a wider range of operation. The aeroderivatives also have higher full load efficiency due to a higher compression ratio and firing temperature. Aeroderivative engines are physically smaller than industrials. They are also modular in design, which allows maintenance and major overhauls to be done “off site.” Industrial units are typically maintained and overhauled in place. A major item impacting the decision on the use of industrial or aeroderivative gas turbines is their ability to handle large variations in fuel composition and the rate of change between these fuels. Given the larger combustion system and longer residence times in the industrial gas turbines, they are more tolerant of fuel variation compared to aeroderivative gas turbines. There are a number of additional features that impact the comparison between aeroderivatives and industrials, including emission characteristics, engine degradation, performance at site conditions (site rating), and fuel pressure requirements. Both aeroderivatives and industrial gas turbines are well proven selections for use in LNG refrigeration service.

**POWER AUGMENTATION FOR GAS TURBINES**
All gas turbines have a degradation of power output with increasing ambient temperature. Power augmentation can be used to level out the available power from the gas turbine, as well as optimize LNG production at all ambient conditions. The degradation of power output is normally more pronounced with higher compression ratio gas turbines, such as aeroderivative ones. The LM6000 has a compression ratio of 30:1, resulting in a higher power lapse rate with ambient temperature compared to industrial gas turbines. Compared to other aeroderivative gas turbines, the lapse rate is similar for the higher ambient temperatures but more significant at the lower ambient ranges. This is shown in Figure 3, which shows the gas turbine lapse rate between typical average and extreme high ambient conditions. This clearly shows that aeroderivatives have a much greater lapse rate compared to industrial gas turbines. It also shows that adding inlet air humidification (IAH), also known as evaporative cooling, to an aeroderivative turbine reduces the lapse rate from about 25% to 5% when high temperatures occur. This reduction is dependent on site specific conditions.

![Gas Turbine Lapse Rate (Avg Ambient to Extreme High Ambient)](image)

Figure 3: Gas Turbine Lapse Rate between Average and Extreme Ambient Temperatures

Figure 4 shows the same information over the whole range of ambient conditions. The data is normalized to the power output at 26 deg C. The purpose of the curves is to show the relative lapse rate given the available power at the average ambient temperature.
For gas turbines with IAH, the turbine inlet temperature is a result of evaporative cooling of the ambient air. The average coincident humidity plus one standard deviation was used in the calculations to determine the effectiveness of the IAH system. The selection of plus one standard deviation was made to minimize the occurrences of high humidity conditions limiting the ability to reach the anticipated turbine inlet temperature. By choosing plus one standard deviation, the humidity will only be higher than the design basis approximately 16% of the time. As seen in Figure 5, the pinch point in power is only anticipated to occur between 32 to 39 degrees Celsius. Based on 11 years of coincident hourly data, the dry bulb temperature is in the 32 to 39 degree C range approximately 10.5% of the year. Therefore, the occurrence of high humidity coincident with this temperature range is anticipated to be less than 1.6% of the year. This compares to the use of the average relative humidity which would have resulted in power below the minimum design power over 8.5% of the time.
Figure 5: Impact of Coincident Relative Humidity vs. Derated Power with IAH

As seen in Figure 4, the addition of IAH to the LM6000 for Wheatstone Project site conditions results in a lower lapse rate at the higher ambient conditions compared to any of the alternative gas turbine selections. At the low temperature ranges, the lapse rate is less impacted by the IAH since the humidity at site conditions under these scenarios is high. At the low ambient conditions, the humidity is close to 100%, giving very little, if any, benefit from the evaporative cooler. Since the power at the average ambient conditions is higher for the IAH option, the lapse rate to the lowest ambient conditions is less even though the power output with IAH and non-augmented LM6000 is equivalent at this condition.

DRIVER SELECTION STUDY

The selection of the type and configuration of the mechanical drivers for a liquefaction refrigeration system is a key decision during pre-Front End Engineering Design (pre-FEED). For the Wheatstone Foundation Project, a study was performed to evaluate various refrigeration compressor driver and train configuration options.

The purpose of the study was to determine the most cost effective refrigeration compressor driver type and configuration to allow the LNG trains to reliably produce LNG. The selection process for the refrigerant compressor drivers involved completing a technical and economic comparison of a number of alternative drivers and driver configurations; this was carried out by study contractor, Bechtel, as part of the pre-FEED concept selection studies. The information developed by the contractor was then assessed by the owner’s team, and the capital and operating cost figures were used to prepare a value analysis using the project economic model.

The study basis that influenced the driver selection was:

- Feed stream composition and rate
Based on the upstream resource and offshore pipeline design, the feed gas rate to the LNG facilities was fixed. Therefore, any excess driver power that might be available was not directly usable for significant additional annual production of LNG.

Feed stream nitrogen content for the Wheatstone and Iago Field ranged from 5 to 6 mol%. However, the plant design needed to be flexible to handle feed gas with up to 16 mol% nitrogen from Apache/Kufpec’s Julimar and Brunello fields. Since excess nitrogen content increases the refrigeration specific power required, gas turbine power margin improves the ability to process gas with higher nitrogen content and still achieve design capacity.

- Site ambient conditions

The site ambient temperatures that formed the basis of design for the Wheatstone plant are summarized in Table 1.

<table>
<thead>
<tr>
<th>% Exceedance</th>
<th>&lt;0.05%</th>
<th>1%</th>
<th>5%</th>
<th>50%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>Extreme High</td>
<td>High-High</td>
<td>High</td>
<td>Average</td>
<td>Low</td>
</tr>
<tr>
<td>Design Relative Humidity (%)</td>
<td>15.0</td>
<td>31.6</td>
<td>58.1</td>
<td>81.8</td>
<td>92.1</td>
</tr>
</tbody>
</table>

The key criteria for the selection of the refrigeration compressor driver for Wheatstone Foundation Project trains included the following:

- Total installed cost of the refrigeration system
- Net present value analysis, taking into consideration LNG production and operating cost amongst other parameters
- Greenhouse gas emissions and potential greenhouse gas emission taxes
- Technical, operational, and schedule risk assessments
- Thermal efficiency and impact on LNG production
- Potential for processing feed gas with higher nitrogen content

The type, number, and power output of the LNG refrigeration compressor drivers are key determinants of the capacity and onstream reliability of the LNG trains. The ConocoPhillips (COP) Optimized Cascade® natural gas liquefaction process comprises three pure component refrigeration loops using propane, ethylene and methane. The Optimized Cascade technology-based plants built or designed to date have all used simple cycle gas turbines as their refrigeration compressor drivers, typically in a configuration with at least two gas turbines driving parallel compressor strings for each of the three refrigeration loops (2 x 2 x 2 configuration).

LNG industry operating experience is an important criteria to owners and financiers when selecting a turbine for refrigeration service. Both industrial (‘Frame’) and aeroderivative gas turbines have been used in the Optimized Cascade process to drive the refrigeration compressors. Most plants in operation have used variants of the GE Oil & Gas Frame 5 gas turbine. However, the Darwin LNG Plant in Northern Australia uses GE Oil & Gas PGT25+G4 (LM2500+G4 gas generator section with high speed power turbine) aeroderivative turbine. The Angola LNG plant uses Frame 7 and Frame 6 industrial gas turbines. All trains designed since the successful startup and operation at Darwin in 2005, have been based on the LM2500+G4.

Based on Bechtel-COP operating and earlier study experience, a short list of configuration options were evaluated in parallel with other pre-FEED activities:

i. 6 x LM2500+G4 with mechanical refrigeration for inlet air chilling (IAC)
ii. 6 x LM2500+G4 with Inlet Air Humidification (IAH)
iii. 7 x LM2500+G4 with no power augmentation
iv. 6 x LM6000PF with IAH
v. 7 x LM2500+G4 with IAH
vi. 7 x LM2500+G4 with IAH and waste heat recovery steam generation units, with steam turbines to generate electric power and steam for process heating
vii. 2 x Frame 7EA and 2 x Frame 5D.

The 6 x LM2500+G4 with IAC (Option i) configuration was the basis for the initial pre-FEED work; this case was also used for comparing the capital cost for the other alternatives. The cases without steam generation use gas turbine generator sets for electric power production. Inlet air cooling using evaporative humidifiers or mechanical chilling was considered in a number of alternatives to augment power output and mitigate severe seasonal swings in LNG output. Upon further review, the ambient air temperature swings and resulting gas turbine power fluctuations at the Ashburton North site precluded using aeroderivatives without either IAH or IAC.

Table 2 summarizes the comparison on some of the parameters for the different alternatives from the study.

<table>
<thead>
<tr>
<th>Driver Alternative</th>
<th>Description</th>
<th>LNG Output, Two trains, (MTPA)</th>
<th>Estimated Power Margin, (%)</th>
<th>Total Installed Cost (US$ MM)</th>
<th>CO₂ Emissions, (TPD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>6 x LM2500+G4 with IAC</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
</tr>
<tr>
<td>ii</td>
<td>6 x LM2500+G4 with IAH</td>
<td>Base - 0.06</td>
<td>Base + 0</td>
<td>Base - 63</td>
<td>Base - 100</td>
</tr>
<tr>
<td>iii</td>
<td>7 x LM2500+G4</td>
<td>Base + 0.02</td>
<td>Base + 2</td>
<td>Base + 39</td>
<td>Base + 50</td>
</tr>
<tr>
<td>iv</td>
<td>6 x LM6000PF with IAH</td>
<td>Base + 0.02</td>
<td>Base +12</td>
<td>Base – 57</td>
<td>Base – 40</td>
</tr>
<tr>
<td>v</td>
<td>7 x LM2500+G4 with IAH</td>
<td>Base + 0.02</td>
<td>Base + 9.5</td>
<td>Base + 119</td>
<td>Base + 70</td>
</tr>
<tr>
<td>vi</td>
<td>7 x LM2500+G4 with IAH  and combined cycle power generation and steam for process heating</td>
<td>Base + 0.19</td>
<td>Base + 9.5</td>
<td>Base + 448</td>
<td>Base – 400</td>
</tr>
<tr>
<td>vii</td>
<td>2 x Frame 7EA &amp; 2 x Frame 5D</td>
<td>Base - 0.29</td>
<td>Base + 6</td>
<td>Base – 256</td>
<td>Base + 620</td>
</tr>
</tbody>
</table>

Because the total feed gas supply was fixed for the study, some configurations resulted in excess power available. The much higher power output of the LM6000 units with IAH provided opportunities for optimization and cost reduction elsewhere in the process. A list of potential total installed cost (TIC) reduction opportunities with savings totalling up to ~$200MM were identified if the excess power available from the LM6000s was used to eliminate equipment and optimize the LNG train design. The TIC for alternative iv also includes a cost penalty for an extended startup period because LM6000s have not previously been used in a refrigeration drive application. Cases with lower fuel gas consumption and adequate refrigeration power could potentially produce more LNG under a feed rate constrained scenario.

While alternative vii has the lowest estimated TIC cost, it also has lower thermal efficiency, with the highest fuel gas use (resulting in less feed gas available for LNG production) and highest CO₂ emissions. Due to these factors and the longer maintenance down time required for the industrial (frame) gas turbines, alternative vii resulted in significantly less annual LNG output compared to the other options.

Alternative ii has the next lowest TIC, but this configuration has no excess power and is not able to achieve the target LNG output. Modifications to this design could result in achieving the target output by reducing the propane condenser approach temperature, adding limited IAC, or other methods, however, any of these would increase the TIC of this alternative. In addition, the power margin was still insufficient to provide the flexibility needed to handle higher nitrogen content feed gas, such as that expected from Apache/KUFPEC’s Julimar and Brunello fields.
To compare the relative NPV and capital efficiency of the alternative driver configuration cases, the TIC, LNG production, and operating costs were used to compare each case. The results are shown in the NPV vs. Present Value Capex plot in Figure 6 below.

The case generating the highest NPV was alternative vi. The increased revenue from higher LNG production and lower CO2 emission costs clearly offsets the higher capital cost. The NPV and capital efficiency appear superior to the alternative cases using 7 x LM2500 drivers. However, the investment efficiency parameters, such as discounted profitability index (DPI) and rate of return (ROR), for alternative vi were approximately the same as that LM6000PF case (alternative iv), which has a lower TIC of about $500 MM. In addition to lower TIC and comparable DPI/ROR, the alternative iv has a higher excess power margin, which, as noted above, can translate into:

- Higher LNG production if feed gas supply rates can be increased
- Increased operational flexibility, including the ability to handle higher N2 content feed gas streams
- Reduced operating load on the LM6000PF gas turbines, leading to extended maintenance intervals, reduced downtime, incremental LNG production, and lower operating costs

The combined cycle / cogeneration system in alternative vi provides higher thermal efficiency, but it results in a more complex operating system. It has higher water demand and additional water treating requirements. More significantly, it would also be a first-of-a-kind design for the Optimized Cascade process. It was estimated that the overall FEED timetable would need to be extended by about three to six months to incorporate the new design aspects resulting from the addition of a steam system, combined cycle power generation, etc. The LM6000PF drivers, while also not previously used, can be used in the same basic design configuration used successfully in many operating plants while maintaining the current Wheatstone schedule.

Overall, the driver configuration using 6 x LM6000PF with IAH provides the optimal combination of relatively low initial TIC, attractive NPV, DPI and ROR, operating flexibility, and acceptable technical and schedule risk, and was thus selected for the Wheatstone Project.

HIGH AMBIENT TEMPERATURE OPERATION

The design at various conditions were closely reviewed to ensure that the upstream and LNG plant operations would not be negatively impacted by the large range of ambient temperatures and relatively high summer temperatures at the plant site.
The project Basis of Design required that the plant operate at ambient temperatures up to 46°C. At these conditions, the propane system was approximately 5% short of power and the compressors could not operate under these conditions. Several options were evaluated to manage the high ambient temperature operation, as summarized below:

**Overfiring of the Gas Turbines**

GE allows short-term, periodic overfiring of turbines, which provides a 6% increase in the power available from the turbine. The overfiring can affect the expected maintenance schedule of the hot section. Based on the site ambient temperature information, it is expected that overfiring will be required about 25 hours/year. The overall maintenance schedule of the propane GT requires a major hot section overhaul shutdown at 25,000 hours (or ~3.2 years). Considering that the aeroderivative gas turbine maintenance is an on-condition based maintenance, it is anticipated that the impact of the overfiring will not be noticeable in the plant maintenance schedules.

**Higher Purity Refrigerant Propane**

The current design is based on assuming a 98 mol% pure propane refrigerant. This assumed 1 mol% ethane and 1 mol% i-butane in the propane. A simple simulation showed that a 99 mol% purity propane (with 1 mol% i-butane) would decrease the overall propane compressor power required by about 2% due to the ability to condense the propane at a lower pressure when the light components are removed. Based on information from the propane supplier, higher purity propane should be available. However, no credit for this enhancement can be assumed until the plant is operating and the imported propane purity is confirmed.

**Add SPRINT to Propane LM6000 Gas Turbine**

Based on GE’s information, the SPRINT system would allow for approximately 3 MW additional power from the GTs. This is about 9% of the current power requirement and would cover the power shortage. However, this resulted in about 50% increase in the facility’s demin water system. Furthermore, while this system was reviewed in detail by GE, there are no operating units utilizing the low pressure injection system for a hot end drive application. The hot end drive application used for mechanical drives requires the SPRINT nozzles to be supported on the inlet compressor struts, and this arrangement has not previously been used.

**Add Inlet Mechanical Chillers to Gas Turbines**

The addition of mechanical chillers to the inlet of the GTs was evaluated during the main driver study in the early phase of the project. Because the possible power increase with the mechanical chillers was estimated to about 20%, it was determined that it would only be economically viable if it could be used year-round to produce more LNG. However, under the basis that the facility is feed gas limited, the high capital cost associated with this option was not warranted to only provide additional power during the extreme ambient days.

**Add Lithium Bromide (LiBr) Chiller Package to Gas Turbines**

High-level research on the use of LiBr chillers showed that their performance tends to drop off quickly in high ambient temperature environments (>95°F, 35°C) due to crystallization of the absorbing solution. Therefore, this technology was not deemed feasible to address the issues posed by Wheatstone Project’s ambient conditions.
Add Helper Motors to the Propane Gas Turbines

The potential of adding a helper motor to supply additional power was evaluated. This too would be a first-of-a-kind design, because large helper motors have not been used on 2-shaft GTs, as they are able to start without the assistance from large starter motors. The addition of a helper motor with associated variable frequency drive is a significant capital cost. Additional power generation may also be required. The high capital cost associated with this option did not warrant further evaluation.

Utilize Impeller Technology with More Turndown Capability

As the ambient temperature increases, the pressure ratio in the refrigeration compressor increases and the power consumed will increase. If the gas turbine is power limited, a reduction of flow through the compressor will reduce the required compression power. The flow through the compressor can only be decreased until the flow is at the surge control line, at which time the recycle valves will start opening and essentially lock in the compression power. Any further increase in the ambient temperature will result in the gas turbine slowing down and the compressor suction pressures rising. A significant amount of work and qualification was performed with GE Oil & Gas to utilize their T5.3 high Mach impellers, which offer more turndown capability than the standard propane compressor impellers.

Many other options were also evaluated for which credit could not be taken during the design phase of the project but might be available during operations: margins on equipment, quality of the propane refrigerant, using the GTs with the highest tested power on the propane strings, good operational practices to ensure that GTs are washed regularly and utilization of high efficiency air filtration, etc.

Based on the overall evaluation, it was recommended that for the limited amount of time where this additional power is required, the GTs be provided with an overfiring option and the T5.3 impellers implemented for propane service. Implementation of any other option seemed unwarranted. Future plant enhancements, once actual operational limitations are known, could be implemented as debottlenecking options. To limit the over-fire hours, the control system limits the activation of the over-fire mode to high ambient conditions and times when the compressors are operating with the recycle valves open. Additionally, the over-fire controls are only activated on the propane compressor due to the direct impact of higher temperatures on propane condensing. The selection of the LM6000 gas turbine drivers for refrigeration compressors resulted in the first use of the LM6000 engine in a mechanical drive application. The final decision to use the LM6000 engine was based on a detailed technology qualification. A collaborative qualification was performed with representatives from the EPC contractor, process licensor, end user/operator, and the equipment manufacturer. The remainder of the paper provides an overview of LM6000 engine and the technology qualification process.

LM6000 OVERVIEW

The LM6000PC/PD/PF family was derived from the CF6-80C2 aircraft engine that has over 3,731 engines in service with more than 188.8 million flight hours and 43.8 million flight cycles. The LM6000PF, which is the specific variant used for the Wheatstone Project, is shown in Figure 7.
The LM6000PF engine is a DLE (dry low emissions) configuration of the LM6000 and is the GE current offering for mechanical drive and power generation applications. The PF was derived from the PD model to improve operability and fuel flexibility. The following modifications are made to the LM6000PD engine:

- Improved combustors and pre-mixers
- Additional manifold and fuel valve
- Control software changes

No other changes have been made to the LM6000PD hardware and the rated output of the engines is identical.

The modifications to the combustors and pre-mixers are shown in Figure 8.
Design Changes from DLE1 to DLE1.5 technology

The experience of the LM6000 engines includes 1076 engines with total operating hours of more than 25,405,471 hours. There are 260 LM6000 PD/PF machines operating with total operating hours of greater than 5,552,252 hours with the high time engine greater than 95,937 hours. The fleet leader PF engine has over 54,766 operating hours.

The LM6000 is unique from other 2-shaft gas turbines in that the power turbine (LPT) is connected to the low pressure axial compressor (LPC) section of the gas turbine (Figure 9). Therefore, the starting and shutdown characteristics are unique to this engine and were identified as areas requiring detailed review.

Figure 8: LM6000PF Combustor and Pre-mixer Details
The basis of the qualification was a dry low emissions (DLE) unit since all recent mechanical drive gas turbines currently operating in Western Australia use dry low NOx technology, and environmental permitting requires that the best available technology to be applied. The LM6000PF engine is capable of achieving a 15 ppm NOx level. The 15 ppm NOx guarantee is based on operation of 70% and higher power levels. The LM6000PF engines have been guaranteed to operate down to 50% load with a NOx level below 25 ppm.

**CHEVRON TECHNOLOGY QUALIFICATION PROCESS**

Chevron’s Technology Qualification Process (TQP) is a systematic process for reducing uncertainty associated with new technology by breaking the system into subsystems and/or components and determining the risk associated with each. The primary elements of the TQP for the use of the LM6000PF as a mechanical driver for the Wheatstone Project started in October 2008 and were concluded in December 2009.

During the TQP, emphasis was placed on subsystems and components with the highest degree of uncertainty because this offers the greatest opportunity for risk reduction. The TQP is one part of an overall technology deployment strategy that includes leadership behavior, accountability, training, communication, data capture/metrics, and feedback. The TQP methodology involves the following elements.

**Preparation**

Preparation involves integration of TQP into the Chevron Project Development and Execution Process (CPDEP) and mobilization activities, such as TQP team selection, identification of subject matter expert (SME) requirements, budget and schedule development, and an overview of techniques to be used.

**Technology Specification**

The Technology Specification defines all requirements for the technology, including target reliability. Progress of the technology toward deployment is measured by use of initial and target Technology Development Stage (TDS). The TDS definitions are shown Figure 10.
Threat Assessment identifies threats associated with each subsystem or component. Threats are defined as failure modes and mechanisms and are identified for the entire lifecycle of the technology.

Threats were converted into ranked risks. The risk rankings were established on a qualitative basis and considered both the severity and likelihood of actually realizing each identified threat. Risks were ranked as Low, Medium or High according to the intersection of likelihood and severity.

The Qualification Plan identifies all analysis, testing and procedure development needed to reduce the risk of each threat. Associated schedules and costs are then developed.

Performed in accordance with the Qualification Plan, Qualification Execution gathers evidence from analysis, testing and procedure development to assess performance of the technology. Quality, accuracy and statistical significance of this evidence are critical to the TQP.

Performance Assessment evaluates the results from Qualification Execution against requirements of the Technology Specification. This step determines if the technology can be deployed for a specific set of
conditions, if additional refinement and another iteration of the TQP are warranted, or if the technology should be abandoned for that project.

**Deployment Preparation**

For technology that complies with the Technology Specification, Deployment Preparation documents the TQP results and recommendations. Thorough documentation and traceability of the TQP will provide an audit trail for future projects to evaluate any new technology and consider its use.

**LM6000PF Mechanical Drive System and Sub-Systems**

The LM6000PF mechanical drive system was split into sub-systems to facilitate the qualification process. The sub-systems identified and evaluated are included in Figure 11. Based on the identified sub-systems, the following is a summary of the work and major findings.

![Figure 11: LM6000PF Mechanical Drive Sub-systems](image)

**LM6000 PF Lateral and Torsional Analysis**

Lateral analysis, torsional analysis, and unbalance response for the LM6000PF in both a cold end drive and a hot end drive configuration were provided during the qualification phase. In addition, GE performed a combined lateral-torsional vibration analysis of the LM6000 engine with the load coupling, gearbox and compressor on the methane train.
Temperature & Stress Profiles

GE shared data for the stress levels within the blading from testing during loading as a mechanical drive unit. GE demonstrated that the stresses developed within the components were all within their standard design ranges.

Subsequent to the above, GE performed a study including a rapid stop of the LM6000 LP shaft. Based on this analysis, GE confirmed that the temperature and stress profiles within the LM6000 were within their standard design criteria for the individual components.

Aero Matching of Components during Shutdown and Startup

Aero matching of components during startup and shutdown was reviewed. The review was based on GE simulations that forced the LP rotor to stop in 4.4 seconds simulating the braking load from a centrifugal compressor. To accomplish this, GE imposed an external load on the engine in excess of the engine rating. GE utilized this increase in load and fast shutdown to demonstrate a worst case scenario for the engine’s ability to withstand a fast stop. A load of 59,580 kW was imposed on the gas turbine at the same instant the fuel valve was closed. The residual fuel in the manifolds continued to provide combustion for approximately 0.75 seconds after the fuel valve was closed. The load was then decreased to 23,012 kW over the next 4.4 seconds. The IGV’s (Inlet Guide Vanes) and VBV’s (Variable Bleed Valves) were stepped fully opened when the fuel valve was closed. The VSV’s (Variable Stator Vanes) modulate closed based on the speed of the HP spool. The HP spool decelerated very quickly through the first 4.4 seconds. At 4.4 seconds, the HP spool was at ~44% of its initial speed.

The simulation had the ability to predict stall within the axial compressor sections. Based on the above scenario, no stall events occurred within the machine. The simulation also evaluated the component stresses, and similar to stall, no components exceeded acceptable stress levels.

Figure 12 shows the ramp down rate for the Bechtel Simulation and the fastest deceleration achieved by GE using their simulation data without having stall within the gas turbine axial section or modifying their standard controls.
Based on the simulations performed by Bechtel and GE, there was sufficient margin within the machine to be able to accommodate a trip of the gas turbine from full load conditions without resulting in stall occurring within the axial compressor section of the gas turbine.

**Continuous Base Load Operation**

The mechanical drive applications in an LNG facility required that the gas turbine be run in a base loaded condition for extended periods of time. A review was made of engines operating under base load conditions. Figure 13 includes a subset of engines operating under base load conditions that were considered during this evaluation.

**Service factor for baseloaded units**

![Service factor for baseloaded units graph]

**Figure 13: LM6000 Base Loaded Units**

**LP Rotor Turning Gear Operation**

To perform off-line water washes of a mechanical drive LM6000, a turning gear needed to be provided for the LP rotor system. This turning gear system was designed based on previous experience with 50 Hz applications, industrial gas turbine experience, and previous experience with turning gear systems for large steam turbine driven systems.

For 50 Hz, LM6000 power generation applications, a turning gear is installed on the speed reduction gear box. For industrial gas turbines, the turning gear is installed on the auxiliary gear box. For the LM6000 mechanical drive application, the turning gear will be installed on the far end of the compressor train in line with GE experience on previous compressor trains. The actual turning gear components were developed from proven equipment supplied by Koenig.

The turning gear must overcome the large break-away torque, develop the required speed to operate above the lift-off speed for the dry gas seals, and at a speed sufficient to perform the off-line water wash. To perform this function, GE proposed a turning gear with two motors. One motor included an additional reduction gear to develop the required break-away torque. This motor rotates the LP shaft at approximately
10 rpm. A second motor will then be used to turn the rotor at approximately 300-350 rpm to allow an off-line water wash. This configuration was similar to designs previously used by GE on steam turbine applications.

**Mark VIe Control Logic**

The basis of the evaluation is the use of a dual redundant Mark VIe control system for the LM6000PF. There were differences in the IGV (inlet guide vane) and VBV (variable bleed valve) schedules between power generation and mechanical drive applications.

Further reviews were performed during the FEED phase of the project for the control system modifications, but no issues were identified that required further qualification.
The mechanical drive application requires that the gas turbine be capable of variable speed operation. GE has been working on mechanical drive applications for the LM6000 since 1992. GE has performed testing on the LM6000 at various times to demonstrate the variable speed capability of the engine from 50% to 105% of rated operating speed. Variable speed testing of the engine was performed as shown in Table 3.

<table>
<thead>
<tr>
<th>Test Date</th>
<th>Test Engine</th>
<th>Test Type</th>
<th>Time on Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>LM6000PA</td>
<td>Locked rotor testing to demonstrate break-away torque capability. This was the second engine to test (SETT) for the PA model.</td>
<td></td>
</tr>
<tr>
<td>Nov-Dec 1996</td>
<td>LM6000PD</td>
<td>Variable speed from 1800 to 3780 rpm.</td>
<td>70 hours</td>
</tr>
<tr>
<td>May-Jul 1997</td>
<td>LM6000PD</td>
<td>Variable speed from 1800 to 3780 rpm including no-load over-speed at 3960 rpm.</td>
<td>165 hours</td>
</tr>
<tr>
<td></td>
<td>LM6000PC</td>
<td>Multi-engine vibration signature validation and testing.</td>
<td>8 hours</td>
</tr>
<tr>
<td></td>
<td>LM6000PC</td>
<td>Multi-engine vibration signature validation and testing.</td>
<td>8 hours</td>
</tr>
<tr>
<td></td>
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<td>8 hours</td>
</tr>
<tr>
<td></td>
<td>LM6000PC</td>
<td>Multi-engine vibration signature validation and testing.</td>
<td>8 hours</td>
</tr>
<tr>
<td></td>
<td>LM6000PC</td>
<td>10,000,000 cycle endurance testing.</td>
<td>60 hours</td>
</tr>
<tr>
<td>Sept-Oct 2005</td>
<td>LM6000PC</td>
<td>Endurance test for ABS-SVR Certification. Testing from 800 to +3600 rpm.</td>
<td>168 hours</td>
</tr>
<tr>
<td>June 6-7, 2006</td>
<td>LM6000PC</td>
<td>Starting torque capability from 700 rpm to 3780 rpm. Demonstrated operation at 3400 to 3450 rpm.</td>
<td>18 hours</td>
</tr>
<tr>
<td>January 23-26, 2008</td>
<td>LM6000PF</td>
<td>Variable speed from 1500 rpm to 3780 rpm in the Evendale test cell using a variable speed generator.</td>
<td>12 hours</td>
</tr>
<tr>
<td>June 17, 2009</td>
<td>LM6000-PD</td>
<td>Locked rotor testing</td>
<td>4 hours</td>
</tr>
<tr>
<td></td>
<td>LM6000-PD</td>
<td>Low power/low speed testing</td>
<td>16 hours</td>
</tr>
<tr>
<td></td>
<td>LM6000-PD</td>
<td>No. 1 Bearing Load vs. Variable Speed/Power</td>
<td>24 hours</td>
</tr>
<tr>
<td>June 12 – 18, 2012</td>
<td>LM6000-PF</td>
<td>Variable Speed operation 950 – 3780 rpm</td>
<td>45 hours</td>
</tr>
<tr>
<td>July 30 – Aug 1, 2012</td>
<td>LM6000-PF</td>
<td>Low power / low speed optimization testing</td>
<td>20 hours</td>
</tr>
<tr>
<td>Total test time</td>
<td></td>
<td></td>
<td>&gt; 600 hours</td>
</tr>
</tbody>
</table>

Subsequent to placing the order for the Wheatstone Project, all 17 engines ordered (12 mechanical drive, 4 generator drive and 1 spare) have undergone variable speed testing as part of the contract with GE.

Starting Torque Capability
The starting capability of the engine is a combination of the break-away torque and the engine torque available across the speed from zero to 105% speed. To support the Wheatstone Project, GE performed a locked rotor test of the LM6000 engine in a PD configuration on June 17, 2009. This testing confirmed the break-away torque available from the engine.

Dynamic simulations to predict the starting torque requirements of the Methane compressor string were conducted during the FEED phase of the project. During the EPC phase, dynamic simulations were also conducted for the ethylene and propane compressor services. The methane compressor string was selected during FEED for the simulation because of the use of a gearbox and three compressor bodies. The results of the simulations and studies indicate that the LM6000 is capable of starting the compressor strings from full settle out conditions.

### Load Gear Selection

Based on experience, a Lufkin load gear was selected. A design review of the gear was held during the qualification phase, and analysis was performed to demonstrate the ability to manufacture the gear with a single piece design.

### Couplings

The load coupling proposed for the LM6000 mechanical drive will include a torque meter to aid in monitoring the performance of the gas turbine. The torque meter will add additional weight to the coupling half supported by the gas turbine and will impact lateral dynamics of the gas turbine. In addition, the torsional stiffness of the coupling will impact the overall train torsional. The final coupling selection included Ameridrive couplings following previous GE experience for aeroderivative applications.

### Train Torsional

A train torsional analysis was conducted for all compressor trains. The methane train is considered to be the most complex from a torsional perspective because it has three compressor bodies and a speed increasing gear. The analysis was conducted using experience available to GE from previous projects and was considered preliminary. During detailed engineering, the torsional analysis was finalized and fatigue analysis was completed to demonstrate that no issues would result in the compressor trains operating range.

### Train Alignment

The train alignment study was conducted to determine the amount of axial stretch required on the flexible element couplings. The study calculated the thermal growth of each piece of equipment as well as the growth of the coupling spool. The resulting deflections and pre-stretch were used to confirm the axial loading on the gas turbine.

### Axial Load Limitations

Selection of the coupling is critical for the hot-end drive configuration to ensure that allowable axial load limits are maintained. Based on the alignment study and the growth calculations, the axial loading on the gas turbine is acceptable and within their standard limits for the machine.

### Train Starting


The LM6000 does not utilize a free power turbine similar to the LM2500 or Frame 5D gas turbines. The power turbine section of the LM6000 is connected to the LP axial compressor of the engine. Based on this difference, it was important that the starting capability of the engine be fully analyzed. To address this, GE performed a locked rotor test of an LM6000PD, and Bechtel performed a dynamic simulation of the LM6000 compressor trains. In addition, testing was conducted on a LM6000PF to demonstrate the engine torque capability through the complete speed range (0% to 105%). The dynamic simulation was completed and included the starting torque requirements for a full pressure restart of the compressor train from settle-out pressure.

Based on all analysis and test data, the LM6000 will be capable of a full pressure restart of the compressor train.

**Fuel Composition**

The predicted Wheatstone fuel gas compositions have been reviewed with GE. The primary issue with the fuel compositions is the rate of change of modified Wobbe index (MWI) impacting the required controls (Wobbe meter and calorimeter) in addition to the configuration of the fuel system piping for the fuel supply to the engines. Detailed fuel gas simulations were performed during the EPC phase of the project to understand the rate of change and to properly design the configuration of the fuel system and the placement of the Wobbe meters and gas chromatographs. Additionally, the gas turbine controls utilize the Wobbe meter to actively control the combustion parameters and fuel flow splits of the engine based on the fuel gas composition.

**Compressor Selections**

Preliminary compressor selections were made by GE based on the average feed composition operating conditions to support the LM6000 TQP efforts.

The impellers proposed for the Wheatstone Project using the LM6000 as a mechanical driver fall within proven experience for GE for the Methane and Ethylene services. The T5.3 impellers used for the propane service were selected based on a separate technology qualification subsequent to the selection of the LM6000's as mechanical drives.

**General Arrangement**

Based on the project layout of the gas turbines and safety concern with having the compressors handling flammable gas located under inlet air ducting to the gas turbine, the basis of the qualification was a hot end drive configuration.

The major advantages of the hot end drive are:

- Gas turbine layout is similar to other gas turbine drives including the LM2500s
- The torque is not transmitted back through the entire low pressure rotor
- Lower vibration levels are observed when operating in the hot end drive configuration
- The inlet ducting is routed away from the process compressors

The hot end drive configuration was reviewed from an operability and maintainability perspective and an optimized package was designed for the Wheatstone Project. No issues were identified that impacted the technical feasibility of the LM6000 in a mechanical drive application.

**RISK MITIGATION ACTIVITIES**
A risk mitigation plan was developed for the LM6000PF mechanical drive and included as part of the purchase order with GE. The risk mitigations identified included not only the TQP identified items but lessons learned from other large gas turbine driven compressor strings. A summary of the major mitigation items are summarized as follows:

- **Design Reviews**
  - Vendor Meetings
    - Pre-award Meetings
    - Coordination Meeting
    - Design Review Meetings
    - 3D Model Reviews
    - FMEA Analysis
  - Project Meetings
    - HAZID
    - HAZOP/SoA
    - SID Review Meetings

- **Modeling and Simulations**
  1. Compressor Stage CFD
  2. Impeller FEA
  3. Compressor Stage Model Testing
  4. Lateral Dynamic and Stability Analysis
  5. Torsional Analysis
  6. Dynamic Simulations

- **Quality Control and Inspections**
  - Pre-inspection Meetings
  - Weld Procedure and Qualification Reviews
  - Verification of Materials
  - In-process Inspection of Manufacturing and Assembly Activities
  - Dimensional Checks and Visual Inspections
  - Loop Checks
  - Cleanliness Checks
  - Assembly Compliance Checks (per approved drawings)
  - Australian Standard Compliance Checks
  - Non-destructive Examination
  - Final Shop Inspections
  - Preservation and Shipping Inspection

- **Testing at Supplier Facilities**
  - Hydrostatic Testing
  - Impeller Overspeed Testing
  - Rotor Balancing
  - Mechanical Run Testing
  - Unbalanced Response Testing
  - Gas Turbine Performance Testing
- Compressor Performance Testing
- Assembly Leak Test
- FAT Testing
- Control Functional Testing
- Control Integration Testing
- FLFS String Testing

- Field Inspections and Testing
  - Receipt Review
  - P&ID Walk-down
  - Preservation Checks and Monitoring
  - Megger Tests
  - Equipment Level and Co-planar Checks
  - Alignment Checks
  - Loop Checks
  - Control Function Checks
  - Sub-System Testing
  - Gas Turbine Solo-run Testing
  - Nitrogen Run Testing
  - Performance Testing
  - Surge Testing

Of specific interest for the qualification, special gas turbine testing and full load string testing were specified.

**Gas Turbine Performance Testing**

All gas turbines shall undergo a full load performance test. The performance test is used to confirm the power produced meets or exceeds the predicted power at a heat rate equal to or less than the quoted heat rate (efficiency equals or is great than quoted). The gas turbine performance testing is the GE standard production testing and only tests the gas turbine engine.

All LM6000 engines (GTCs, GTGs and spares) for Wheatstone shall include full power testing at 3060, 3450, 3600 and 3780 rpm. In addition to the emissions testing taken at full load, emissions testing will be performed at 50% and 72% load at 3600 rpm.

**Full Load Full Speed String (FLFS) Testing**

The FLFS testing was required to validate the performance of the LM6000 PF driven compressor trains and to mitigate operational and schedule risks with the use of LM6000 PFs as mechanical drivers. Based on the qualification, it was determined that full load string testing shall be performed to confirm the following items:

- Confirmation of train starting from settle-out conditions
- Confirmation of train torsional dynamics
- Confirmation of compressor stability. Excitation of frequencies with a magnetic bearing and calculating log decrement values is required for the HP Methane Compressor Casing. For all other compressors, the stability will be demonstrated by meeting the API-617 test criteria for sub-synchronous vibration levels.
• Confirmation of LM6000PF thrust bearing loading

In addition to meeting the requirements from the TQP, the following items are confirmed during execution of the string testing:

• Operation of the evaporative cooler system and resulting inlet losses
• Check-out of complete control system including Mark VIe and B/N System 1
• Compressor thermal and aero performance under full load conditions
• Demonstration of gas turbine stability through rapid changes in gas composition. Nitrogen will be added to the fuel gas to control the MWI. The tested range of fuel MWI shall cover the entire range specified in the fuel gas datasheets.

The FLFS test proposed shall be full load, hydrocarbon gas test designed to match the volume reduction ratio of the individual compressors. This test shall use a gas blend agreed that can simulate compressor performance at full load.

Because the volume reduction ratios are matched across the stages, mechanical behavior is almost identical to field operation. This results in similar aerodynamic forces at full load and therefore similar rotordynamic behavior.

Testing at full load allows for fully loading of the entire train including the LM6000PF and all the drive couplings. Full load testing also allows for demonstrating the startup and trip behavior of the train at the suppliers facility.

Strain gages shall be installed on the couplings to monitor the torsional performance of the compressor train and confirm the results of the train torsional analysis.
ACKNOWLEDGEMENT

The authors would like to thank GE Power & Water and GE Oil &Gas for the support provided during the qualification of the LM6000’s for mechanical drive applications. GE’s support has been instrumental in the application of the engines for the Wheatstone LNG Project.