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Operational experience with LM6000 PF aero-derivative gas turbine in mechanical drive service at Wheatstone LNG Facility

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Chevron Australia, as part of the Wheatstone Project, operates a two-train liquefied natural gas (LNG) facility and domestic gas plant at the Ashburton North Strategic Industrial Area, 12 kilometers west of Onslow on the Pilbara coast of Western Australia.

Both trains of the Wheatstone LNG facility have been successfully operating utilizing the first installation of LM6000PF gas turbines for mechanical drive service. This paper shares the learnings from the ten-year journey including alternative analysis, technology qualification activities, design development, testing, risk mitigation, development of operational capability, dry low emissions (DLE) mapping, startup and early operation of the gas turbines for LNG production.

The learnings developed over this period include recommendations on the application of new technology, implementation of the technology qualification plan and operation of low NOx combustion systems with variable fuel composition.

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Introduction

Chevron Australia, as part of the Wheatstone Project, developed 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 two-train facility has an annual average design capacity is 8.9 million tonnes per annum (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 to establish the LNG train process configuration. This driver study resulted in the selection of a General Electric (GE) LM6000PF aero-derivative gas turbines[1] for driving the refrigeration compressors in the LNG train. This was the first installation of the LM6000PF gas turbines for mechanical drive application in the industry. For reducing the uncertainty associated with the application of this new technology to LNG trains, a technology qualification was undertaken by Chevron's project team supported by the Vendor, Licensor and the Contractor [1]. A risk mitigation plan was developed and executed for the LM6000PF mechanical drive application and included as part of the purchase order with GE. The risk mitigations included not only the items identified in the technology qualification but also lessons learned from other large gas turbine driven compressor strings. As part of the risk mitigation, all LM6000PF gas turbines were scheduled to undergo a full load performance test. Subsequently, successful completion of full load - full speed testing of the LM6000PF is documented in Patwardhan et al [2]. This testing concluded the technology qualification phase of the project, but risk mitigation was continued throughout construction, commissioning and early operation.

This paper covers the initial startup and early operation of the LNG train refrigeration gas compressor drivers with a goal of highlighting lessons learned through the application of the first LM6000PFs gas turbines in mechanical drive service. The paper will focus on decisions made during the early phases of the project and actual results of operation of the gas turbines.

Dry Low Emissions (DLE) Operation

Operation with a wide range of fuel composition and high rates of change were considered one of the highest risks with using LM6000PF gas turbines in mechanical drive service for the Wheatstone facility. The high firing temperatures and short residence times of an aero-derivative gas turbine require active controls to maintain a stable lean flame for combustion. The nitrogen content of the fuel gas varied from 6 to 15 mol% depending on the source of fuel gas and mode of operation. Based on simulations, the anticipated rate of change in fuel quality was 7 % change in Modified Wobbe Index (MWI)/min. The design specification was written for 10 % change in MWI/min and the string testing was performed up to 20% change in MWI/min.

The layout of the facility has six gas turbines per LNG train and all six units are fed from a common fuel system. The fuel system incorporates two Modified Wobbe Index Analyzers and two Gas Chromatographs. The location of these instruments was selected far enough upstream that even with all six gas turbines operating at maximum power, the data from the MWI Analyzer would be available before the gas molecules entered the gas turbine combustor. This design allows for the fuel system controls to adjust the split between fuel nozzles and actively control the combustor based on the instantaneous heating value of the fuel. For this system to function at reduced fuel flow rates (reduced power, reduced number of machines) the controls include a calculation for a time delay based on the fuel flow to each individual gas turbine. All active control is performed with the MWI Analyzer while the nitrogen content is updated based on the Gas Chromatograph measurements. This allows for fast response of the combustor based on the heating value and allowing for a slower time for updates on the nitrogen concentration.

Field experience has shown this system to function and allow significantly faster than 20 %MWI/min rate of change without DLE stage down events or combustor upsets. Tuning of the system was possible in the field because the high pressure (HP) rotor speed reacts very quickly to differences between the actual fuel heating value and the parameters used for calculations. This allowed for identification of field piping volumes that didn't match the volumes used in the control calculations and further refined the performance of the control system.

Operational upsets did allow for significantly higher than 7 % MWI/min rate of change, however the control system was able to handle the fuel upsets without impacting operation of the gas turbines. Only review of high speed data after the event indicated the magnitude of the rates of change that were handled by the gas turbines. Figure 1 shows the fuel MWI and rate of change during one of the upset conditions.

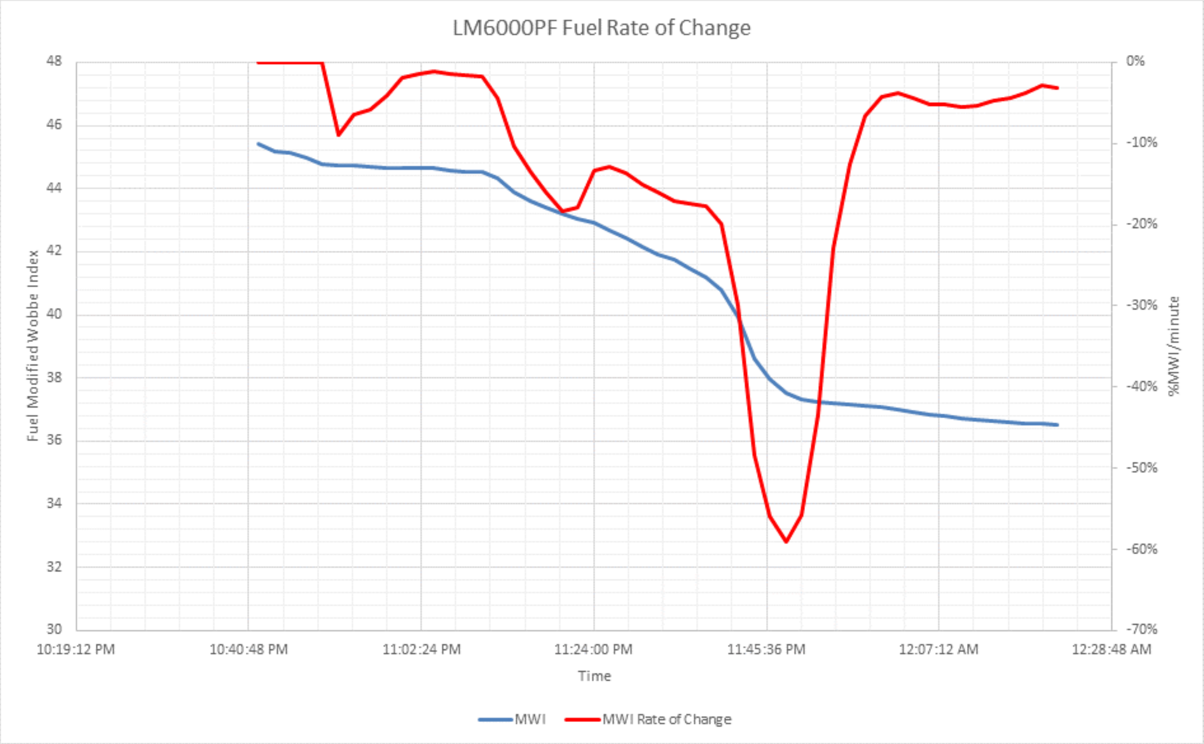


Figure 1- MWI Rate of Change Capability

This figure indicates the capability of the fuel system to handle large variations in fuel without impacting the performance of the gas turbines. The maximum rate of change observed for this incident is almost an order of magnitude higher than the normal fuel transients seen at the facility.

The ability to handle these fuel swings is the direct result of both the fuel control system and the DLE Mapping. Significant effort was put into DLE mapping during commissioning and early operation of the LNG train. One of the three refrigerant compressor services were operated on both LNG trains on nitrogen prior to starting up the facility. This gave more flexibility for DLE mapping across the lower speed ranges and allowed for multiple starts to ensure proper DLE staging under high power starts. Running on nitrogen was limited to lower speeds because of the high discharge temperatures from the low-pressure process compressor. For this reason, DLE mapping was integrated in the startup schedule to allow for complete mapping though out the power and speed ranges. DLE mapping allows for the split between rings of combustor nozzles to be correctly set and ensure good margin between combustor acoustics and lean blow-out conditions. The LM6000PF engine proved to allow for significantly larger operational windows than previous DLE combustors. This supported the original decision to adopt the PF variant of the LM6000 engine for improved combustion.

Mapping of the engine provides as wide of an operating range as possible to allow the gas turbine to run through items like fuel transients without experiencing either high acoustics or lean-blow out. The larger the available window, the farther off the controls can be without impacting stable combustion. DLE mapping with large overlap of burner modes and large stage windows was the goal for the Wheatstone gas turbine mapping. Site specific mapping procedures have been developed and continue to be updated as opportunities to improve the consistency in mapping between engine are identified.

While mapping will always remain a critical part of Wheatstone operations, the use of turbine inlet temperature dependent mapping tables and evaporative cooling have simplified the mapping of the gas turbines. The evaporative cooling minimizes the range of temperature changes at the inlet of the gas turbine. The remaining variation in temperature can be accommodated with the temperature dependent mapping tables. These factors are removing the need to seasonally map the gas turbines.

High Ambient Operation

The variation in ambient conditions for air-cooled LNG facilities is a significant challenge when balancing the power available from a gas turbine and the power required for a propane compressor. The discharge pressure of the propane compressor floats on condensing pressure which is directly related to the ambient temperature. A summary of the design ambient temperatures and relative humidity at the Wheatstone facility are included in Table 1.

Table 1 – Design Ambient Conditions

% Exceedance	0.05%	1%	5%	50%	95%
Case	Extreme-High	High-High	High	Average	Low
Temperature (ºC)	46.0	39.6	35.1	25.3	15.2
Relative Humidity (%)	15.0	31.6	58.1	81.8	92.1

The variation in ambient conditions and resultant changes in available power from the LM6000 PF gas turbine was recognized and discussed by Shah et al [1]. This was a significant reason for selecting the evaporative cooling at the inlet of the gas turbine and reducing the power lapse rate of the LM6000PF. In addition, technology qualifications were conducted to select new impellers for the refrigerant compressor that allowed for a wider operational range to allow reducing the flow rate further prior to reaching surge.

All testing of the compressor sections met the expected impeller performance and the increased operating range was achievable. However, in practice, factors such as noise in flow signals and system dynamics related to the volumes of the compression loop and the relatively flat compressor curves required the surge control lines to be further to the right than originally anticipated during design. This results in the need for additional power during extreme high ambient conditions to avoid bogging down the gas turbine. Operations has been able to manage the extreme high ambient conditions by being more proactive on reducing production and balancing the loads between the three refrigeration circuits of the ConocoPhillips Optimized Cascade process.

In addition, Wheatstone has upgraded the propane and ethylene services to LM6000PF+ to provide more operational flexibility during the high ambient conditions. At the time of this writing, Train 2 is successfully operating with the LM6000PF+ engines installed. Operating the PF+ engines at part power is expected to increase operational flexibility and increase the maintenance intervals for the engines since they will be fired at a lower temperature than design.

Variable Speed Operation

The use of the LM6000PF gas turbine in mechanical drive service resulted in the first industrial application of the engine as a true variable speed machine. Most of the design development for the package were directly related to the variable speed application and the ability to start a loaded compressor instead of only overcoming the inertia of a generator. To accomplish the starting sequence, sump pressurization and sump evacuation systems were included in the design of the package.

The sump evacuation system incorporates the addition of a blower on the mist eliminator system to ensure negative pressures within the bearing sumps. This system only operates during starting of the gas turbine and is turned off by the time the unit reaches minimum operating speed of 3060 rpm.

The sump pressurization system includes a blower and a back-up connection from the instrument air system. This system ensures bearing sump seals are properly pressurized until the gas turbine speed is approximately 3200 rpm. The use of the sump pressurization system allows for utilization of the full available engine torque throughout the entire operating speed range of the gas turbine. Based on learnings from site, the blower could be deleted on future packages and only rely on the instrument air connection. This would simplify the package. The instrument air system needs to be suitably sized to accommodate the air usage.

Under normal operation, both systems are off and the engine functions like generator drive applications. Other than minor controls tuning for the starting and stopping of the blower, no issues were found with these systems during the commissioning and operational phase of the project.

The LM6000PF engine has demonstrated its ability to start compressor strings without the assistance of turning gears or starter motors. This is a result of the ability to start the high pressure (HP) rotor and provide torque to the low pressure (LP) rotor. Figure 2 shows two typical compressor starts relative to the LM6000PF gas turbine capability.

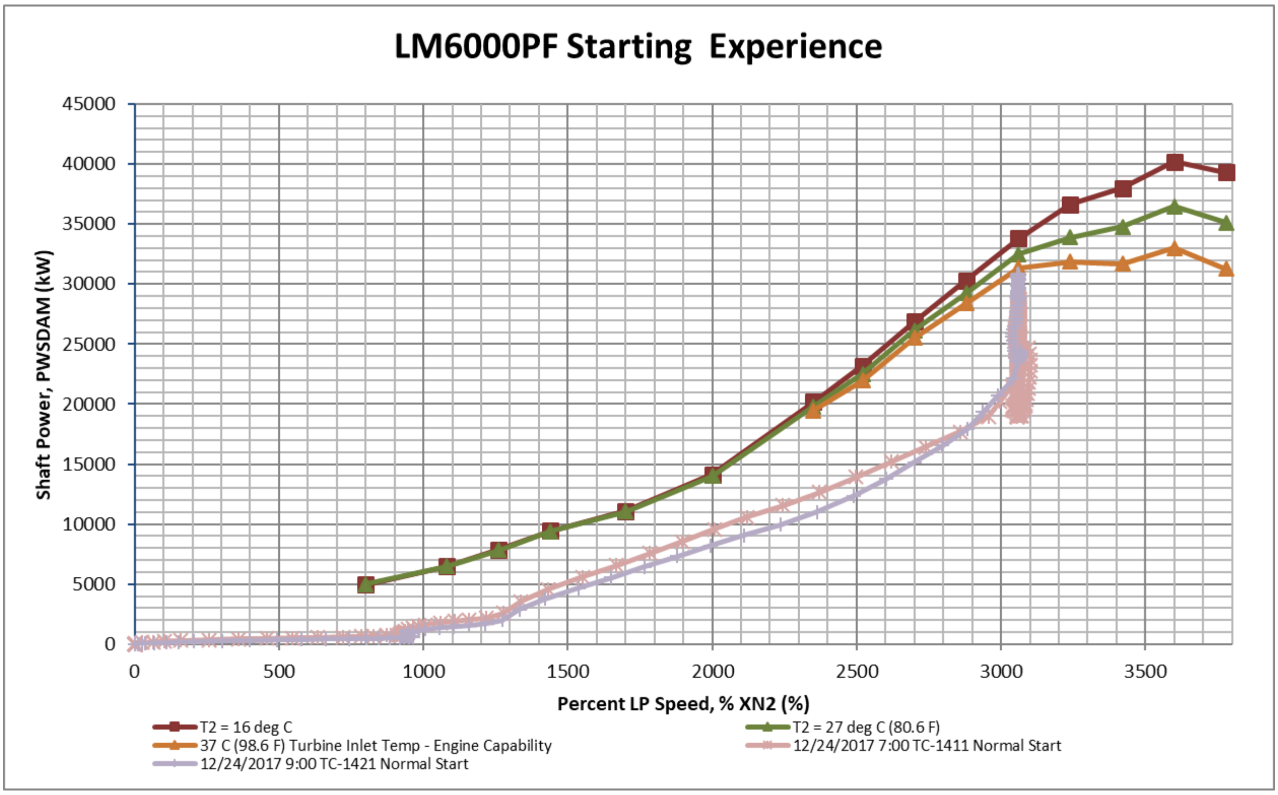


Figure 2- Starting Capability

For process duty, normal operating speeds range from 3350 to 3780 rpm. Maximum operating range includes down to the minimum operating speed of 3060 rpm. The Wheatstone LM6000PF packages have demonstrated their ability to start centrifugal compressor strings and operate in a variable speed application.

Controls and Control Systems

The control system was recognized as a technology step-out during the initial qualification phase. The control system that was specified had been used with aero-derivative gas turbines by other packagers and by the packager for the Wheatstone project for industrial gas turbines. While the step-out was recognized, the level of attention required during the commissioning phase was underestimated.

In general, all complex equipment control systems should be specified with negative testing of the control systems. The focus is to understand the behavior of the system when not all permissives are present or when the sequence is interrupted. During commissioning minor controls errors or inconsistencies required addressing. The gas turbine supplier worked closely with the site teams to rectify the issues.

The controls issues covered a range of topics, key items include the following:

1. Incorporation of 1st out logic for trouble-shooting.
2. Logic definition for managing items like lock-out following an emergency shut-down sequence.
3. Proper filtering of input signals to avoid noise and control oscillations.
4. Use of limit switches for permissive that can give spurious signals based on component vibration.
5. Use of daisy-chained signals on door limit switches and motor starter cubicles preventing trouble-shooting of individual components.

The controls issues required diligence to ensure all items were fully corrected and then implemented across the 16 gas turbine packages at site. While none were individually significant, they represented the type of issues that arise on a new controls application that justifies an increased level of review and testing throughout the project phases.

Planned Maintenance

As discussed by Shah et al [1], the LM6000PF is an on-condition engine meaning that maintenance is based on the condition of the gas turbine and not strictly a time-based activity. During the engineering phase of the project assumptions were made regarding the maintenance requirements.

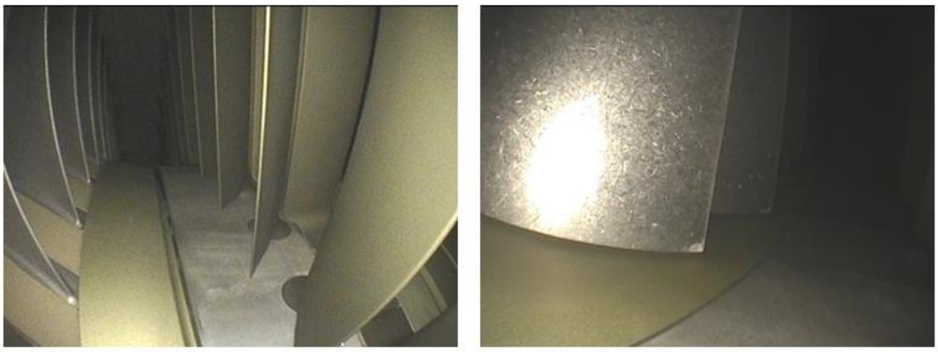
Based on industry experience, the 30:1 compression ratio of the LM6000PF makes the impact of compressor fouling more pronounced. For this reason, three items were considered to minimize the risk for the Wheatstone Project.

1. F9 pulse pre-filters combined with E10 HEPA filters were specified.
2. Automated daily on-line water washing system was designed and installed.
3. Off-line water wash was included in the project economics every 2000 hours (4 times per year).

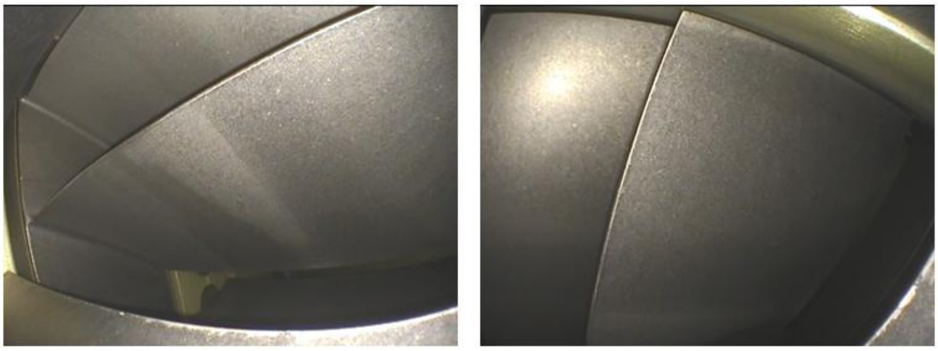
During initial startup of the facility, the demineralized water system was not initially available. For this reason, neither the on-line or off-line water wash system were commissioned.

The Train 1 units have run at full load conditions for over a year and have showed no degradation in either axial compressor or overall gas turbine performance. This is attributed to the filtration system employed since the engines have not yet been on-line or off-line water washed.

Figures 3 through 5 show sample borescope photos from the 8000-hour inspection of the gas turbine. These photos are without any water washing and show the cleanliness downstream of the filtration system.

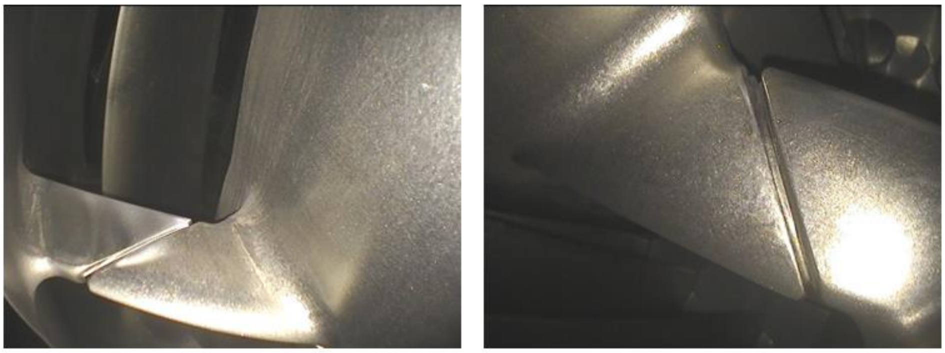


VIGV & Stage 0 Blades

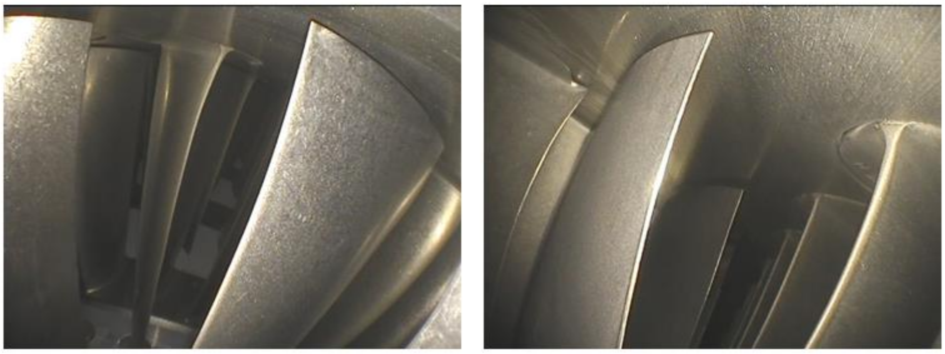


Stage 1 Blades

Figure 3- LP Compressor Sample Borescope Photos

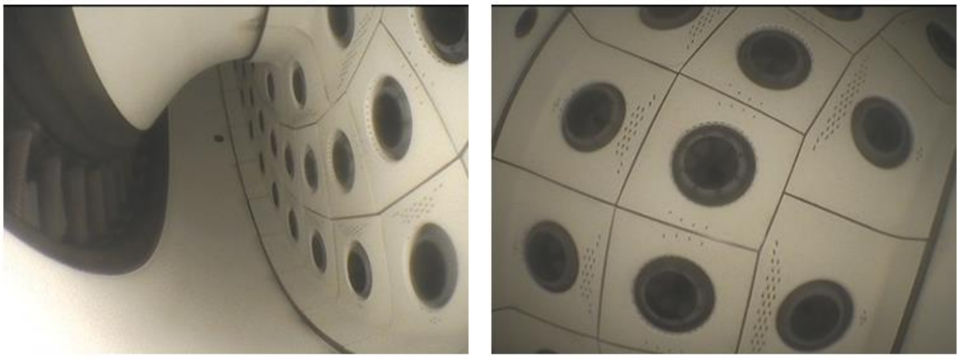


Stage 1 Blade Midspans

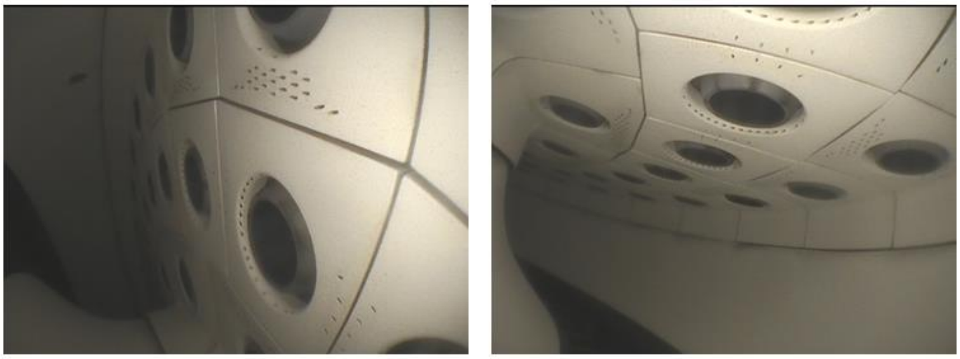


Stage 2 Blades

Figure 4- HP Compressor Sample Borescope Photos



Combustor Heat Shields



Combustor Heat Shields

Figure 5- Combustor Borescope Sample Photos

Another factor assisting with cleanliness of the gas turbines is potentially the evaporative cooling system. It is anticipated that the evaporative cooling system is assisting with removing any salts that can pass through the filters on humid days.

Dust storms occur regularly in North-west Australia and these are evident from the pulse cycling seen for the F9 pulse filters. During the first year of operation, the permanent DP across the filters has been low and none of the filter elements have required replacement.

As a test, three of the gas turbine strings on Train 2 are running E12 HEPA filters instead of the E10 HEPA filters. Based on the performance of the E10 HEPA filters currently installed, it is targeted to make it 3 years without water washing.

Beyond the planned water wash schedule, the original Wheatstone maintenance strategy included the following activities.

1. 4000-hour borescope inspection (BI).
2. 25000-hour hot gas path inspection (HGPI).
3. 50000-hour major inspection (MI).

Based on the experience gained from other sites with base loaded LM6000PF units, Wheatstone has extended the 4000-hour BI to an 8000-hour BI. The photos shown previously (in Figures 3, 4 and 5) are from the 8000-hour inspection and no 4000-hour inspection was performed.

It was recognized early that much of the reason to shut-down and borescope is related to the package inspections and remaining items that require replacement or repair.

The DLE bleed valves (Stage 8 and Compressor Discharge Pressure (CDP)) have had reliability issues. Based on Service Bulletins issued by the gas turbine manufacturer there were two options to improve reliability. The first was an overhaul for the existing valves and the second was a new manufacturer with an improved valve design. The improvements are related to the valve bearings and seals. Wheatstone had all existing valves upgraded prior to commissioning and purchased the spare valves from the alternative manufacturer. To trial the valves, the facility has installed both. At time of this writing, Wheatstone has experience no failures with the DLE bleed valves from either the overhauled valves or the new manufacturer. It should be noted that while the mechanical drive units operate at maximum load with less actuation of the bleed valves, the power generation units operate at part load and see significant number of bleed valve cycles.

As part of the original qualification work, reliability targets were decreased to account for the application of new technology. This was incorporated in the original reliability analysis for the project. Based on proactively addressing items such as the bleed valves, there have been no issues impacting reliability associated with the selection of the LM6000PF engine versus other potential engine options.

To support the maintenance activities and ensure that Wheatstone LNG facility operates with high reliability, a significant amount of effort has been aimed at increasing our operational capability with regards to the LM6000PF and DLE systems. Based on working with other users, a Gas Turbine Team was structured that includes maintenance and control systems specialists. In addition, there was a focus on control system specialists that have DLE mapping experience.

The benefits in this operational capability focus can been seen in the planning and tooling that has been designed and purchased for the Wheatstone facility in addition to the positive experience with DLE mapping at the site. The operations capability of the Operations team coupled with the experience from the equipment manufacturer has allowed for decisions to be made that improve the availability of the facility while understanding the constraints for the equipment.

Conclusion

The use of an LM6000 gas turbine in a mechanical drive application has been successfully demonstrated at the Wheatstone LNG facility. This technology has met and exceeded the expectations from the original qualification phase.

The qualification attempted to address novelties in the design as well as address lessons from LM6000 power generation applications. Two categories of risks were developed; technology qualification and lessons learned. During the execution of this project, both were found to be equally important. Lessons associated with DLE mapping and bleed valves greatly assisted the Wheatstone project. Both areas would have been considered “proven” from a technology qualification perspective since they don’t constitute new technology.

While the high risk items such as large variations in fuel and the first application of variable speed were technically challenging, they have been successfully demonstrated for the Wheatstone project.

The application of new complex technology that is integrated in a complex process requires close collaboration between the equipment manufacturer, liquefaction technology licensor, engineering and construction contractor and the operator. All parties must work closely to ensure that the units will operate as anticipated. The first of a kind application of LM6000PF for mechanical drive service on Wheatstone LNG trains was a success ultimately because of the close collaboration between all parties involved.

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