TECHNICAL VALIDATION AND SELECTION OF THE SIEMENS INDUSTRIAL TRENT 60 DLE FOR COMPRESSOR DRIVE SERVICE FOR THE LAKE CHARLES LIQUEFACTION PROJECT

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ABSTRACT

This paper outlines the methodology used and presents the results obtained by BG Group and Siemens in the validation and selection of the Industrial Trent 60 DLE aeroderivative gas turbine for the main refrigeration compressor driver service at BG Group’s planned Lake Charles export project in the US.

Engine validation workshops were held with Siemens engineers to review key technical issues and to review lessons learned. Feedback from Industrial Trent 60 end users provided valuable data for further improvements to equipment online availability.

Once the Industrial Trent 60 DLE engine was validated for use in mechanical drive service, a driver selection study was performed on the Lake Charles Liquefaction Plant (LCLP). The result of the driver selection study was that the project selected the Siemens Industrial Trent 60 DLE engine, making it the world’s largest mechanical drive aeroderivative gas turbine to be used in an LNG liquefaction facility.

A Technical Assurance Plan was then conducted to ensure optimal engine performance and online availability. The Technical Assurance Plan investigated the Industrial Trent 60 DLE engine suitability for the specific project operating conditions.

After close collaboration between Siemens and BG, the Technical Assurance Plan results confirmed that the Industrial Trent 60 is suitable for operation in a refrigeration compressor driver application for a mega-LNG liquefaction facility.

AUTHORS NOTE

The paper was written soon after Rolls-Royce Energy was acquired by Siemens AG. As such it was written around activities for qualification that occurred in conjunction with Rolls-Royce at that time, as well as for plans for future work with Siemens. The authors have tried to be respectful of the fact that the Industrial Trent 60 would be supplied by Siemens Aero Derivative Gas Turbine.
INTRODUCTION

GENERAL

The LNG Industry has traditionally been very conservative in the design phase of a liquefaction facility, particularly with regards to the introduction of new technology or new suppliers for a particular service. The introduction of a new supplier requires a thorough understanding of the risks and benefits associated with utilizing the supplier’s equipment and the development of risk mitigation contingency plans.

The majority of the first baseload LNG plants utilized steam turbine drivers, but since ~1980 industrial gas turbines became the primary industry standard for the main refrigeration compressor drivers. Recently, the trend has shifted ([1] Wehrman et al) to include aeroderivative gas turbines in order to take advantage of their relatively higher thermal efficiencies, as shown in Table 1.

<table>
<thead>
<tr>
<th>Gas Turbine Engine Model</th>
<th>Heat Rate (kJ/kWh)</th>
<th>Thermal Efficiency (%)</th>
<th>Continuous Output at ISO Conditions (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial Gas Turbines</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GE MS5002D</td>
<td>11,900</td>
<td>30.3%</td>
<td>32,600 kW</td>
</tr>
<tr>
<td>GE MS6001B</td>
<td>11,517</td>
<td>31.3%</td>
<td>43,963 kW</td>
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<tr>
<td>GE MS7001EA</td>
<td>10,730</td>
<td>33.5%</td>
<td>90,500 kW</td>
</tr>
<tr>
<td>Aeroderivative derivative Gas Turbines</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GE PGT25+G4 DLE</td>
<td>8782</td>
<td>41%</td>
<td>33,679 kW</td>
</tr>
<tr>
<td>RB211-GT61 DLE</td>
<td>8940</td>
<td>40.3%</td>
<td>32,782 kW</td>
</tr>
<tr>
<td>GE LM6000 PF</td>
<td>8468</td>
<td>42.5%</td>
<td>43,854 kW</td>
</tr>
<tr>
<td>Trent 60 DLE</td>
<td>8260</td>
<td>43.5%</td>
<td>54,263 kW</td>
</tr>
</tbody>
</table>

Table 1. Industrial and Aeroderivative Characteristics. [2] Diesel, 2014

Meher-Homji et al. [3] describes in detail the NPV benefits of using high efficiency aeroderivative gas turbines in LNG liquefaction facilities. The higher efficiencies of aeroderivative gas turbines contribute to a significant reduction of liquefaction plant fuel consumption, which translates into more LNG production over the life of a finite gas supply/field. The higher aeroderivative thermal efficiencies also provide lower CO2, CO and NOx emissions tonnage per year (tpy) due to the decrease in fuel gas consumption. This enables the facility owner to reduce the environmental impact as well as any taxes on emissions.

In addition to the fiscal advantages, aeroderivative gas turbines offer technical advantages to operators. Some advantages can include wider operating speed ranges, capability to start at full settle-out pressure, less time required to startup, and better equipment online availability due to shorter maintenance outage durations. A detailed review of aeroderivative gas turbine characteristics can be found in Meher-Homji, et al (2008).

As BG’s corporate policies increasingly focus more on “green” operations to minimize any adverse effects of facility operation on the environment, the selection of aeroderivative gas turbines has become a key component in achieving this goal.

OVERVIEW OF THE INDUSTRIAL TRENT 60

The Industrial Trent 60 gas turbine, based on the Aero Trent 800 (Boeing 777) has been in service since 1997 and currently has >750,000 hours in power generation and >370,000 hours over 12 units in mechanical drive duty (3 more in commissioning). The gas turbine is available with aero based standard combustion system (up to 66MW), and DLE (55.0MW Dry). The DLE system proposed for the project is the standard two-stage, torch-less system that needs just two fuel metering valves supplying the primary and secondary fuel circuits on each engine. Mapping is completed once every three years for emissions as the system is of a low noise design. This means less shutdowns required per year, with full annual maintenance possible in just 48 hours. The engine change out every 25,000-30,000 hours is also able to be completed in 48 hours. The engine has three independently rotating shafts (LP, IP and HP); as such the starting capability (full train start on just 350kw) and torque capability (startup from settle out pressure without the need for additional helper motors) are significant product attributes, saving in additional power generation demand, equipment count and capital expenditure. Continued investment in the engine and package is seeing the development progress with marine / offshore versions now developed.

Figure 1. Industrial Trent 60 DLE Engine and Package
PROJECT BACKGROUND

In an LNG liquefaction facility, the main refrigeration compressor packages are arguably the most critical pieces of rotating equipment in the facility. The LCLP selected APCI as the LNG technology licensor, and subsequently selected the Propane (C3) / Mixed Refrigerant (MR) process for liquefaction. LCLP consists of 3 x 5 MTPA process trains, each of which is configured for 2 x 50% C3 refrigeration strings and 2 x 50% MR refrigeration strings. Figures 2 and 3 show each compressor string arrangement, C3 and MR respectively.

Figure 2. C3 String Configuration

The C3 string, which is decoupled from the MR string (i.e. not split MR configuration) consists of four pressure levels of propane, compressed in a single compressor casing that is direct driven at 3400 rpm by a Siemens Industrial Trent 60 DLE engine. The C3 gas turbines have both Waste Heat Recovery Units (WHRU’s) and Selective Catalytic Reduction (SCR) Units installed in the exhaust stacks to limit NOx and CO emissions as much as reasonably possible.

Figure 3. MR String Configuration

The MR String is a two compressor body configuration, also direct driven at 3400 rpm by an Industrial Trent 60 DLE engine. The MR gas turbines utilize inlet air chilling to cool inlet air to 460°F (80°C) so that seasonal production remains steady and enables a more efficient use of the LNG shipping fleet into and out of the Lake Charles region. The MR gas turbines have SCR’s installed in the exhaust stacks.

ENGINE VALIDATION PROCESS FOR MECHANICAL DRIVE SERVICES

CORE GAS TURBINE DESIGN WORKSHOP

Before serious evaluation and comparison with other options, any gas turbine needs to be validated for that service. This is especially important in LNG liquefaction duty, where sparing is not possible and production and reliability are very important.

To qualify a product for a given application or project, Siemens believes that the end user should have direct access to the Chief Engineers and Subject Matter Experts to ensure that ample opportunity for questions and dialogue exists. This not only facilitates an early understanding of both customer needs and product capability, but also allows for early identification of any technical hazards / limitations that may be present.

Coordinating this process and event is the Product Manager for the gas turbine being qualified, whose role is to ensure that all areas of interest are identified prior to the qualification session. This allows the experts to focus on relevant areas and maximize the value of the meetings.

Siemens has found that these sessions have a tremendous value, with customers having a greater understanding of the product and hence, better able relate it to the process in question.

The initial qualification activity focused strictly on the technical capabilities of the Industrial Trent 60 gas turbine engine, with no particular project specifics considered. With this premise, a two day qualification session was held to cover the benefits and capability of an individual engine and (not a combined plant).

The first session was held between Siemens and BG Group on May 14/15, 2012 in Montreal, Canada. Subjects covered in detail were:

- Industrial Trent 60 Product Overview:
  - Aeroderivative Pedigree – how an Industrial Trent 60 is derived from an Aero Trent 800 engine.
  - Industrial Product Portfolio – Dry Low Emissions and Wet Low Emissions,
  - Installed Base & Operational Experience in Power Generation (500k hours) and Mechanical Drive (300k Hours)
• Industrial Trent Performance Ratings & Operability
  • Performance, Emissions and Heat Rate (efficiency) ratings
  • Starting and Torque capability
  • Transient performance
  • Fuel Transfer (G-L, L-G) on WLE
• Availability & Reliability
  • Contributors to un-reliability with relevance on today’s packages, designed solutions.
• Industrial Trent 60 DLE
  • Validation
  • Progression of the design
  • High Inert fuel capability
• Marinization of the Gas Turbine
  • Considerations for materials and coatings for coastal and offshore use.
• Facility Tour - Engine build and test

PACKAGING WORKSHOP

Industrial Trent 60 gas turbines are built and tested in Montréal, thus the first qualification session was biased towards the engine. The packages however are built in Mount Vernon, Ohio and so a second session was conducted to cover the supplementary systems such as fuel and fuel conditioning, synthetic oil skid, base plate, noise enclosure, ventilation, inlet air filtration, water wash and F&G, with emphasis on accessibility / maintainability. This session between BG Group and Siemens Experts was held on July 26/27, 2012. Specific issues discussed included:

• Tour of the Controls Flow Line
  • View of Controls Systems being built and tested via simulator
• Tour of the Industrial Trent / Industrial RB211 Packaging Flow Line
• BG Group Standards
  • DOORS – Automatic specification alignment between BG Group & Rolls-Royce
  • Working practices
  • Comments to BG Group engineering standards
• Controls
  • Introduction to hardware and software
  • Inputs and outputs available to customers
  • Flexibility of engine trips or trip to idle based on plant requirements
  • Factory Acceptance Testing of Controls.
• Industrial Trent 60 Package Review
  • Marinization of the package – Materials
  • Baseplate – 3-Point Mount and Compressor & GT Base mating joint
  • Inlet Filtration, on line lube oil filter switching and reservoir top-off
  • Water Mist F&G system

END USER SITE WORKSHOP

A site workshop was conducted for an Industrial Trent 60 DLE mechanical drive end user in the Middle East. The end user’s configuration was N+1 in the summer time and N+2 in the winter, thus the operating mode and the maintenance philosophies were different than would be expected in a LNG liquefaction plant. However, there were valuable lessons learned about packaging issues and Siemens’s strong field support capabilities.

Key among the issues discussed was the closely intertwined working relationship between Siemens and the end user during commissioning/startup, plant operations and resolution of DLE combustor issues.

Some of the packaging issues brought to our attention during the workshop were site specific, while others were considered to be “fleet-wide” issues. Learning details of the end user packaging issues enabled BG and Siemens to focus on the root cause of the problems and develop a time frame for resolution of the issues prior to initiating a new capital project with an Industrial Trent 60 DLE engine.

This end user has since procured three more identical Trent 60 DLE packages for their facility. BG/Siemens attended their site performance test of the Industrial Trent 60’s in the first half of 2015 to witness the test and gather more lessons learned during engineering, testing, installation, commissioning and startup activities.

WARWICK RM&D WORKSHOP

A workshop was held at Siemens’ Warwick site in the UK to discuss Siemens’ aftermarket support capabilities. Siemens explained the customer response protocol system in place with designated Levels as follows:

Level I, Regional Office (either onsite or in country/region). Level one is typically the front line, immediate response center

Level IIA, Operational Support Desk (OSD) in Service Management Centers (Warwick only for now). The OSD addresses mainly quick response issues that need immediate attention

Level IIB, Engineering for Service (E for S) group in Service Management Centers. The E for S group typically covers issues that are not immediate, but rather require or can tolerate a longer term resolution

Level III, Engineering Group in either Montréal or Mount Vernon, Ohio. The Engineering Group addresses and resolves long-term, fleet-wide engineering issues.

Siemens utilizes its experience from all Siemens business sectors (Airline, Defense and Marine) to interactively remote diagnose equipment issues in the field via their OSYS Predictive Equipment technology. This equipment health monitoring includes automatic data processing, continuous trending and benchmarking results against the Siemens fleet.
Siemens shared some of their future plans for improved engine diagnostics for the Industrial Trent 60 that should benefit operators by helping them to make more informed decisions about shutdowns, crank washes and overhauls. Siemens also presented some case studies that demonstrated the capabilities of their Equipment Health Monitoring (EHM) system. The Warwick RM&D workshop assured BG that Siemens could provide strong technical aftermarket support for their engines.

The Workshops for the Core Engine Design, Packaging Design, End User feedback and the Warwick RM&D all contributed significantly to BG validating the Industrial Trent 60 DLE engine for mechanical drive services on future BG capital projects, including LNG liquefaction facilities.

**SELECTION OF THE INDUSTRIAL TREN'T 60 DLE ENGINE**

Once technically qualified, the Industrial Trent 60 could be included in a detailed driver selection study on a project. At the beginning of the LCLP FEED, a driver selection study, based on life cycle costs for an assumed facility life of 25 years, was conducted to select the most advantageous gas turbine driver for the main refrigeration compressors. Only simple cycle gas turbine driver configurations were considered (no combined cycle drives configurations were included in the evaluation due to limited plot space for the LCLP and BG preference to avoid the high maintenance and operational requirements of a steam plant in an LNG facility). The following were the main criteria used during the selection process:

- Cost (Capex/Opex for 25 years of Operation)
- Footprint (Very limited for 3 Process Train Configuration)
- Thermal Efficiency
- Controls Simplicity (Multiple compressors in parallel operation)
- Emissions (Needs to meet BG Business Core Principles)
- Availability

BG Standards mandate aeroderivative gas turbines; however a high level comparison was made of industrial frames versus aeroderivative gas turbines to obtain a general, rough evaluation of the two types of engines. Industrial frame gas turbines required large (~22 MW) starter/helper motors in order to meet the nominal production rate of 5 mmtpa of LNG per train. The following main configurations were compared:

- 2 X Industrial Frame Gas Turbines with ~22 MW starter/helper motors + GT Inlet Air Chilling (IAC)
- 4 X Large Aeroderivative Gas Turbines + GT IAC
- 5 X Smaller Aeroderivative Gas Turbines + GT IAC

The relative CAPEX values for aeroderivative versus industrial frame gas turbines were comparable, when the costs of the additional power generation to support the starter/helpers were considered. However the OPEX values were significantly different. Fuel gas consumption was considered at cost, which is the Henry Hub price, so the substantially lower thermal efficiency of the industrial frame gas turbines translated into higher OPEX. The higher fuel gas consumption resulted in much higher emissions, which were converted to annual CO2 and NOx emission tax costs. In addition, the industrial frame gas turbine availability was lower than those of the aeroderivative engines mainly due to extensive downtime during major overhauls (50,000 hours). As a result, the industrial frame gas turbines were eliminated from further consideration due to much higher overall life cycle costs.

Note, electric motors were also considered in the driver selection study but were found to require a large amount of electrical power, almost 800 MW. The electrical motor option would have also required a very complicated electrical system with complex Variable Frequency Drivers (VFD’s) that could have introduced plant system harmonic issues. As such, further consideration was not given to electric motors for the refrigeration compressor drivers.

The final stage of the driver selection study focused on comparing larger aeroderivative gas turbines (Industrial Trent 60’s) to smaller aeroderivative gas turbines, per below:

- 4 X Industrial Trent 60 Gas Turbines + GT IAC
- 5 X Smaller Aeroderivative Gas Turbines + GT IAC

CAPEX costs were similar for the two aeroderivative engine configurations until inclusion of Total Installed Cost (TIC) was considered, which provided a small commercial benefit to the option with the least amount of equipment. However, OPEX was the key differentiator when comparing the two options. With fewer quantities of engines installed, cost savings were realized in NOx and CO2 emission taxes, as well as fuel consumption and maintenance costs. Finally, controls were considered to be simpler with a 2 X 50% C3/MR configuration versus a more complicated 2 X 50% C3 and 3 X 33% MR configuration.

The 4 X Industrial Trent 60 DLE configuration scored favorably in critical evaluation categories and was selected as the supplier for the LCLP main refrigeration compressor drivers.
TECHNICAL ASSURANCE PLAN

Once the Engine Validation Process was completed and the Industrial Trent 60 DLE aeroderivative gas turbine was selected for the LCLP, the next step was a detailed Technical Assurance Plan to ensure that all risks are properly managed.

A Technical Assurance Plan (TAP) was drafted to ensure that the Trent 60 could fulfill all critical requirements necessary for the project, and to highlight any risks or concerns that would require further evaluation during EPC detailed engineering. The purpose of performing the various TAP studies prior to and during FEED was to identify risks early in the design and develop mitigation plans for those issues that could not be resolved prior to the commencement of EPC detailed engineering activities. The FEED TAP must confirm that there are no design flaws found with the Industrial Trent 60 DLE MD service when it is applied to the specific requirements of this project, and identify issues that need to be addressed during EPC phase.

The industrial Trent TAP would require detailed assessment with specific compressor vendors; therefore potential compressor vendors were technically short-listed to support the FEED TAP studies.

STRING TORSIONAL AND LATERAL STUDY

A String Torsional and Lateral Study, per API 617 7th Edition, was performed during FEED, in order to demonstrate the critical or resonant conditions that should be avoided during various operational scenarios. A complete understanding of the train resonances is required to determine if there are any limitations on starting at full settle-out pressure, starting with system volume blown down to suction pressure, idle dwell speed, starting ramp rates and propane string operational characteristics from hot ambient to cold ambient conditions.

All critical lateral and torsional speeds were found to be outside of the engine operating speed range, as well as the engine warm-up (dwell) speed range. Separation margins were also confirmed as compliant with the minimum API 617 requirements for all train operating and dwell speeds.

As the torsional and lateral analyses are preliminary in nature during FEED, they will be repeated during EPC detailed engineering after the compressor supplier is selected and their detailed rotor/coupling design is finalized.

DYNAMIC RESPONSE MODELLING STUDY

Dynamic response modelling studies were conducted for both the C3 and MR services, to determine the transient behavior and potential consequences of process disturbances on process safety and equipment integrity. The dynamic model was used to simulate a range of process upsets and operating cases such as emergency trip, start-up, rapid changes in inlet flow and conditions, and changes in discharge pressure. Of particular concern was the relatively small inertia of an aerodynamic gas turbine and the impact that might have on a prolonged coast down duration.

The following factors were considered in the design of the anti-surge control system:

- Piping and equipment volumes, particularly compressor discharge volume as determined by the discharge pipe-work and location of check valves
- Anti-Surge control valve response time
- Characteristics of the compressor and inter-stage and parallel interactions
- Characteristic behavior of the driver, including the rotational inertia

While only a limited number of simulations were performed during FEED (due to schedule constraints), those dynamic simulations that were conducted demonstrated that the compressors would operate within their safe limits during worst case transient conditions, i.e. no operation in the surge/choke region and no over speed occurred. Hot gas bypass valves were deemed necessary for both the C3 and MR services, as well as quench valves for the C3 recycle lines (in order to minimize the discharge piping volume).

All of the dynamic simulations will be re-performed during the EPC detailed engineering phase, once the compressor supplier has been finalized and the piping and controls systems have more detailed definition.

TURNING GEAR STUDY

The purpose for this study was to determine if the centrifugal compressors required a turning gear to prevent rotor bow at shutdown. This study only addressed rotor bow concerns due to excessive thermal stratification on the rotor vertical axis. Rotor bow issues resulting from an extended period of down time are considered separately from this FEED TAP, as they are different in nature and involve different turning requirements (i.e. partial rotation every week).

Rotor bow due to thermal stratification occurs when the compressor is shut down and various parts of the compressor rotor either cool down (areas near the discharge flange, where gas temperatures are higher) or warm up (areas near the suction flange, where gas temperatures are lower). Process gases within the compressor casing mix and stratify, causing a hot to cold temperature gradient from the top of the rotor to the bottom. This temperature stratification can cause rotor bow or hogging that creates a bend in the shaft. When a compressor re-start is attempted, the now eccentric rotor causes high vibration that typically
trips the machine on high vibration (and may cause damaging internal rubbing). The turning gear allows the rotor mass to come to thermal equilibrium in a uniform manner that prevents rotor bows.

A compressor rotor bow study was conducted with each of the technically acceptable short listed compressor vendor’s offerings. Note that rotor bow is not an issue for the Industrial Trent 60 gas turbine, as its rotors are of stiff shaft design. This study addressed the following high level technical issues:

• Dry gas seal system suitability with turning gear operation
• Compressor Vendor’s recommended turning gear minimum time duration
• Lube oil and utility (N2, Air, kW) requirements during turning gear operation
• Jacking oil requirements, if required

The study determined that turning gears are indeed required for the C3/MR compressor rotors, in order to minimize the risk of rotor bow.

BREAKAWAY TORQUE STUDY

The purpose of this study was to confirm that the Industrial Trent 60 engine can develop enough breakaway torque during startup to initiate the LP rotor rotation. The concern was that the refrigeration compressor rotors typically have large moments of inertia in LNG service which need to be overcome in order to successfully accelerate from 0 rpm to operating speed.

Inertia data was gathered from the qualified technically acceptable short listed compressor vendors for comparison against proven breakaway torque capabilities that Rolls-Royce collected on their test stand in Montreal.

Figure 4 shows the speed-torque characteristics curves as proven on the test stand by Siemens Montreal, as well as speed-torque curves at varying ambient temperatures.

The study concluded that the Industrial Trent 60 has proven capability to provide almost double the maximum required compressor breakaway torque. The study also concluded that the Industrial Trent 60 has adequate available torque margin to accelerate any of the compressor supplier’s selections for C3 and MR from breakaway up to maximum continuous operating speed.

STARTING SEQUENCE FOR MECHANICAL DRIVES

The purpose of this study was to develop the detailed starting sequence for each mechanical drive service. This study integrated the results of the String Torsional and Lateral Study and the Dynamic Response Modeling Study.

Rolls-Royce developed a detailed starting sequence diagram for the propane and mixed refrigerant compressor trains to demonstrate that dwell speeds have adequate critical speed separation margins. The starting sequence study also accounted for maximum/minimum allowable ramp rates and torque requirements during full settle out pressure starts.

The Starting Sequence Study indicate that both the C3 and MR compressor services could be safely started and accelerated through critical speeds up to the ready to load speed.

HAZOP OF SIEMENS INDUSTRIAL TRENT 60 GAS TURBINE P&ID’S

A HAZOP of the Trent 60 engine and auxiliary P&IDs was performed during the FEED, with Rolls-Royce engineers in attendance.

No major safety, design, operation or maintenance issues were discovered during the FEED.

RAM ANALYSIS FOR INDUSTRIAL TRENT 60 MECHANICAL DRIVES

The RAM Analysis included the Trent 60 mechanical drive engines as part of the plant wide LNG production RAM Analysis. It was imperative that Siemens be involved and provide technical support during the RAM analysis. Siemens supplied planned maintenance schedules, outage durations, and reliability data as requested.

3-D MODEL REVIEW OF INDUSTRIAL TRENT 60 MECHANICAL DRIVE PACKAGE

This activity was carried out during the plant design 3-D model review. The 3-D model review included detailed equipment layouts for the compressor skids and the gas turbine packages, as well as all of the ship-loose auxiliary packages.
The 3-D model focused primarily on accessibility/maintainability issues; including maintenance pull volumes, laydown areas, heavy lifts, and other material handling requirements.

**COMPRESSOR SELECTION STUDY**

A compressor selection study was performed during the compressor bid evaluation process. The goal of the compressor selection study was to short list to a manageable number of technically acceptable compressor vendors for the remainder of the FEED and the associated TAP studies. The process of short-listing was based on technical evaluations, including meeting minimum experience requirements in similar service.

The results of the compressor selection study concluded with 3 technically acceptable qualified compressor suppliers with valid experience in similar services.

**INDUSTRIAL TRENT 60 PARETO ANALYSIS**

Rolls-Royce performed a Pareto Analysis on the entire Trent 60 package, including the engine and all auxiliaries. The analysis was based upon data collated through ORAP (Operational Reliability Analysis Program), with additional data taken from their Resolve Customer Issues (RCI) process. Siemens uses RCI to enable effective support of the entire fleet.

Availability and reliability statistics for the fleet population were collected; 67% of which were WLE engines and 33% of which were DLE engines. The fleet population is also heavily weighted in cyclic operation rather than base load continuous service, with the split being 33% base load continuous and 67% cyclic.

The analysis differentiated between those trip issues that are resolved and embedded in the fleet, those issues resolved and being campaigned to the fleet, ongoing root cause analysis trips and issues to be investigated in the future.

The results showed the individual effects of each trip and the resulting fleet improvement as each trip is addressed. Several key issues were identified whose resolution will result in a substantial improvement in the Industrial Trent 60 package reliability. The status of these key issues will be tracked during the EPC detailed engineering phase.

**COUPLING SELECTION / AXIAL THRUST STUDY**

Due to substantial temperature differentials and massive compressor casings, LNG compressors have the potential to create large axial loads during starting due to cold offset. Such axial loads in the compressor would translate through the drive coupling and create thrust forces in the Trent 60 LP rotor thrust bearing.

The purpose of this study was to ensure the Industrial Trent 60 LP rotor/bearings are not adversely impacted by this phenomenon. The study also confirmed the design of the load coupling and the means to minimize the axial thrust load translating through the coupling to the GT rotor and internals.

For each of the three compressor suppliers, it was demonstrated that the Industrial Trent 60 LP rotor thrust load limit was not exceeded by the cold offset, nor by the thermal growth experienced during startup until thermal stabilization was realized. The compressor casing dowel location, as well as the location of the compressor thrust bearing played key roles in minimizing the algebraic sum of the Industrial Trent 60 LP and process gas compressor rotor growths.

**FOLLOW ON ACTIVITIES**

An independent, third party consultant was contracted to audit several of the key FEED TAP studies after they were completed. This process enabled a cold-eye review of the TAP study results to check for fatal flaws or omissions.

A Technical Assurance Plan (TAP) was developed for EPC detailed engineering, which included recommendations from the third party audit of the FEED TAP studies. The EPC TAP consisted mainly of continuing or follow-up studies from the FEED phase or new studies based on findings from the TAP conducted during FEED.
SUMMARY

When considering a new equipment supplier or new technology, it is important to develop a methodical step by step plan to ensure the technology is sound and then to ensure that the technology may correctly be utilized in a specific application under particular conditions.

The Industrial Trent 60 DLE engine was validated and approved by BG for mechanical drive services in BG projects, including LNG liquefaction facilities. The validation process is still ongoing in some respects, with quarterly updates on new combustor designs and continuing efforts to improve reliability through the Pareto Analysis findings.

The FEED TAP confirmed that there were no design flaws associated with using the Industrial Trent 60 DLE engine for the Lake Charles project in a parallel C3/MR (decoupled) configuration. An EPC TAP was developed to continue the assurance on the Industrial Trent 60 and Siemens is to continue providing quarterly updates on their new combustor design fleet performance and feedback on reliability improvement initiatives.

REFERENCES


NOMENCLATURE

APCI Air Products and Chemicals, Inc.
C Degrees Celsius
CAPEX Capital Expense
C3 Propane
DLE Dry Low Emissions
IAC Inlet Air Chilling
EPC Engineering, Procurement and Construction
F Degrees Fahrenheit
FEED Front End Engineering and Design
HAZOP Hazard and Operability Study
HP High Pressure
IP Intermediate Pressure
LCLP Lake Charles Liquefaction Project
LNG Liquefied Natural Gas
LP Low Pressure
MR Mixed Refrigerant
MTPA Million Tons per Annum
OPEX Operating Expense
SCR Selective Catalytic Reduction