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Co-creation between pipeline operator and machinery OEM in the development of a modern gas turbine

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Increasing challenges are being faced by the pipeline industry: variability in flow demand, infrastructure acceptance by local communities, pressure on transportation impact on gas commodity price. Therefore, pipeline operators need to continuously reposition their business and leverage modern technologies, to provide high transportation reliability, greener solutions, and lower life cycle cost.

Baker Hughes, a GE company (BHGE), has a legacy of turbo-machinery solutions that have been employed in pipeline applications for more than 60 years in 2 million km of pipelines around the world.

The modern “industrial” type NovaLT16 Gas Turbine (17.5 MW @ ISO conditions), is the latest evolution in the BHGE family of gas turbines, designed for lowest life cycle cost and emissions.

To achieve high reliability, a pre-commercialization validation campaign was held, including: component-level and full combustor testing, fully instrumented prototype and endurance testing.

A new approach of co-creation with a first-class pipeline operator company TC ENERGY (TransCanada Pipelines Ltd) was also applied, through a close cooperation in the definition of the engine and package characteristics, in order to inject features capable of optimizing reliability, maintainability, un-manned operation, and life cycle cost profile of the gas compressor station.

In its first installation for mechanical drive application, NovaLT16 has been running reliably since early November 2017—with healthy behavior in terms of: transient response to load variations, low NOx emissions throughout a wide load range, ambient temperature ranges, and bearings vibration amplitude.

The Pipeline Operator shared their technical evaluation and product experience with other peer Companies operating in other Countries.

Collaboration between BHGE and TC ENERGY is continuing, to optimize servicing of the turbo-compression train and to further improve GT combustion technologies towards lower-and-lower emissions.

1. Introduction

Transportation of natural gas from the extraction fields to the consumption points is rapidly changing from the past time. In fact, the old model of "one way" transportation in a seasonal cycle is changing for two main reasons: shale gas ramp-up and natural gas liquefaction (LNG) for sea transportation. Such changes in capacity of gas dispatching in certain routings, involve needs for adaptation of the network and/or construction of new pipeline systems.

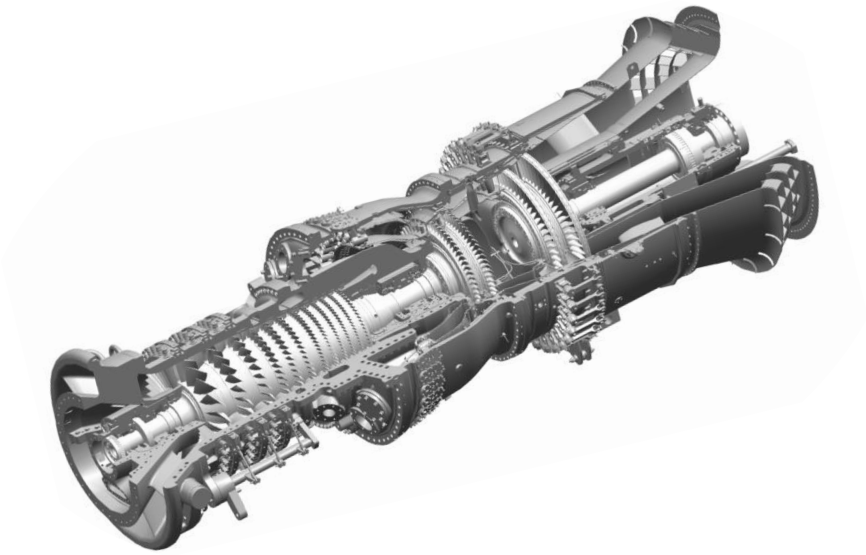
Pipeline operators are always committed to plan and execute "in time" and "safely" the expansion of pipeline network in the interest of the entire Country and with the largest possible consensus of the local communities. Design of gas pipeline network expansion shall also target the best cost of the investment (CAPEX) and cost of the operation (OPEX).

In this paper, the authors describe the experience of introducing a modern model of gas turbine, which was designed and validated for lowest life cycle (=CAPEX + OPEX) cost and for lowest possible emissions of air pollutants. In the following paragraphs, it is also described how, even with the introduction of a novel technology, the capacity increase was executed on time and on budget. Close collaboration between the turbomachinery OEM and the pipeline operator was key to expand the gas pumping capacity with design and construction characteristics which delivered very high operational reliability, easy maintainability, and un-manned operation of the gas pumping station.

2. Design and architecture

The operation of a pipeline has some very straightforward quality parameters: availability, performance, emissions, operability, maintainability and life cycle cost. How each of these parameters influences the design is discussed in this paragraph.

Figure 1: NovaLT16



Availability, differently than reliability, takes into account the planned outages. Simply, the fewer the outages, the higher the economic advantage. What is not so simple is how to achieve long stints between planned maintenance events. It all starts from the choice of a suitable thermodynamic cycle, considering both performance and durability. A demanding cycle may be good for performance but may pose limitations to the robustness of operation of the hot gas path. The ideal trade-off was found to be an average firing temperature of ~1200°C, combined with the adoption of materials that are usually employed at far greater values (~1400°C). High pressure turbine buckets, for example, are made of single crystal N4 and coated with Platinum and Aluminum, a configuration that can very easily double, at 1200°C, useful life; high pressure turbine nozzles are made of Re108, an alloy that GE Power uses for F-class machines: in this league of operation, durability is very high, as well as susceptibility to engine to engine variability. Similarly, low pressure turbine materials belong to a higher class. All in all, better alloys can be beneficial for availability and can be cost effective when a co-designed with suppliers.

Pressure ratio is then another paramount choice: on the one hand, it is beneficial to cycle efficiency, but on the other hand it affects emissions and the required pressure for the fuel gas. The optimal selected value, in combination with the chosen firing temperature, was selected to be just slightly below 20:1. For this reason, an additional stage was added to the compressor module of MS5002E, increasing pressure ratio from 17 to more than 19. Consequently, the outlet section of the compressor was adjusted to take into account the higher discharge temperature.

To further increase availability, the role of current boroscopic inspections was reviewed. A statistical analysis was performed on a very wide data set coming from boroscopic inspections of aeroderivative engines. Specifically, an assessment was performed on how reliability would have been affected if such inspections had not been carried out. It was found that the main predictive information comes from the axial compressor and is related to defects that are almost always caused by ineffective air filters in the very first hours of operation; when HEPA filters are correctly put in place, no such damage occurs and therefore it becomes safe to forgo boroscopic inspections.

This is how a 35000-hours Mean Time Between Maintenance was achieved with no boroscopic inspections in between.

Having set the thermodynamic cycle of the engine as a function of availability, there are ways to extract performance levels that are suitable for modern industrial gas turbines. Firstly, the aforementioned materials require little cooling; just to make one example, stage 2 bucket is uncooled and yet, based on the actual measured temperatures, is well within its design life. An additional contribution to high efficiency comes from the adoption of modern clearance control systems. Unlike the complex systems used in aeroderivative engines, the one in LT16 is “simply” based on the natural in-phase warm up of stationary and rotoric parts: as the engine starts up and achieved thermal steady state, its clearances close virtually to 0, extracting every bit of performance form the available mass flow rate. 3D fine aerodynamic design can be considered a standard practice in BHGE, resulting in the adoption of some of the features that are typical of the aviation engines, such as the endwall contouring on stage 4 bucket.

Regarding emissions, a high residence time was chosen to eradicate CO emissions from a very wide portion of the operating envelope; once CO is virtually eliminated, NOx can be more freely tackled by means of pilot injection strategies, burner configuration and dampers adoption. It is common practice to start testing various concepts, in view of the final validation on the real engine.

Specifically, a very thorough testing path was adopted, including the following phases:

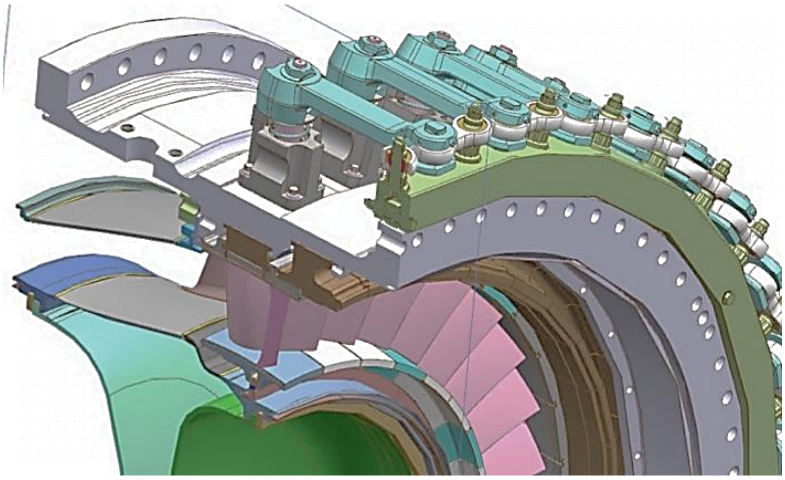
- Burner concepts screening. At GE Global Research Center, various designs were comparatively tested, selecting the most promising one as well as those whose technology readiness level is lower and whose emissions level will be even lower
- Full Annular Rig. The NovaLT16 features an annular combustion chamber, with the benefit of more uniform exit temperature profile. A full combustor set up was created in an experimental facility at Sesta, Italy, to explore the whole envelope of static operating conditions
- Full prototype. A real engine was extensively used to explore the whole envelope of static and dynamic conditions, under real acoustic boundaries

Moving on to operability, TC ENERGY’s input was:

- Ability to operate reliably and continuously at low loads, down to 20%. Moreover, also emissions should be very low at this partial load, without the need to parasitically bleed axial compressor air
- Ability to operate reliably and efficiently at part speed, to cope with the flexibility required by pipeline operations and seasonal variations in mass flow rate.

The second requirement is simply translated into design by selecting a two-shaft engine architecture, with a free power turbine. The first requirement led to more numerous decisions. One of the most common sources of poor reliability at low load is the continuous overboard bleed of air flow. The air extracted from the axial compressor, a dissipative form of regulation, is usually re-injected into the exhaust duct, often leading to its failure due to cold spots and vibrations, not to mention the noise that is produced. A goal was set for LT16 to operate bleed-less. The bleed line is used only for start-up and acceleration and is closed as soon as the engine reaches its idle; from idle on, the engine operates without any bleed of air. This outstanding behavior is achieved by means of a mechanical feature that is distinctive of BHGE production: the variable geometry nozzle between the high pressure turbine and the low-pressure turbine (Figure 2)

Figure 2: variable geometry nozzle



By means of the mechanism shown in the figure, this nozzle can adjust its throat area to control the enthalpy drop across the high-pressure turbine. As a result, this nozzle controls the high-pressure turbine speed and, in turn, the air mass flow rate that is sent to the combustor. This means that, to allow for stable premixed operation of the combustor, no air extraction is needed, since air is reduced by reducing speed (nozzle closing). The fact that there is no bleed is beneficial not only to part load operability but also to part load efficiency: the LT16, at 70% load, is more efficient than common existing engines by ~3 percent points and this advantage becomes even higher at lower loads.

When it comes to maintainability, it is common to find pipeline compression stations in remote areas, where maintenance activities would be difficult. As it would be impractical to disassemble the engine where tools and personnel are not easy to be sent, the wise choice is to go for the swapping of the old engine with a fresh one. The engine swap time is evidently a factor in the outage duration and for this reason the NovaLT16 was designed with fast and easy mechanical and electrical connections; as demonstrated on a real situation, a complete engine swap can be completed in 24 hours by means of just the standard tools.

3. Pre-commercialization validation campaign

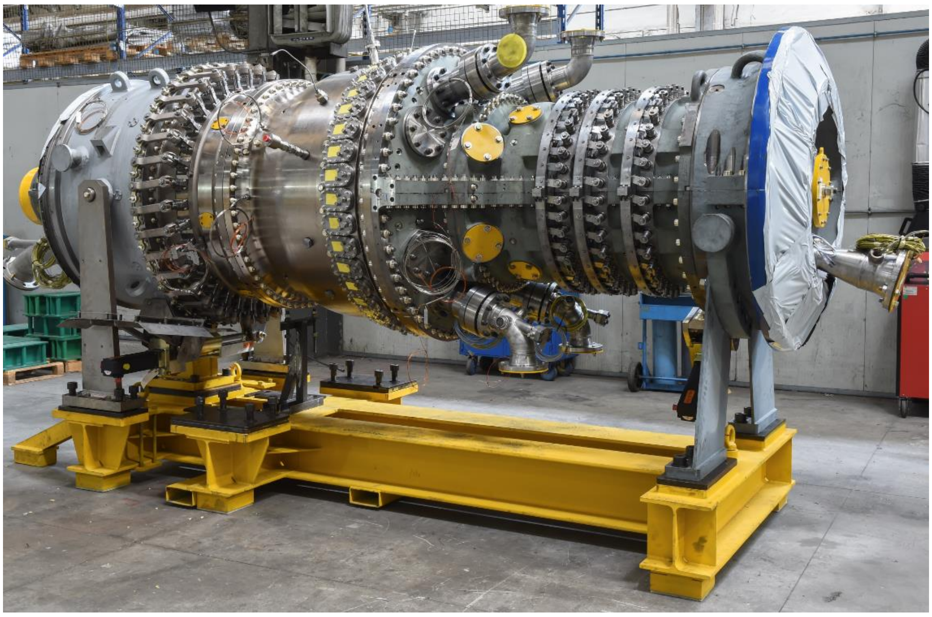
The validation campaign of a new engine needs to thoroughly investigate its behavior. Some of the key parameters affect each other in a measurement. For example, certain mechanical features require dedicated instrumentation that is invasive in the flow path and therefore may alter the performance. To make sure that the alteration is as little as possible, two prototypes were built with different criteria:

- A production unit, suitable to measure new, clean and unaltered power and efficiency; this unit can be used also to verify emissions and to develop control strategies
- A specially instrumented unit, hosting a range of sensors such as pressure probes, gas and metal thermocouples, thermocameras, strain gauges, clearance meters. This unit is devoted to verify mechanical durability, to match thermal models, to test for rotordynamic effect of lube oil conditions and to utilize special evolutive hardware

The production unit was built and tested in 2015, achieving the following performance figures: 17.5MW power and 37.5% efficiency. After the test, it was sent to its final Customer in Russia.

The special prototype accrued more than 500 hours and 25 cycles, achieving full validation for: aeromechanics, operability boundaries, thermal behavior, clearance behavior, thermodynamic mapping, rotordynamic behavior, power generation control strategy.

Figure 3: one of the NovaLT16 engines



4. Endurance testing

The tests that were discussed in the previous paragraph serve the purpose of setting up a new engine, but then the reliable operation must be accomplished by means of some different validation, one aimed at intercepting residual defects before they reach the final Customer.

To accomplish this, an endurance test was set up.

The special prototype was refurbished by replacing special parts with production ones. All the special instrumentation was removed, to revert to a standard configuration.

The engine was assembled in a power generation package, with the electric generator connected to the electricity provider, with whom a deal was made on the operating profile: the turbine, to maximize revenue from the sale of electricity, would run at 15% load during nights, at 100% load during working days and at 50% load over weekend days. The engine would automatically follow this operating profile, ramping load up and down.

The initial machine configuration was assessed by a third-party Inspector, Poyry Italy, whose goal was to independently certify time in operation and reliability. Intermediate boroscopic inspections were witnessed by the designated Inspector. Poyry Italy also had access to consumption data as well as daily reports and data trends.

After commissioning, the engine performed its power generation duty during the period Jan-Dec 2017, completing 6400 firing hours.

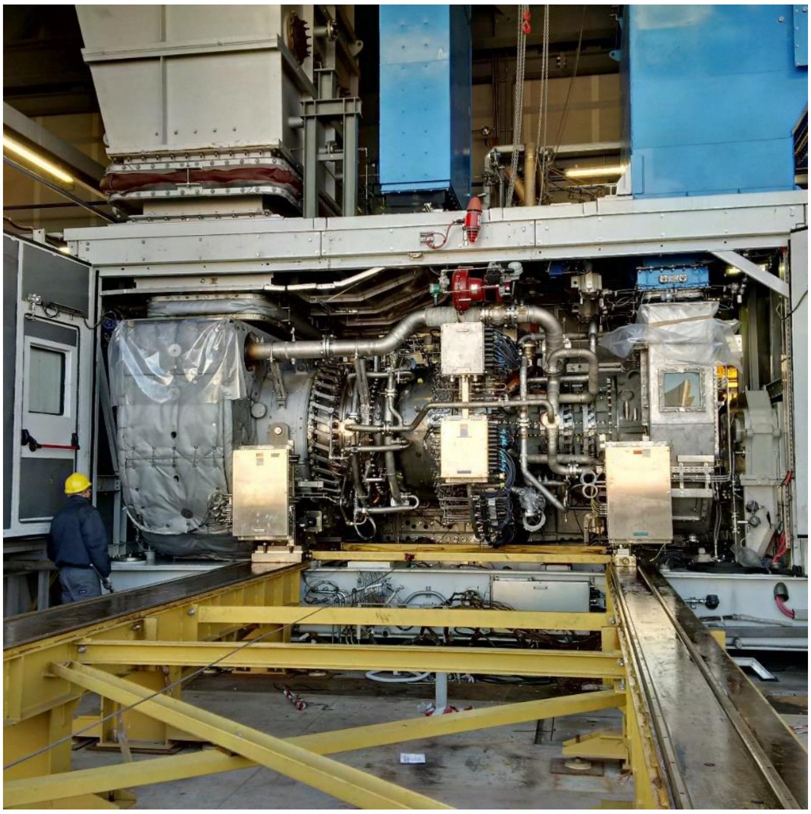
Besides 15ppm NOx emissions in the 50-100% load range, 25 ppm NOx were achieved in the 15-50% load range, which is also desirable for variable operations.

A total of 2 trips were attributed to the engine:

- One due to a software threshold value in Jan 2017: corrected and never returned
- One due to gas detection in the package. Maintenance was ongoing to the fuel system of the adjacent test cell and gas likely entered the package. Since it proved impossible to demonstrate that gas came from the adjacent test cell, the trip was attributed to the unit

The value of the endurance testing was to be able to provide Customers with equipment that already proved reliable.

Figure 4: the endurance Unit

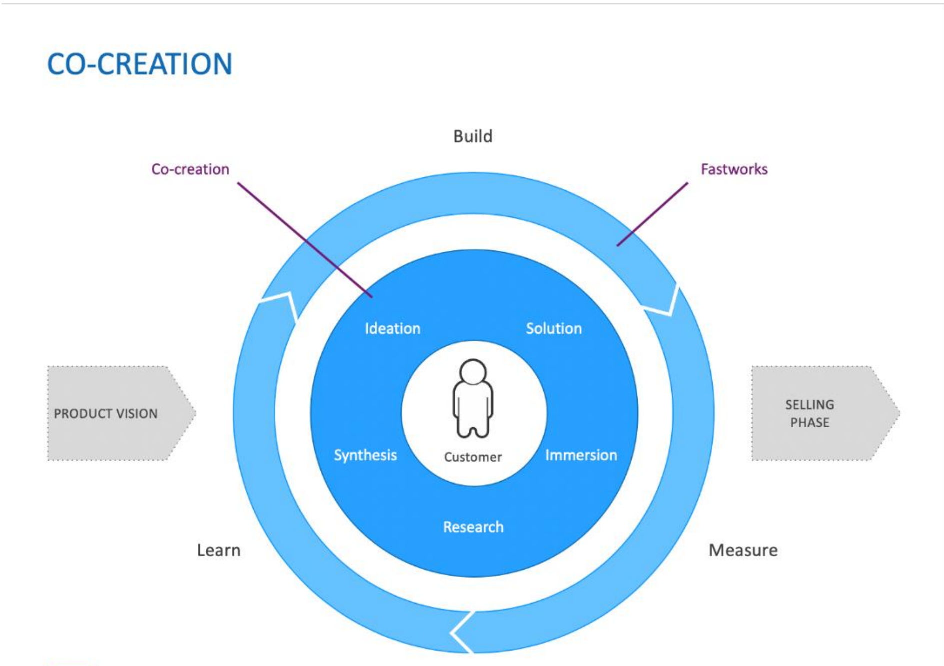


5. OEM/Customer co-creation

Four years ago, BHGE proposed to TC ENERGY to co-create a new gas turbine in the size of 16 MW (model NovaLT™16) to provide high transportation reliability, greener solutions, and lower life cycle cost.

Co-creation means collaboration in a program of innovation since its early design phase. Co-creation is part of "FastWorks", which imply a product/solution development approach based on versatility and fast-decision since early conceptual phase. As a matter of fact, through "FastWorks" methodology, in just 30 months after concept, the first gas turbine NovaLT™16 was build, with a significant reduction in previous model's development time which was 5-6 years for the previous similar products.

Figure 5: Co-creation and Fastworks



For the co-creation activity, BHGE also engaged a global design firm: Frog Design Inc. (FROG) to support this exercise. Frog greatly helped in methodology which includes: site visit at Customer's premises, face-to-face interviews and workshops. This was a "pace-change" from the traditional "back-and-forth" of communication and emails, while FROG encouraged OEM and Customer teams to sit together at the same table and share challenges and solutions.

In April 2014, BHGE and FROG visited TC ENERGY in Calgary and there interviewed six TC ENERGY departments (Eng., Maintenance, Procurement, Fleet management, Gas dispatching control, Environmental specialists) to better understand the value requested to the gas turbine product. During the same trip, the TC ENERGY service shop in Airdrie, and the Gas Dispatching Control Center in Calgary were visited.

During these visits, BHGE and FROG took face-to-face interviews to TC ENERGY senior personnel, and group technical discussion and observation sessions were also conducted.

Another key event attended by TC ENERGY+BHGE+ FROG on June 2014 was the workshop held in BHGE headquarter in Florence (Italy). Selected topic for the collaboration workshop was the definition of the NovaLT16 pilot program, from both the package and the contractual frame point of view. During the workshop, as visualized in the following pictures, different GT package layouts were prototyped in an informal idea-sharing process, using LEGO® bricks.

In this manner, different package/building design possibilities were explored aiming to minimize life-cycle cost and to achieve easy maintainability.

Figure 6: June'14 workshop of co-creation, hands-on

Figure 7: June'14 workshop of co-creation, simulation of maintenance using LEGO® bricks

Most of the outcomes of the workshop were applied on the unit that TC ENERGY ordered after it.

Some examples of workshop outcomes applied on the real built unit were: building crane (20t) with the same orientation of the skid; 11,25° inclination on same side for inlet and exhaust ducts; large (>4 meters) corridor between machinery skid and building wall to facilitate maintenance.

Figure 8: NovaLT16 in TC ENERGY gas pumping station, looks similar to the model developed during workshop

As follow-up from the layout selected during the workshop, BHGE worked-out on TC ENERGY inputs. In particular, the elimination of enclosure around NovaLT16 engine was thoroughly assessed with analytical and experimental checks. Checked areas were: clearance stator-rotor during transient, max temperature for casings and for instrumentation, noise, fire-fighting and gas detection.

Un-enclosed NovaLT16 configuration was also tested in Florence on August 2015 on a proxy-layout. Option of enclosure addition on NovaLT16 remained available, and in fact was applied in other projects with different site needs.

In fact, for TC ENERGY the collaboration work was key to mitigate risk of adopting a new turbine with limited run-time, while enjoy the superior efficiency, durability and un-manned operation capability. For BHGE this collaboration activity was functional to extend its gas turbine portfolio below 20MW in a technically and commercially attractive manner. In conclusion the co-creating activity was a “win-win” for both companies.

TC ENERGY and its predecessor affiliates (NGTL) have long pioneered innovative approaches in machinery for pipeline applications, being early adopters of dry gas seal technology and magnetic bearing applications more than 25 years ago, as well as operators of numerous first of type machines from a variety of OEM’s. The modern business climate however has necessitated a thorough documenting and mitigation of perceived risk as part of such adoptions today. Thus, the Co-creation effort also played a key role in allowing TC ENERGY an opportunity for technical design review and audit on specific areas of interest, as well as the opportunity to visit the Full Annular Rig and witness prototype testing with data-match reviews of development results, well before the production of the contract unit.

It is regarded that this partnership with BHGE allowed TC ENERGY significant and unprecedented access to the technical process and design to allow any concerns to be allayed, and was viewed by TC ENERGY as a critical aspect of early unit adoption. An area of specific attention to TC ENERGY in the deployment of a new Dry Low

Emission (DLE) designed machine included emissions performance and combustion acoustics, the means for abatement and the effects of a specific environment where the machine would be installed in a relatively harsh near arctic-climate (ambient temperature range expectation of -40 to +40 °C possible).

Other mitigations that were employed included:

- Long Term Service Agreement (not typical for TC ENERGY)
- In-theatre presence of a contractual spare machine.
- Remote Monitoring and Diagnostics (RM&D) by BHGE machinery experts.

The collaboration also saw cost-sharing on mutually beneficial package additions including a permanent torquemeter on the load coupling and EN1822 EPA 12 class combustion inlet air filters to allow component degradation to be followed closely for this initial application with a minimal influence of axial compressor fouling.

While the local TC ENERGY requirements in Alberta allowed NOx emissions of up to 25 ppmv @ 15% O2, TC ENERGY have also remained committed to working with BHGE to achieve an eventual implementation of a <15 ppmv solution at the Alces River B3 site. This is with a view of potential competitive applications for machinery of this size in other TC ENERGY jurisdictions as well as the likely future evolution of requirements which both corporate cultures seek to exceed, rather than simply meet.

6. Factory testing prior to shipment

As was customary for the first units, a complete full load test of TC Energy's unit was performed, until contractual performance and emissions levels were achieved.

After the contractual boroscopic inspection, the engine was ready to be shipped.

7. Commissioning test at gas pumping station

The commissioning effort at site did benefit heavily from a sizeable delegation from BHGE, given the novel product introduction. This was certainly helpful at a remote location in Northern Alberta in minimizing delays as in most cases, discipline expertise with suitable delegated authority were on site and allowed timely resolution and progress of issues.

Following dry-commissioning and pre-start up safety reviews were completed, site wet commissioning involved:

- First fire followed by controls assessments and stability checks by BHGE. This also included matching end of sequence to some hot recycle valve setpoint demand scheduling. This was slightly different to TC ENERGY's experience in that end of sequence and PT minimum speed are reached more quickly than many other units, with a consequence of reaching more elevated gas compressor discharge temperatures than desired. Closing the recycle valve earlier in the sequence allowed the discharge check valve to open as PT minimum speed was gained, which resolved this issue.

- Combustion mapping by BHGE specialist resources.
- Detailed vibration assessment and baselining of the turbomachinery train.
- Gas compressor surge control validation and testing.

Subsequent to commissioning, in April 2018 additional tests that were more difficult to coordinate were undertaken:

- Gas turbine field performance test. This testing found shaft power reported at reference condition of 16580 kW and a heat rate at 9175 kJ/kW.hr which significantly bettered contractual guarantees, even with the unit being at roughly TSI = 3800 hours at that point.
- While BHGE monitored and scrutinized emissions levels throughout commissioning, tuning and the performance test, nonetheless a formal emissions survey was conducted by a third-party source sampling consultant (Maxxam Analytics) accredited in the jurisdiction. This testing verified emissions of the oxides of nitrogen NOx @ 15% O2 were <17 ppm at the test points, less than the site guarantee of 25 ppm. Carbon Monoxide Levels were near measurement detection limits (<2 ppm).

Figure 9: NovaLT16 in TC ENERGY gas pumping station

8. Customer experience

Since the commissioning and entry into service at the beginning of November 2017, the LT16 driven PCL502 compressor unit at Alces River B3 site located in Alberta, Canada, has accrued, at time of writing, just over 10,000 successful operating hours in this first of type mechanical drive application. This operating experience has been gained over a challenging ambient temperature range from -38.4°C to +33°C, without any problem in terms of combustion pressure oscillations. Of these hours, 741 have been with at inlet temperatures cooler than -18°C, and roughly 50% of the total have been below 0°C (Figure 10).

TC ENERGY operate many mechanical drive turbo-compressor sets exactly for the flexibility of operation that they afford, being able to be matched to pipeline hydraulic requirements, which can change depending on contracts, seasons, or outage conditions, planned or unplanned, in the wider system. The unique approach on the LT16 of preserving thermal efficiency as much as possible through design (variable PT vanes) and elimination of parasitic axial compressor bleeds at part load was a key attractive feature for TC ENERGY. This capability and benefit of preserved part-load efficiencies has been exploited at Alces River B3, to which Figure 11 attests. The B3 unit can operate standalone or in a parallel configuration with another unit at the site, whose elevation is 734 m above sea level. The bimodal shaft-power histogram reflects operation in these different scenarios where the power range of 75-100% has been largely utilized. Observed peak power on cold day was 18.6 MW.

Power turbine speed ranged from 75% to 105%, however less than 200 hours were at speeds less than 88%.

In respect to reliability, over the operating interval, the achieved statistics for the unit since service entry are as follows:

Utilization: 97.25%

Availability: 98.46%

Reliability: 98.44%

Of the hours negatively affecting availability and reliability, these were not related to turbomachinery. Rather, they were associated with ancillaries/actuator and instrumentation issues, and minor controls adjustments that could not be affected with the unit operational. Such control schedule adjustments remained consistent with expectation on a new product with a complex control architecture in a climate with drastic seasonal changes.

It is worthy of note that these achievements have been made at a site that is considered "unattended". This means site technicians are dispatched for scheduled and regulatory maintenance activities but are on call for days when no routine activity is ongoing at the site. TC ENERGY resourcing returned to near expected levels in mid-December 2017, albeit with a resident GE technical resource (part of LTSA) being resident in the vicinity (100 km) of the site. Higher-frequency TC ENERGY technician call-outs than anticipated were initially encountered. This was due to a combination of some conservatively set thresholds needing minor tuning changes, but also is related to the fact that this unit represented a new control platform for TC ENERGY (MK6e). Some issues occurred which were primarily in the form of difficulties in adequately resolving, in TC ENERGY's SCADA and HMI remotely viewable systems, the differences in diagnostic and status annunciations from true alarm conditions which required an actionable response.   BHGE and TC ENERGY continue to work collaboratively on a standard which addresses the systems interface and rationalizes alarm & trip matrices to de-burden the remote gas control center operators from messages related to status indications and routine process annunciations.

Figure 10: Distribution of Inlet Temperature for Operating Hours

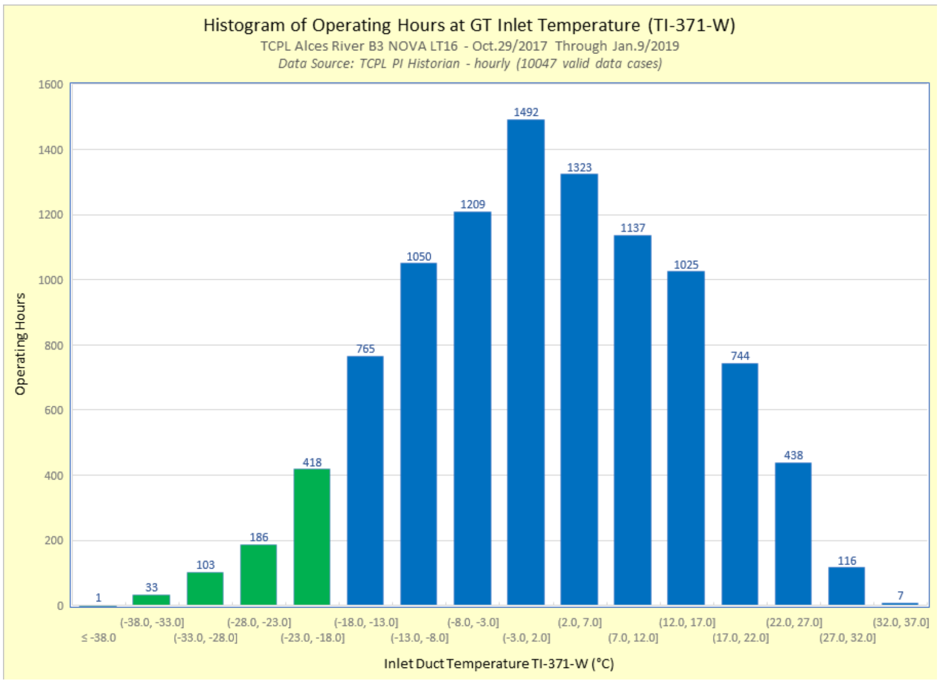
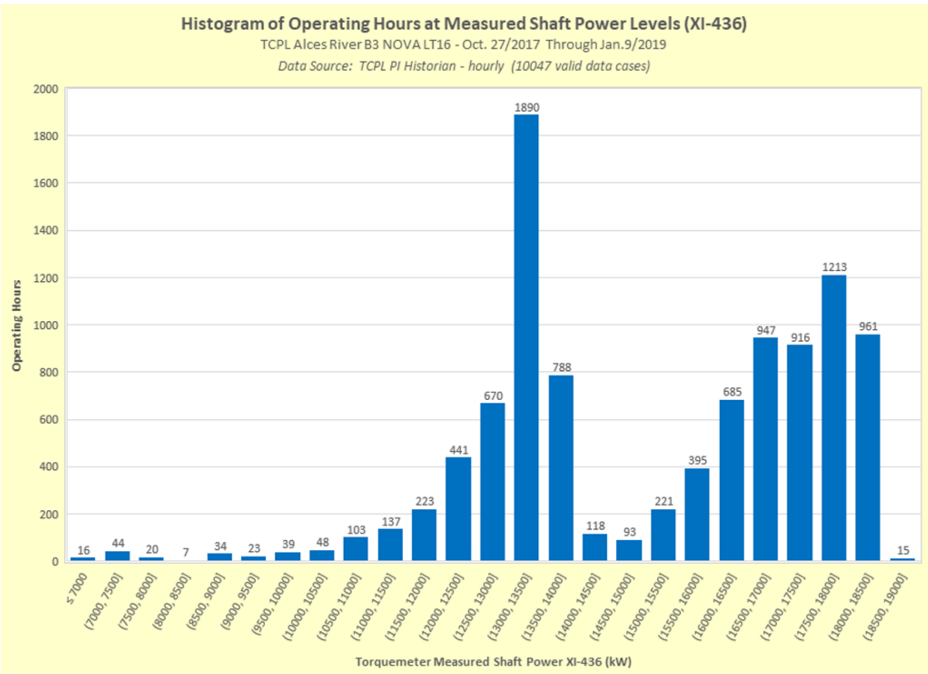


Figure 11 Distribution of Shaft Power for the Operating Points to January 9, 2019



9. Conclusions

Working collaboratively, BHGE and TC Energy have learned and acted upon mutual priorities and improved their business intimacy. Meanwhile, the NovaLT16 has been found well suited for the operational needs of a major Pipeline operator (TC ENERGY) and fully built and experimentally qualified according with the most rigorous standards.