Paper No: 03-IAGT-101

15TH SYMPOSIUM ON INDUSTRIAL APPLICATIONS OF GAS TURBINES

DEPLOYMENT OF THE NEXT GENERATION ROLLS-ROYCE RB211-6761 DLE GAS TURBINE AT TRANSCANADA COMPRESSOR STATION

by

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Presented at the 15th Symposium on Industrial Application of Gas Turbines
Banff, Alberta, Canada - October 13 - 17, 2003
The IAGT Committee is sponsored by the Canadian Gas Association.

Biographies Session 1.1

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Redeployment Program for under-utilized, small MW Units on Alberta Pipeline Evaluation of Pipe and Power Equipment Technology Developments to drive facility total cost reduction and economic Project Developments, e.g. Deployment of high efficiency upgraded RB211 6761 at Nordegg C/S. Currently working in the area of technology evaluation and project development for delivery of low total cost facility solutions that meet customer needs. Remote, cold weather (Northern) Pipeline Facility solutions and Energy Efficiency technology opportunities are some areas of interest.

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ABSTRACT

This paper will describe an innovative project developed to beneficially deploy and obtain operating experience on the first Rolls-Royce RB211-6761 DLE gas turbine installed in a compressor drive application.

The first part of the paper will provide insight into the collaborative development of the project concept and scope: to meet TransCanada and Rolls-Royce key objectives, to deliver key project benefits, and to reduce project risk. The discussion will include project concept innovations and solutions developed for site selection and baseload gas turbine operation, low project capital costs, demonstration period and assessment of equipment performance, and provision for project exit. The second part of the paper will detail the technical advances made in the 24GT DLE gas generator and the RT61 power turbine. Discussion will cover RB211 gas generator enhancements achieved using components and technology previously proven in Rolls-Royce aero applications. The RT61 discussion will cover design features and benefits for the new three stage power turbine developed by Rolls-Royce. This information is provided as an update to the Rolls-Royce paper published in 1997.

The paper will conclude with a discussion of results from the Nordegg Unit site performance testing and operating experience to date, plans to complete the performance assessment, and future opportunities for the 6761 gas turbine package.

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SECTION 1 – PROJECT DEVELOPMENT

1.1 Introduction

Rolls-Royce developed the upgraded RB211-6761 DLE gas turbine driver (6761) for gas compression and power generation applications with an ISO rating of 33 MW and 40% simple cycle thermal efficiency. Rolls-Royce approached TransCanada in 2001, based on its interest in collaborating with a major pipeline company, to deploy and obtain operating experience on this gas turbine in a natural gas compression drive application.

TransCanada entered into discussions with Rolls Royce in the first quarter of 2002 to consider project opportunities to install and operate the 6761 at one of its compressor stations. TransCanada was interested in the potential benefits to be derived from having the 6761 unit proven for pipeline compression duty and available for potential applications to transport natural gas volumes from the Western Sedimentary Basin and/or Northern Development pipelines. Some of the potential technology benefits available from the 6761 gas turbine included:

- 33 MW ISO power for increased flow capability and/or station spacing
- Modular power turbine for reduced overhaul downtime
- High combustion efficiency DLE gas turbine for reduced fuel usage and emissions

TransCanada and Rolls-Royce worked closely together over a period of several months to work out solutions to various project concept constraints and challenges and to fully exploit the benefits of deploying the upgraded RB211 in the pipeline system. The end result from this collaborative effort was an innovative and economic project concept to deploy the 6761 gas turbine.

1.2 Project Concept Development

Site selection was a key element to successful development of the 6761 project concept for the pipeline system. TransCanada's Engineering and System Design groups evaluated a number of potential sites for their ability to support key project objectives as follows:

- Allow for base load operation of the 6761 up to its full site power
- Station outage window available
- System capacity backup available during demonstration period
- Provide a lowest cost incremental power solution that meets customer flow requirements
- Preference to be given to a remote, cold weather site for optimal assessment of this equipment's fit for purpose

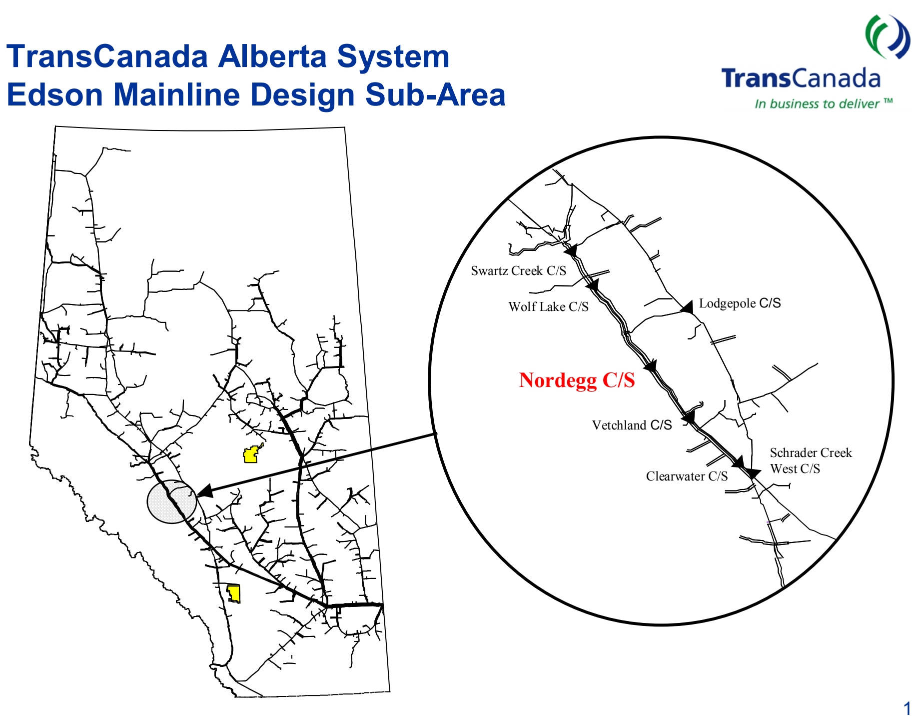
Rolls-Royce project objectives were also identified for consideration during the site selection and to ensure a fit with respect to operational duty as follows:

- Install an RB211-6761 gas turbine in a variable speed compression application
- Acquire up to 24,000 hours of operating experience
- Prove DLE short combustion system in cold ambient climate
- Prove the 6761 unit for existing pipeline and Northern Development pipelines

Workscope and costs were carefully assessed for the potential compressor station sites. An important concept was to maximize the reuse of existing site equipment to reduce project costs. TransCanada's assessment of project alternatives indicated that the lowest cost 6761 installation would be achieved by replacing an existing gas turbine driver and reusing the balance of plant compression facilities such as: process compressor, existing high pressure gas piping, the existing compressor building, the existing control building, and the compressor station auxiliary systems.

Another important concept for site/unit selection was to deliver significant site technology benefits through replacement of an "older generation" conventional combustor gas turbine with the newest generation RB211-6761 DLE gas turbine.

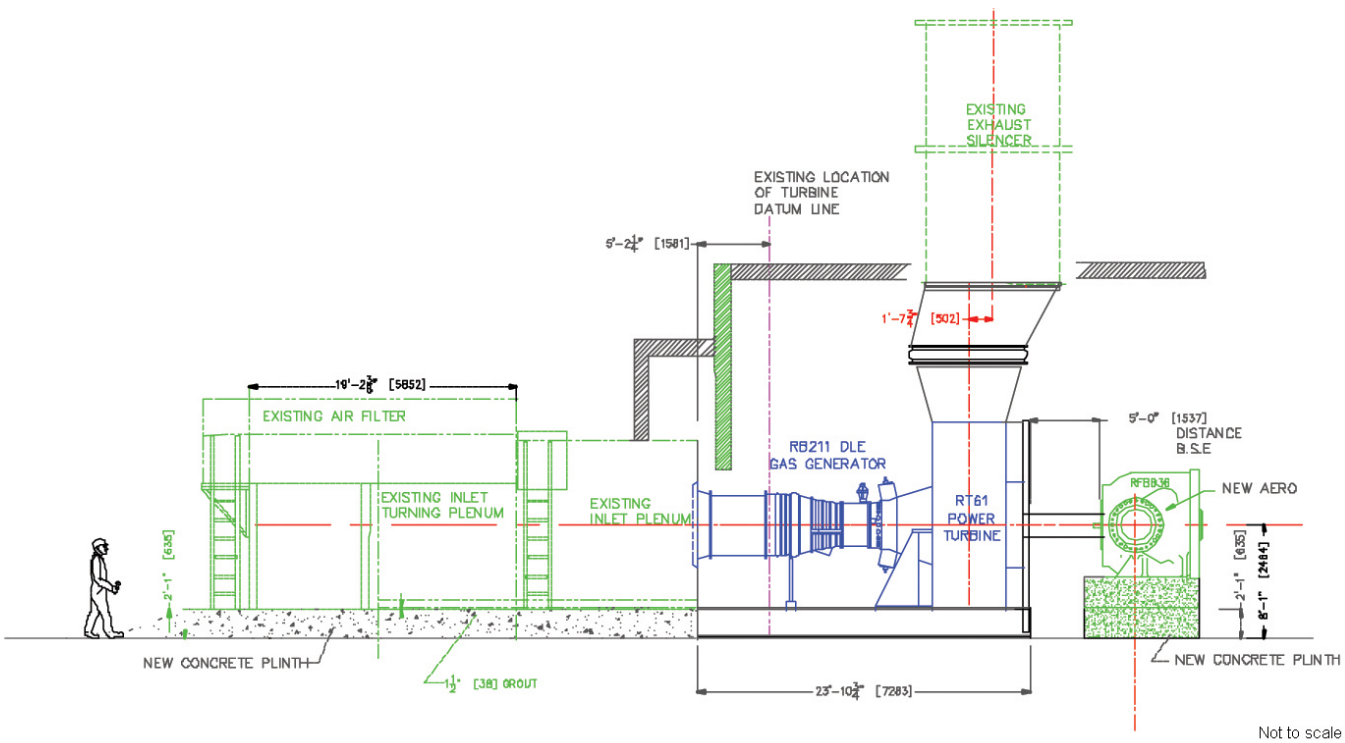
TransCanada's Nordegg Compressor Station was finally selected as the site for installation of the 6761 gas turbine based on its ability to meet the site selection project objectives, its delivery of significant customer benefits, and finally its strong fit for technology benefits from replacement of an "older generation" gas turbine. Nordegg Compressor Station is situated on TransCanada's Alberta Pipeline System, compressing natural gas on the Edson Mainline(s), and is located approximately 90 km northwest of Rocky Mountain House.



1.3 Low Cost Project Design Definition

TransCanada and Rolls-Royce worked collaboratively to define the 6761 gas turbine package scope of supply that would complement the existing Nordegg plant facilities and reduce capital costs for the project.

The existing gas turbine compressor package in service at the Nordegg compressor station featured a Rolls-Royce RB211-6456 gas turbine driving an RFBB36 centrifugal compressor that was installed and operational since 1989. The Nordegg project workscope specified removal of the existing gas turbine skid for replacement with the new 6761 gas turbine skid. The existing compressor building was reused with modifications to its foundations, wall openings and supports to accommodate installation of the 6761 skid to suit its dimensions and elevations.



RB211-6761/RFBB36 Compressor Side View

The existing building floor and foundations top of concrete elevation remained the same but it was necessary to raise the process compressor and high pressure connecting piping centerline by over two (2) feet to match the raised centerline elevation of the new 3-stage RT61 power turbine and its coupling connection. It was also necessary to extend the GG/PT skid foundation towards the inlet plenum, which was moved outwards to accommodate the longer skid.

All compressor station auxiliary systems were reused with modifications or changeouts completed to suit the new package connections and/or duty requirements. The fuel gas system was upgraded for the DLE engine with the addition of a coalescing fuel gas filter and gas chromatograph, new GG and PT oil consoles and a new oil cooling system were installed, and the compressor building HVAC system was upgraded to deliver additional gas turbine cooling air. MCC motor starters were added or upgraded to match the 6761 package requirements. Existing and new power and control cables were rerouted for connection to both new and relocated equipment. The existing control room was reused and the control panels modified to accommodate installation of new En-Tronic FT-110 fuel controller cabinets for the new DLE engine, and installation of a new Bently Nevada 3500 vibration monitoring system in the existing unit control panel. Finally a modification was made to the station Human Machine Interface (HMI) by upgrading to a FactoryLink system.

The project design team reused major components of the existing 6456 gas turbine package in order to reduce project costs wherever possible. Some equipment components needed to be modified or added to suit the 6761 package and its duty requirements. The existing air intake plenum and filter system was reused with new air filters installed prior to startup. The existing exhaust stack and silencer were reused with provision of a new transition piece and expansion joint to match the 6761 exhaust. The existing RFBB36 compressor fitted with original magnetic bearings, dry seals, process impeller and stationary aerodynamic components were reused. A new high strength, vaned diffuser assembly was installed in the gas flow path downstream of the impeller to reduce compressor rotor side load and to improve compressor isentropic efficiency near the design point. A new coupling and compressor shaft with increased diameter on the drive end was provided to handle the increased torque delivered by the 6761 gas turbine.

1.4 Project Benefits

TransCanada, through close collaboration with Rolls-Royce on this project, was able to deliver significant pipeline system (Alberta shipper) benefits with the 6761 installation at Nordegg Compressor Station. An incremental 8 MW of power installed at Nordegg #3 provides the lowest cost of service facility alternative to meet system flow requirements anticipated after 2006. The high combustion efficiency 6761 DLE gas turbine provides specific fuel and emissions reduction at Nordegg . Finally, installation of the 6761 gas turbine resulted in scope and costs reduction for TransCanada's 2002 operations and maintenance program. A summary of the benefits and equipment performance improvements at Nordegg Compressor Station is provided below.

Benefits of 6761 Installation at Nordegg Compressor Station

- 8 MW additional site compression power
- 9% reduction in gas turbine specific fuel consumption (heat rate)
- Process compressor vaned diffuser addition eliminated side load speed restriction and increased isentropic efficiency up to 4% near the design point
- Delivers ~ 82% reduction in site NOx emissions
- An existing RB211-24C gas generator was traded in to Rolls-Royce for the new package, reducing project cost and avoiding a scheduled gas generator overhaul in 2002
- The existing RT56 power turbine was moved into the spare fleet, also avoiding 2002 overhaul costs

1.5 Demonstration Period and Assessment of Equipment Performance

The 6761 gas turbine project equipment will be assessed for its installed operational performance during the demonstration period which extends from May 2003 to January 2006. Power, heat rate, and emissions will be measured against guaranteed levels within the first 50 hours of operation, and again prior to completion of the demonstration period. Acceptable vibration levels and unrestricted operation over the speed range will be also be assessed during the demonstration period.

Another aspect of the 6761 performance assessment is to determine the average availability factor achieved during the demonstration period. A contract guarantee has been agreed between TransCanada and Rolls-Royce. TransCanada and Rolls-Royce have also put in place an "Availability Support" process with key staff contacts identified to plan scheduled maintenance or system improvement outages, and to provide for the appropriate technical response for any unscheduled outages.

1.6 Project Risk

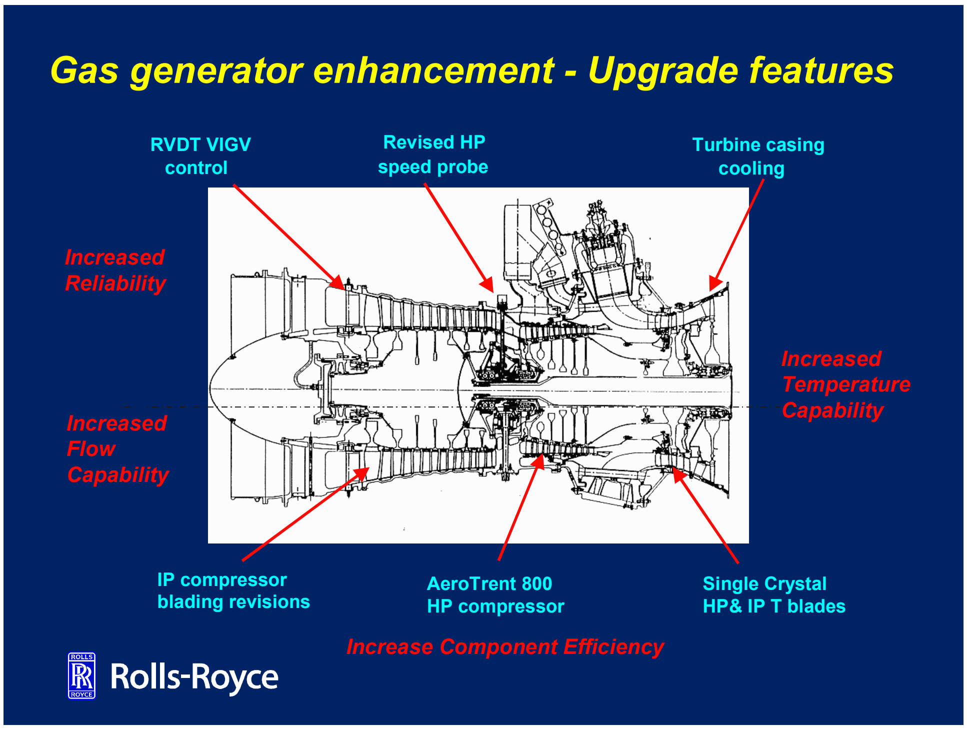
An important element to successfully developing this project was to provide a means to address any risk related to the arrival of incremental gas volumes at Nordegg between 2006 and 2010, and to manage any risk related to the introduction of the 6761 DLE gas turbine technology in a cold weather, compression drive application. The uncertainty in gas volumes arrival was accounted for in developing an appropriate 6761 package commercial agreement and in defining a risk adjusted cost of service benefit for customers from installation of the 6761 at Nordegg. A project exit strategy was also put in place to define the paths forward should the technology not meet performance requirements.

In the unlikely event that the project equipment does not meet the project performance assessment criteria, TransCanada has the option to have equipment replaced so that customer flow volume requirements are met. The 24GT gas generator can easily be replaced with a 24G if necessary. The RT61 power turbine can also be replaced with an RT62, but with an increased station outage impact.

SECTION 2 – TECHNICAL ADVANCES FOR THE RB211-6761 DLE

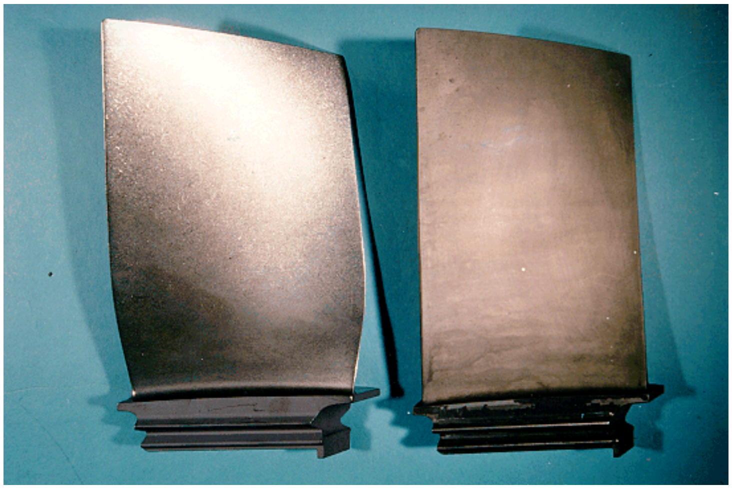
2.1 RB211-24GT Gas Generator

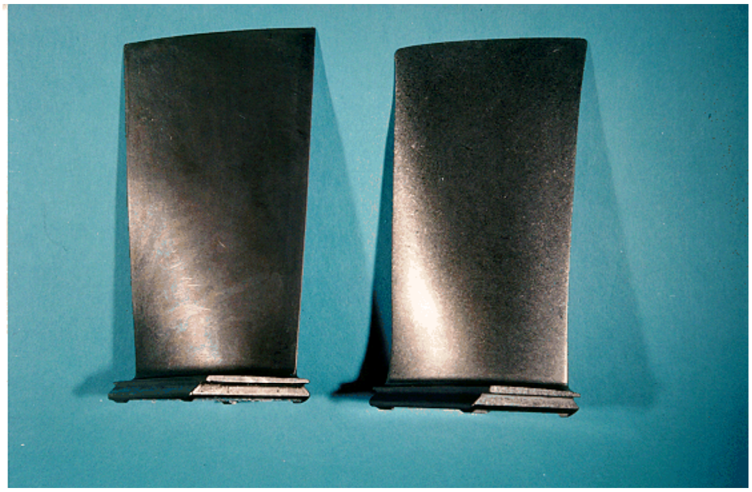
The RB211-24GT gas generator installed at Nordegg is an upgrade of the RB211-24G that has been in production since 1990, of which over 140 units are installed. The upgrades to the power output and the efficiency of the engine were achieved by 1) a 7% increase in air flow capability through a simple modification of the IP compressor, 2) the incorporation of the aero Trent 800 HP compressor to improve efficiency and 3) an increase in firing temperature capability through the incorporation of the aero Trent 800 HP turbine with improved material selection. The mechanical changes to the engine that accomplish these tasks use components and technology proven in the aero industry, resulting in the lowest possible technical risk.



2.1.1 IP Compressor

The IP spool of the RB211 is comprised of a seven stage axial compressor coupled to a single stage power turbine. The air flow through the engine was increased by modifying the IP compressor section of the engine. The airfoils of the first two stages of the IP compressor were redesigned based on their counterparts in the Trent aircraft engine which have over 10 million hours of operating experience. Tailored airfoils with controlled diffusion and reduced shock losses have allowed higher duty stages 1 and 2 to produce the required flow increase with higher efficiency and adequate stability margins. Their lower weight results in an 8% reduction in direct stresses.





Revised Blade Existing Blade
First Stage Rotor

Revised Blade Existing Blade
Second Stage Rotor

Stages 3 and 4 vanes have been re-skewed to accept the increased flow. A new outlet guide vane (OGV) design was also adopted, consisting of single aerofoils similar to that employed in the Trent 800, thereby improving inner and outer location. A reduction in the negative incidence resulting from the previous design and the introduction of a 3-dimensional airfoil allow better aerodynamic matching to the HP compressor and provide further optimization of cycle efficiency.

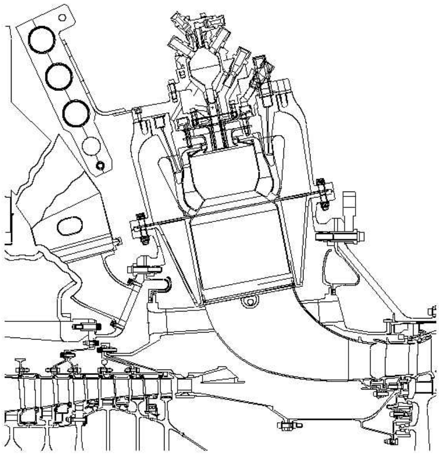
2.1.2 HP Compressor

The HP spool of the RB211 is a six stage axial compressor coupled to a single stage power turbine. The IP and HP spools are mechanically independent, allowing each to run at its optimum aerodynamic speed. The HP compressor section has been replaced with the aero Trent 890B HPC, which has achieved over 2.5 million hours of operating experience and offers a significant gain in efficiency. The advanced airfoils with controlled diffusion and revised work distribution improve disc sealing. Also improving efficiency is the low windage drum construction. The drive arms and casing location required minor reconfiguration to match the industrial engine's interface locations. Careful design attention in the mounting and location of the new HP compressor has resulted in minimal carcass bending deflections. To replace the existing internally mounted speed probe arrangement, 2-off externally mounted HP speed probes have been introduced to facilitate access and service without engine disassembly.

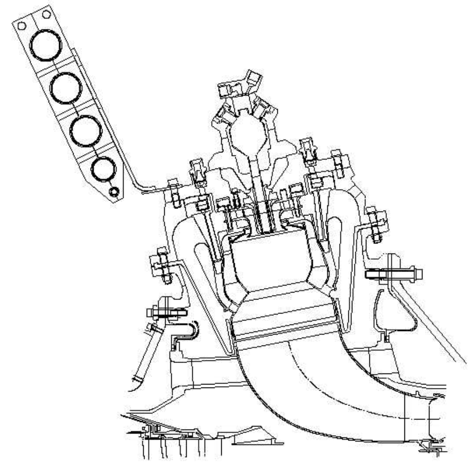
2.1.3 Combustor

The combustion section of the gas generator at Nordegg is the industrial RB211 DLE design with nine radially mounted individual combustors in an arrangement that maintains the existing gas generator length and rotor systems. It is a pre-mix, lean burn series staged system which allows a significant operating envelope in which emissions are controlled to the contract maximum values of 25 vppm NOx and 50 vppm CO.

The introduction of the Short Combustor and Variable Split Secondary to the RB211-24G DLE combustion system design were necessary to 1) lower combustion noise, which caused discharge nozzle cracking through high cycle fatigue in fielded RB211-24G units and 2) maintain low NOx performance at the higher firing temperatures. The improved design incorporates a reduction in the length of the secondary combustion chamber, reducing residence time to improve NOx performance and changing its acoustic signature and thereby reducing combustion noise.



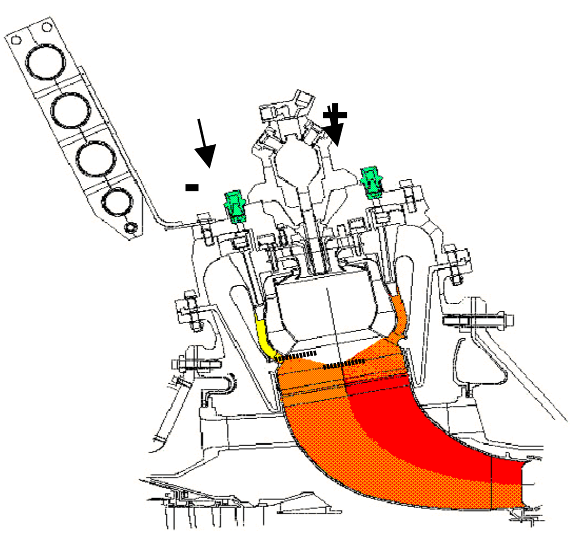
OLD “LONG” DESIGN

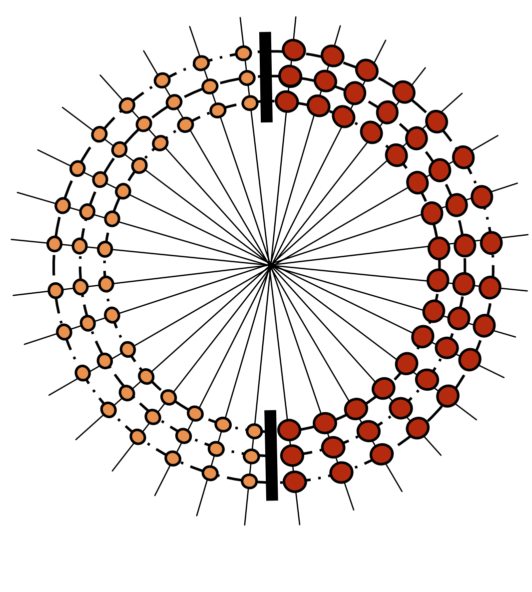


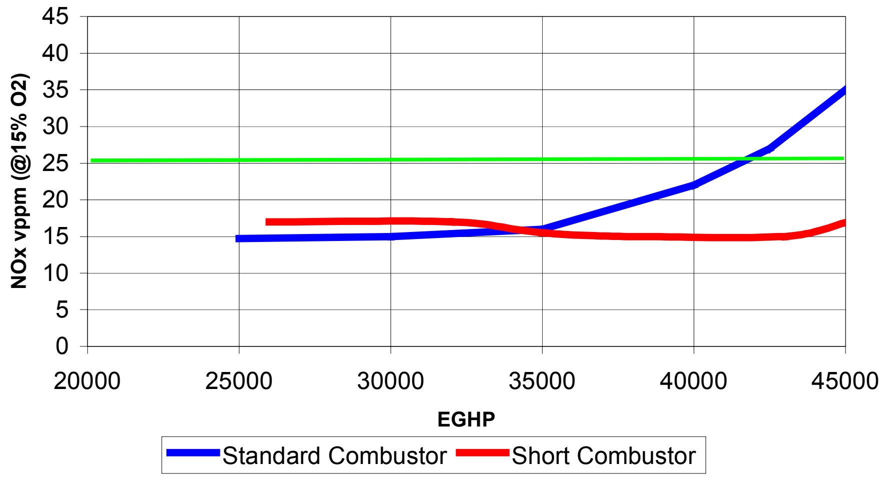
NEW “SHORT” DESIGN

Also incorporated into the design to reduce combustion noise is an automatically variable bias to the fuel flow between each side of the secondary combustion chamber. Two of the engine’s combustors are equipped with CP103 noise probes which continuously monitor noise in the combustors. If noise is found to reach unacceptable levels, the control system automatically adjusts the bias between the fuel flow to each side of the secondary combustion chamber. In addition to providing further capability for automatic noise and emissions control, this improvement reduces wear on the inboard side of the discharge nozzle.

Schematic of Secondary Fuel Flow Bias







Improved NOx performance of the short combustor at higher power vs. 25 vppm target

2.1.4 HP Turbine

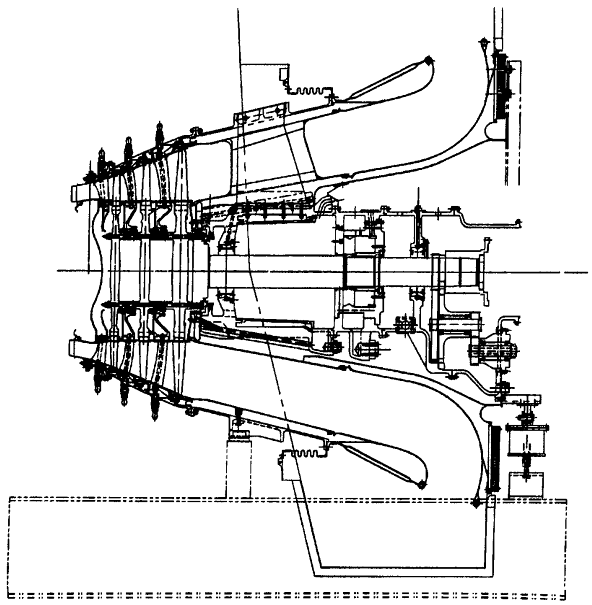
To allow a modest increase in firing temperature without reduction in turbine life, the aero Trent interlocked rotor blade has been incorporated. This rotor blade features an improved cooling configuration and a single crystal material providing the capability to operate at increased firing temperatures.

2.1.5 IP Turbine

The flow capacity of the IP turbine has been optimized to match the up-flowed IP compressor and reduced area RT61 power turbine by a small aerofoil reskew to the IP nozzle guide vane. The rotor blade design is dimensionally unchanged but the material has also been changed to single crystal material, extending creep life even at higher operating temperatures. The embodiment of a turbine case cooling manifold also serves to optimize the IPT blade tip clearances.

2.2 RT61 Power Turbine

The RT61 power turbine is designed to take the greatest advantage of the increased mass flow, pressure and temperature from the RB211-24GT gas generator. In anticipation of future further upgrades of the gas generator, the RT61 is rated at 37 MW. It incorporates the latest Rolls-Royce aircraft engine LP turbine technology to maximize efficiency and mechanical integrity. The design speed selected for the RT61 was 4850 RPM to match the most efficient speeds of existing pipeline centrifugal compressors.



RT61 Power Turbine Cross Section

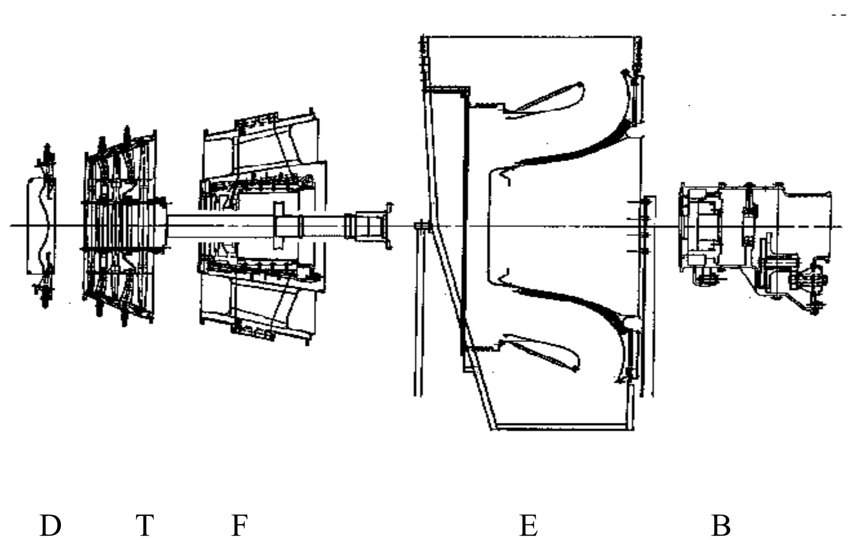
A preliminary design study compared 2 and 3-stage power turbines as options for the final design. The impact on performance, unit cost, mechanical integrity and maintainability were considered and the conclusion was that a close coupled 3-stage turbine was the optimum solution for the 4850 RPM design speed.

This solution resulted in high efficiencies due to moderate blade loading and minimized leaving loss associated with the blade path exit velocity. Work split between the three stages was optimized for maximum overall turbine efficiency with the first stage contributing the most and the last stage contributing the least. This variation reduced the first stage rotor blade metal temperature and minimized the exit swirl to the exhaust diffuser thereby minimizing exhaust system losses.

The power turbine's overall low aerodynamic loading allows the power turbine and gas generator to be close-coupled, allowing for a short, low loss inter-turbine duct. Also, the PT and GG are contra-rotational so the gas deflection across the first stage stator is minimized.

2.2.1 Maintainability

To ensure control of concentricity during manufacture and to minimize maintenance down time, the power turbine design has been organized into five easily separable modules in a fashion similar to the gas generator.

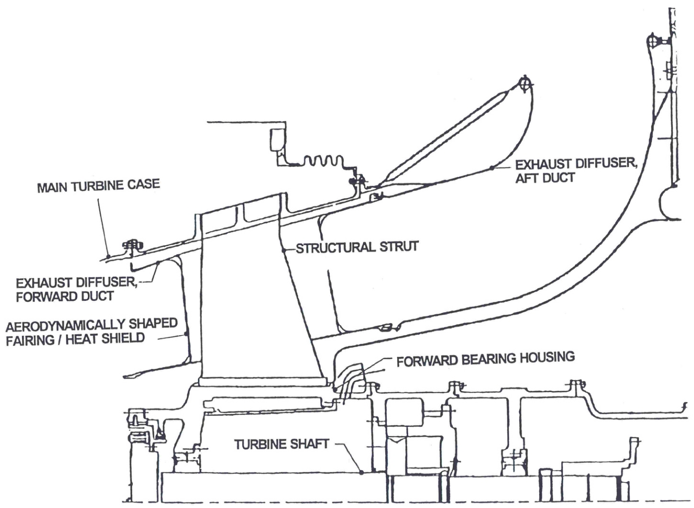


D -	Duct Module	Inter turbine duct and first stage nozzle vanes
T -	Turbine Module	2nd and 3rd stage stators, entire 3-stage rotor and main casing
F -	Frame Module	Exhaust frame structure, forward bearing housing, forward exhaust diffuser, and main supports
E -	Exhaust Module	Aft exhaust diffuser and collector hood
B -	Bearings	Bearing case, bearings and auxiliary drive

The modular concept permits all of the critical and delicate assembly operations to be performed in the controlled conditions of a central service facility. The modules are transported in special fixtures which maintain concentricity while in transit. Only modules D and T are removed for overhaul while modules F, E and B remain in place with their alignment to the driven equipment and exhaust stack undisturbed. Site module exchange is easily accomplished with a small crew and minimum downtime – approximately 12 hours versus the traditional three to four days. The overhaul interval for the turbine is 50,000 hours.

2.2.2 Support Frame

Positive concentricity control of the stator to rotor relationship is provided by seven forged stainless steel structural struts connecting the bearing case with the exhaust case through the forward portion of the exhaust diffuser. The struts are rigidly joined to the outer case with expansion bolts and positively located to the inner bearing case with precision dowels. The use of a strutted frame, which supports the rotor, eliminates the need for the traditional aft support of the bearing case, and serves to simplify base construction and reduce package weight.



RT61 Power Turbine Support System

2.2.3 Rotor and Bearings

All three rotor and blade rows are equipped with positive interlocking tip shrouds running against honeycomb faced casing liners. The rotor blades are mounted on extended necks to reduce heat transfer into the disks. The three rotor disks are joined by precision ground face couplings which accurately maintain concentricity during transients. The disks are joined to the shaft through twelve through bolts. The bearing cases are bolted to the strutted frame support with vertical joints sealed with ‘O’ rings. Journal bearings are babbitt faced hydrodynamic tilting pad type with high load capability so a balance piston is not required. An 1800 RPM auxiliary drive gearbox is included for the main lube oil pump drive.

SECTION 3 – TESTING, EXPERIENCE, AND FUTURE OPPORTUNITIES

3.1 Results of Site Performance Testing

Once installation and commissioning activities were complete, the site performance test was performed by TransCanada on May 16, 2003 to verify the contract performance guarantees. The objectives of the test were to:

- Determine maximum ISO and site power output
- Determine maximum ISO and site heat rate
- Determine maximum NOx and CO emission levels at full load
- Determine maximum vibration levels of the GG and PT
- Validate pipeline booster isentropic performance and efficiency

The test determined that the maximum ISO power output was 33,067 kW at a heat rate of 9100 kJ/kW-hr. This met the minimum guaranteed ISO power output of 32,962 kW, and the guaranteed maximum heat rate of 9198 kJ/kW-hr. The maximum site power achieved was 30,300 kW at an ambient temperature of 5.4 C. The heat rate at this point was 9050 kJ/kW-hr. At full load, NOx (15% O2) was measured at 23vppm and CO was found to be between 4 and 8 vppm, both within contract guarantees and CCME guidelines. The GG maximum vibration level was 9 mm/sec 0-Pk on the front pick-up, and the LPT maximum vibration level was 26 micrometers Pk-Pk on the disk end. This meets the maximum guaranteed vibration levels of 25 mm/sec and 76 micrometers respectively.

In summary, the results from the initial site test at Nordegg Compressor Station conducted on May 16th 2003 were positive, with the 6761 gas turbine meeting or exceeding all performance guarantee requirements. Following are the 6761 performance test results and site performance improvements delivered at Nordegg Compressor Station.

6761 Performance Test Results and Site Performance Improvements

- Delivered 33 MW ISO power (represents 8MW site power addition)
- Delivered 9100 KJ/KW-HR ISO heat rate (represents 9% reduction in site heat rate)
- No speed restrictions in running range (2910 – 5090 (N3 rpm)): addition of vaned diffuser eliminated compressor side load and 4500 rpm restriction, and increased isentropic efficiency up to 4% near the design point
- NOx and CO emissions were acceptable per guarantee and the CCME guidelines at maximum power (~82% reduction in site NOx emissions)
- Gas generator and power turbine vibration levels were well within guarantee

3.2 Operating Experience and Issue Resolution

The unit commenced commercial operation on May 24, 2003. During operation in May some fuel line cleanliness problems caused several shutdowns, requiring fuel injector removal and cleaning. Also, a grounding error in the wiring of the vibration system caused several spurious trips. These problems were both easily resolved. Availability for the month of May was calculated at **80.5%**, June was **97.6%**, and July was **98.4%**. The power turbine auxiliary driven main lube oil pump has also caused some problems. In July, the delivery pressure from the high pressure section of the pump was too low and the system switched to the AC motor driven standby pump. The shaft driven pump design is unique to the RT61 in a compression application and it is still being fully evaluated for this service. Some design changes may be needed for future applications.

Overall, TransCanada field operations has been pleased with the 6761 equipment operation to date based on the unit handover without any operational restrictions, the delivery at site of guaranteed equipment performance, and minimal package problems or shutdowns. The unit has now surpassed the 1,000 hour operation point. The close collaboration and alignment of project objectives between TransCanada Plant Engineering and Field Operations and Rolls-Royce has resulted in the quick resolution of any operational problems.

RB211-6761 DLE installed and running at Nordegg Compressor Station

3.3 Conclusions

It is possible to develop innovative project concepts that beneficially introduce and provide operating experience on advanced gas turbine technology. A collaborative approach by an owner/operator company and an equipment vendor is an effective means to develop an economic project solution that fully exploits technology benefits, and mitigates identified project risk.

3.4 Future Opportunities for the RB211-6761 Gas Turbine

Knowledge obtained from the baseload operation of the 6761 gas turbine at Nordegg will be beneficial to identify aspects of packaging and equipment design/component(s) that meet or exceed performance and service requirements. System improvement opportunities will also be identified so that future 6761 compression applications will benefit from the Nordegg operating experience . As natural gas volumes are tied in from more remote areas of the Western Sedimentary Basin and/or Northern Development regions, opportunities may develop to introduce modular, factory pre-built and transportable 6761 gas turbine packages as a low cost solution.

3.5 Current RB211-6761 Experience in Power Generation Service

End-User	Location	Combustor Type	Operating Hours
Abener Carrico	Portugal	DLE	In-service
Fafen #1	Brazil	DLE	11,000
Fafen #2	Brazil	DLE	8,000
Fafen #3	Brazil	DLE	1,000
Port of Liverpool	UK	DLE	In-service
VCP	Brazil	DLE	In-service 2Q '03

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