Industrial RB211 — 15 Years of History and Development

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INTRODUCTION

The Industrial RB211 was derived from the aero RB211-22B engine in the early 1970's and was first installed at Burstall, Canada in 1974 as a prime mover in the Trans Canada Pipe Lines gas transmission pipeline.

The paper opens by tracing the progressive power uprating of the engine since 1974 and then reviews its proven performance retention. The paper continues with a description of some specific requirements of the industrial engine that differ from aero philosophy.

A review of the major technical challenges that have been encountered during its development is also undertaken. Most of these problems have been occasioned by the fundamental differences between continuous sea level operation and the relatively short cyclic duty of the aero engine.

The paper closes with a brief look at the engineering programme for the aero family of RB211 engines that will provide the technology to further uprate the industrial engine well into the future. The current programme to meet future environmental requirements is declared.

The orientation of components discussed in this paper are shown in Fig.1. Aero terminology is also used for the industrial engine so, for example, what would normally be called the low pressure (LP) compressor in a two shaft machine is referred to as the intermediate pressure (IP) compressor.

Current statistics

The population of Industrial RB211 engines sold or on order at the end of 1989 is 179 comprising 153 mechanical drive and 26 electrical generator units. The corresponding fleet hours stand at 1,67M with over 0.5M of these being in hostile offshore environments. The current lead engine was commissioned in 1978 to carry out process plant duties at Waterton, Canada. This engine has completed 90,000 hours without major overhaul.

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During its years of development the engine has grown from an ISO based rated 30600 exhaust gas horsepower (EGHP) machine to the current engine offering 39000 EGHP.

**POWER GROWTH**

The industrial engine was launched at 30600 EGHP and based on the RB211-22B aero engine (42000 lb. thrust) powering the Lockheed Tristar aircraft. The Boeing 747 'Jumbo' saw the introduction of the RB211-524 rated at 50000 lb. take off thrust. The first uprating of the industrial machine was completed in 1978 by utilising the HP turbine from the -524. Because of its modular construction, (see Fig.1), this was achieved by fitting the HP core module complete. However, the -22B HP compressor (HPC) blading was specified (instead of the -524 aerofoils) for the industrial engine. This decision was taken to obtain optimum speed match between the two spools. These changes enabled the design value of turbine entry temperature (TET) to be increased by 30 deg.K giving an 11% power boost compared to the Industrial -22 engine.

![Fig. 2 Industrial RB211 Power Growth 1974-Future](image-url)

Small modifications were required to the IP turbine module and the change in direction of the HP thrust bearing load required alteration to the lubrication arrangement within the wheelcase.

The resulting gas generator was designated the Industrial RB211-24. Power turbines ('A' size) designed for use with the -22 engine were still suitable for the -24, since no change in turbine throat area was necessary.

Due to interest in the Industrial RB211 from offshore operators and potential customers in the Far East (where ambient temperatures rarely fall below 0°C), RR rematched the thermodynamic cycle of the gas generator by expanding the exhaust gases through a free power turbine of larger nozzle throat area ('B' size). This enabled RR to trade-off loss of 'cold day' power with 'temperate day' gain. The customer now had the option to purchase the RB211-24 gas generator with an 'A' size or 'B' size Power Turbine. Fig.2 summarises the performance ratings then available.

The early 1980's saw enormous resources being poured into the development of aero engines to improve their thermal efficiency in the wake of spiralling fuel costs. The Industrial RB211 was suitably placed to benefit from this technology and in 1983 a further uprating program was completed. However, a balance had to be achieved between proven reliability, advanced technology and cost.

Working through the engine from intake to exhaust, the following design changes were made:

a) The -22 IP compressor with its redesigned (for industrial use) first stage was retained. The new front inner and outer annuli and associated blading of later -524 IP compressors would be expensive to adapt for industrial operation and offered little efficiency improvement.

b) Advanced finished machining processes producing highly polished aerofoil surfaces were read across to the industrial compressor.

c) A thrust balance piston was introduced to offload the IP location bearing thereby allowing useful increases in cold day powers.

d) This increase was intentionally restricted by setting a maximum non-dimensional IP compressor speed limit above which choking of the rear stages would begin to occur. To maximise the power within this limit a new smaller power turbine was specified.

e) As a result of this change the IP compressor passed more flow throughout its speed range, consequently the larger -524 HP compressor was now required. The HP spool speed was now lower than the -24A. This was offset against an increase in TET to provide hot day power uprating without reduction of HP turbine rotor blade creep life.

f) Superpolished aerofoils were a standard feature of the new -524 (HFC) and at the same time both turbines were also specified with superpolished blading.
Attention to internal seals to reduce wasteful air leakage and improved abradable linings in the compressor and turbine casings complete the picture of efficiency improvements.

This new gas generator entered service in 1983 and was offered at two power ratings. The lower corresponding to a TET of 1384K for those operators who wish to retain their existing 'A' size power turbine. This configuration gave a 4% power boost over the old -24A engine. The second rating was a new uprating corresponding to a TET of 1434K where the new 'C' size power turbine is specified, see Fig.2. This rating is designated -24C.

As previously mentioned, an advantage of utilising the free power turbine concept is that the gas generator performance can be optimised for cold ambients or hotter climates by a suitable choice of power turbine throat area. For instance, the power turbine of the Cooper Rolls 6462 can be sized 4% smaller enabling the -24C gas generator to produce 10% more power when operating on speed control. This feature has been offered to enhance the cold day powers for some Alaskan operators. Engine life is not compromised since care is taken to rematch the engine to optimum power levels at different ambient temperatures by setting the appropriate control limits.

A summary of the marks of Industrial RB211, their ISO base rated power and year of first unit installation follows:

<table>
<thead>
<tr>
<th>Engine Mark</th>
<th>ISO Base Load</th>
<th>First Unit Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>-22</td>
<td>30600</td>
<td>1974</td>
</tr>
<tr>
<td>-24A</td>
<td>34000</td>
<td>1978</td>
</tr>
<tr>
<td>-24B</td>
<td>35600</td>
<td>1981</td>
</tr>
<tr>
<td>-24C</td>
<td>35290 'A'</td>
<td>1983</td>
</tr>
<tr>
<td></td>
<td>39000 'C'</td>
<td></td>
</tr>
</tbody>
</table>

From hereafter in the text, the various marks of engine will be referred to by their rating only ie. -22, -24A etc.

PERFORMANCE RETENTION

Fig.3 shows how the engine's specific fuel consumption (sfc) at base load power is maintained with running hours. Performance data has been obtained from engines returning to overhaul/repair facilities and tested in the 'as received' condition. There is good agreement between the industrial and aero machines. Fig.3 also shows how improvements in design have aided performance retention ie. current engines are better at retaining their performance.

The modular construction of the Industrial RB211 has enabled the operator to continue running without returning complete engines to the overhaul base. Therefore, 'as received' data for complete engines is somewhat limited considering the size of the fleet, nevertheless the sample size is of statistical significance.

RB211 design philosophy is based on short rigid rotor assemblies matched to a short stiff basic structure. The short shafts are mounted on separate bearings and compressor drums are of high dia./length ratio. This means reduced case deflections and lower rotor excursions hence improved seal and rotor tip running clearances. Use of inner and outer casings provide isolation of main rotating assemblies from engine mountings.

The RB211 shrouded turbine blades utilise honeycomb tip seals. Many improvements have been made in this area since 1974 allowing axial and radial growths to be more successfully matched to each other resulting in reduced overtip leakage. Any remaining leakage is converted to useful work by employing a tip fence on the shroud.

Developments in X-ray technology have been directed at understanding the transient behaviour of the blade shroud with respect to the casing enabling RR to 'pre-profile' the shroud segment to minimise leakage and prevent shut down seizure.

SPECIFIC INDUSTRIAL REQUIREMENTS

It is RR industrial policy to maintain as much commonality as possible with the Aero RB211 but clearly there are times when this is not desirable or sensible. The following three subjects highlight some areas where deviation from aero policy was decided at the design stage of the industrial machine. After 15 years of service, some encouraging statistics emerge.
Corrosion/Erosion Protection

The more hazardous environment of offshore operation and the ever increasing need to burn a variety of fuels necessitated either improved protective coatings or basic material changes from the aero engine. Protective coatings such as PI164/1 polyimide paint and Sermatel 5375 have been used successfully on IP and HP compressor casings and stator vanes. A coating is excellent whilst it is not breached and the component’s life is only as good as the base material once it has been, except for coatings with sacrificial protection. Material changes for hot end components are always considered to be the best solution to combat corrosion or erosion. Initially INCO 738 material was used for the HP and IP turbines at -24A and B ratings and to maintain satisfactory blade lives at the -24C rating INCO 792 was introduced.

In general, no compressor or turbine corrosion problems have been encountered due to the offshore environment except when there have been unavoidable cases of liquid fuel being contaminated with sea water causing HP Nozzle Guide Vane (HP NGV) distress. As a product improvement an HP NGV cast in INCO 738 material is undergoing service trials, and will be introduced if long term performance of the existing material (C1023) proves to be unacceptable. However, performance to date using a silicon aluminide coating is encouraging with the lead engine at over 33,000 hrs. This engine has been recently stripped and has revealed no problems resulting from the offshore environment.

Lubrication Systems

It was a deliberate policy at the engine’s conception to have a simple 2 shaft system for the IP and HP rotors. There would be no external drives functioning once the engine had been started. This led to the need for the oil to be scheduled to the engine by means of a self-contained off engine lubrication system which would meet the requirements of API 614.

The primary functions of the lubrication system are to:

1) Feed lubrication oil to the gas generator and bearings
2) Scavenge the oil from the bearings
3) Provide hydraulic power for inlet guide vane ram control
4) Provide hydraulic power for the fuel system
5) Remove air from the scavenge oil

API 614 required items 1-4 to be duplicated along with all main relief valves and filters.

Each mark of engine has its own unique requirement of oil flow at a speed for both lubrication and for carrying away heat from the bearing chambers.

The first lubrication system was designed to meet the needs of the -22 engine and has operated satisfactorily for over 0.5 M hrs. with the load unit at over 120K hrs.

An electronic closed loop flow control and protection system has been developed for the latest units now entering service.

Starter Motors

There are three different makes of starter motor that can be fitted to the intermediate casing of the engine, namely Lucas, Volvo and Hilliard. The Lucas starter is a gas expansion turbine unit that has been the subject of product improvement since 1974. Rotor bearing loads have been reduced by a factor of 5; the internal oil pump has been redesigned and oil retention features have been incorporated so that this motor is now a reliable unit fully meeting its demanding service duty.

The Volvo hydraulic motor has been trouble free since its introduction in 1983 and operates on the swash plate principal using the same oil type as that of the engine.

Very recently the Hilliard positive displacement starter motor has entered service to satisfy customers demands for a cheap easily maintained unit. Current service trials are being backed up by development engine testing.

TECHNICAL CHALLENGES

As an industrial engine, its operating environment is very different from its aero counterpart. Aero engines operate on a working fluid that is usually at much reduced levels of pressure and density. Aerodynamic loadings and stresses are often significantly higher for the industrial engine.

The wide range of ambient temperatures around the world and the fact that many operators do not require full power during the development of their total plant highlights the main difference in operating pattern between Aero and Industrial. That is, whilst industrial engines have to be capable of operating continuously at any speed between idle and full power, aero engines have discreet known operating points such as take-off, climb and quickly pass through their speed range before settling at altitude cruise within a 10% speed envelope.

Continuous operation over a wide speed range with a working fluid at sea level densities has created interesting technical challenges.

Bearing Loads

One obvious outcome of operating at sea level air densities is the increased bearing loads. This necessitated the redesign of the thrust bearings for both the IP and HP spools.
Double stack ball bearings are incorporated in the redesigned centre bearing housing. Uprating power levels for cold ambients have been possible by introducing a thrust reduction balance piston on the IP shaft (Fig.4).

The progressively decreasing annulus area of the HP compressor provides suitable airflow conditions through all stages of the compressor and over a wide speed range. However, at very low rotational speed a more uniform annulus would be preferable. At the front of the compressor the slow moving air is unable to follow the rotor blade passage/profiles. Separation from the aerofoils results and local blade stalling occurs (Fig.5).

This uses third stage HP compressor air to pressurise the front face of a rotating piston connected to the IP shaft. This air is sealed from the front bearing chamber by a double sided labyrinth seal. Front bearing oil sealing is maintained by 4th stage IP compressor air. In order to counteract any possible sensitivity to seal wear an extra chamber vented into the nose bullet has been incorporated.

Low Temperature Starting
The Industrial RB211-24A entered service on the North Slope of Alaska in 1984 and operated very successfully using the aero standard of combustion chamber. When a low Nox combustor was introduced in the winter of 1987 a low starting success rate was encountered. This combustion chamber has an increased pressure loss compared with its predecessors and was subject to engine testing at British climatic conditions without any indication of a problem prior to entering service.

The powerful starter motor of the Industrial RB211 is able to crank the HP spool to a fixed speed irrespective of the ambient temperature. Consequently at low ambient temperatures, a larger air flow is delivered to the combustion chamber requiring a greater fuel input to achieve successful light-up. This large injection of fuel combined with the higher pressure loss of the new combustion chamber creates a back pressure on the HP compressor higher than previously experienced during start-up.

The phenomenon described above is well known in axial compressor design and is referred to as 'rotating stall'. It is usually successfully controlled by the use of interstage bleed and/or variable inlet guide vanes (VIGV's). For the RB211, VIGV's are used for the IP compressor and a starting 'blow-off' valve (BOV) in the HP compressor design. No problems had been encountered with rotating stall until employing the new combustion chamber in extremely cold ambients.

The sequence of events during a failed start begins with the starter motor engaging the HP spool. During the subsequent cranking the IP compressor is merely being pulled up to purge speed by the airflow generated by the rotating HP compressor and consequently its speed lags that of the HP. This situation is worsened on cold days due to the increased viscous drag of the lubricating oil. HP compressor entry pressure is therefore depressed during cranking creating favourable conditions for rotating stall.

The new high pressure loss combustion chamber encourages the stall to persist longer. The extra fuel input required for cold day ignition creates additional back pressure on the HP compressor which now begins to operate unstably. Light-up occurs but the HP turbine is unable to drive the compressor out of this condition. The engine trips on high exhaust temperature.
It became clear that the solution was to increase the surge/stall margin of the HP compressor during the start sequence. Two additional HP compressor third stage BOV's were fitted and successful tests carried out in Alaska and on the test bed. These tests showed that rotating stall was absent or dropped out as soon as the IP compressor started rotating. The action of the BOV is to allow more flow into the front stages of the HP compressor so that flow separation off the aerofoils is reduced.

No starting problems associated with rotating stall have been experienced since the introduction of this feature. Since the starting BOV’s close before idle speed, there is no thermal efficiency penalty.

Compressor Blades

The IP compressor stator vanes are the same as those used in the aero engine except that protective coatings have been applied to them. Operating temperatures are also very comparable, however, in the industrial operation, speeds of some units are higher, leading to a resonance condition (Fig.6) not always experienced in the aero engine. Failures have occurred in the later compressor stages, particularly the outlet guide vane assembly (OGV). Coincident with the investigations then being carried out, the airlines were experimenting with the injection of an elastomer into the shrouds of the IP compressor as an anti-frettage feature. This was quickly introduced into the OGV of the industrial engine and its use has subsequently been extended beyond the OGV shroud to all stages of the IP compressor and was found, at the time, to be an entirely effective damping medium.

Increasing service experience however has indicated a time/temperature hardening of the elastomer.

Whilst early compressor stages remained satisfactory, deterioration and hardening was seen in the later stages particularly the OGV which operates at approx. 200°C. More recently an elastomer with a higher temperature capability, has been introduced. This has proved equally effective in damping but still deteriorates with time and temperature although to a lesser extent.

Whilst it has provided an acceptable solution for the aero engine, further improvements are in hand and rig testing is now underway to investigate the effect of heat and frequency (which will in itself generate internal heat) on the effectiveness of state of the art damping media.

The results of this work will be used for rework of the existing assemblies. However, the most effective solution is a mechanical one involving changes to blade form and fixing. A comprehensive redesign is underway to introduce blading with increased chordal thickness so eliminating damaging resonances in the engine operating regime.

The HP compressor is trouble free except for loss of some of the abradable lining in the -24F mark of engine. Development work is now underway to introduce a lining with improved cohesive strength and resistance to corrosion and casing resonances peculiar to this rating.

Turbine Blades - HP

During its service history the HP turbine has been trouble-free except for isolated instances of blade shroud metal loss behind the double pass welded CM64 shroud interlock. The metal loss is considered to be caused by hot corrosion due to high temperature oxidation/sulphidation with very little erosion.

In order to cool the shroud, HP compressor air will be used via drillings in the rear outer rail of the HP NGV. This cooling air can be directed exactly where needed on to the HPT blade shroud (Fig.7) and does not incur any measurable performance penalty.
Turbine Blades - IP

The Industrial RB211 MAR-M-002 IP turbine blade is common with that of the aero engine and has now achieved many millions of hours in airline service. With the introduction of the dual fuel standard of engine the blade material was changed to INCO 738.

It was this standard of blade which experienced failures in 1981 with detachments of the blade shrouds at low hours.

An investigation programme was undertaken which concentrated on reviewing the material properties, build history, quality standard etc. of INCO 738 material since no previous failures had been experienced in MAR-M-002. An engine strain gauge test, supported by Laboratory frequency work, identified that the first torsional mode of the IP turbine blade could be excited by the wake from the 26 IP NGV's at low engine speeds in the speed band 5400-6000 IP RPM. (Base load is nominally 6500 IP RPM) and this together with areas of high microporosity could provide nucleation sites for a high cycle fatigue failure mechanism. The above investigation led to a process change to reduce microporosity by Hot Isostatic Pressing (HIPPING) and to an improved control of shroud clearance by the use of hard coatings on the parallel shroud abutment faces.

No further problems were experienced until late 1984 in Alaska when two engines suffered IP turbine blade failures at very low operating hours.

An immediate investigation of the failed blades showed the same high cycle fatigue as the earlier failures but this time without the previous levels of microporosity. Operating speeds were also similar to those of the earlier failures but at significantly lower ambient temperatures and there were no material defects.

Urgent consideration was then given to the influence of low ambient temperatures on air density at resonant speed conditions which would increase the blade excitation loading. The conclusion reached was that the traditional allowable working stress level should be reduced to give a margin for cold climates. A blade with a shroud interlock which restricts the blades free mode of vibration was introduced in October 1985 only one year after the problem was identified.

The current service hours of this interlock blade now stands at over 352,000 hours with lead assemblies exceeding 23,000 hours and indeed these blades have now further proved themselves last winter operating at temperatures in Alaska as low as -60°C.

Combustion Chamber - Gas Only

Initial gas only operation was carried out using the well proven aero combustion chamber without modification thus maintaining commonality with the aero product. However due to its different duty the chamber's life was limited by burner miniflare (Fig.8) erosion and burning. A change was made to a material better able to cope with these problems and most gas only service engines now use this standard. In recent years an improved standard of combustion chamber has been introduced in which cooling air is swirled over the miniflare Fig.9 so substantially reducing its operating temperature. This standard has been service trialled in the industrial engine with excellent results and will now be adopted for future production units.
**Burner - Gas Only**

Since the aero engine only operates on liquid fuel a gas burner had to be developed. This burner used discreet jets rather than a pintle to control the gas cone angle. Experience on some earlier RR industrial gas turbines, eg Avon, has shown that some gases when burnt can lead to carbon formation and a pintle design of burner is more susceptible to cone angle collapse than one using discreet jets if carbon should be formed on the periphery of the pintle.

Initial problems were encountered due to carburisation and oxidation of the nozzle plate periphery and braze joint (Fig.10). Design improvements have been introduced to resolve the problems as follows:-

- a] Relocate the braze joint
- b] Change nozzle plate material from H188 to N86
- c] Thicken the nozzle plate

These changes have now led to at least five times life improvement over the datum burner standard.

**Combustion Chamber - Dual Fuel**

Development of the dual fuel capability commenced in late 1979. Burner design was achieved by combining the features of the aero liquid burner and the gas only burner with the minimum of geometry changes, however, due to the added requirement of water injection for Nox suppression a larger burner diameter was required.

During service operation, metal loss on the periphery of the liquid fuel pintle has been experienced. Recent development on the aero RB211-535E4 liquid burner to combat ignition, smoke and durability problems has led to the replacement of the burner pintle with a swirler (Fig.11).

A set of dual fuel burners was produced to evaluate a number of potential design changes using thermal paint techniques. A swirler version (Fig.11) proved to be considerably cooler than the other options, its temperatures being close to that of the HP compressor exit air. A programme of starting and handling is now underway to allow this burner standard to be introduced for service valuation in the middle of 1990.

**FIG 10 Gas Burner Improvement Features**

**FIG 11 Dual Fuel Burner**
The combustion chamber differs from the gas only standard in two major mechanical respects, the miniflare is replaced with a floating burner seal and there are only eighteen heatshields (now large enough to accommodate the increased D/F burner dia.) (Fig.12) compared with thirty six of the gas only standard. This combustion chamber entered service with the first dual fuel engines in the North Sea in early Spring 1984 and the lead unit has achieved over 33,000 hours.

**Erosion Appearance**

- Small hole and green discolouration
- 18 off heat shields
- Burner aperture
- Holes with surrounding green discolouration
- Crack from burner hole

**FIG 12 Dual Fuel Heatshield**

Only recently has service operation shown that heatshield life improvements are needed for engines operating at the higher temperatures associated with the -24C rating. A small percentage of the fleet of -24C engines have shown significant metal loss at relatively low hours (Fig.12).

It is important to understand why the heatshields are too hot since high metal temperatures can be caused by either insufficient cooling or combustion heat release very close to the metal surface.

A series of engine tests is programmed for late 1989/early 1990 to evaluate the metal temperatures of various standards of modified heatshields. This will provide diagnostic information on the cause of the high metal temperatures and the effectiveness of the modifications in reducing them.

A revised heatshield will then be introduced based on the results of the tests in the summer of 1990.

In conjunction with the above work a revised dual fuel injector with a non uniform gas jet diameter has demonstrated a reduction in temperature in one area of the heatshield close to the burner. This standard has now been fully cleared for service use.

**THE FUTURE**

**Further Power Uprising**

Recognising the increasing power requirements, in the offshore industry in particular, RR Industrial and Marine is currently engaged in work to uprate the established -24C engine such that increased power is available throughout the ambient temperature range. RR has identified a market for a 15% power increase. This will be achieved by boosting the flow and pressure ratio of the machine by adding an extra stage to the front (ie. zero stage) of the IP compressor. To maintain overhaul lives TET is to remain at today's level. To exploit the extra flow capability of the new gas generator the power turbine size will be increased to approx 340 sq.ins.

The uprated -24 will also include the latest aero HP turbine, this utilise a NGV designed by state of the art computer techniques and sophisticated cooling of the rotor blade. An improvement in HP turbine efficiency is expected. Fig.2 compares the proposed power rating with the current -24C, which will be retained in the product portfolio since it provides adequate power for many applications.

RR consider this engine will be ideally matched to the offshore industry’s power requirements well into the 21st century. However, for other applications where possibly a still greater power will be required, RR could consider an industrial version of the very latest and largest aero RB211 variant, the Trent.

Common with all other industrial versions of the RB211, the Trent fan and LP turbine would be removed. This would leave a core with an 8 stage IP compressor, a new HP compressor of improved efficiency and increased flow and the latest HP turbine matched to the correct size for the industrial version. This turbine would feature rotor blades manufactured using the latest single crystal casting techniques. The most appropriate IP turbine is likely to be the current proven industrial design with a small change to nozzle throat area.

**Emissions**

Worldwide the gas turbine industry is driving towards lower emissions and RR is actively pursuing a programme of work following 3 routes:-

1) Improvement to the current low Nox combustor levels
2) Steam injection
3) New low emissions combustor

A combustion chamber able to comply with the latest German regulations will complete its development evaluation by the end of 1989. In parallel with this testing, the same standard is being used in a comprehensive, primary zone,
steam injection programme aimed at reducing Nox levels to a primary target of 25 vppm. Other benefits will be an increase in power of 6% and a reduction in SFC of 3% in simple cycle performance.

In addition, an exhaustive programme has now commenced to produce a dry fix combustion chamber which will meet all known worldwide regulations without recourse to steam or water injection, since these options may not be suitable or advantageous for a customer.