# Design Evolution, Reliability and Durability of Rolls-Royce Aero-Derivative Combustion Turbines

*Pedigree Matrices, Volume 6*

**1004227**

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# Design Evolution, Reliability and Durability of Rolls-Royce Aero-Derivative Combustion Turbines

## Pedigree Matrices, Volume 6

**1004227**

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# PRODUCT DESCRIPTION

Competitive pressures are driving power generators to exploit aviation combustion turbine technology to create more efficient and powerful generation plants at lower cost. However, the use of aero-derivative combustion turbines (third generation or "next generation") carry a degree of technical risk because technologies incorporated into their design push them to the edge of the envelope. This report reviews the design evolution and experience base of advanced Rolls-Royce aero-derivative combustion turbines in a comprehensive format, which facilitates an assessment of the technical risks involved in operating these high-technology combustion turbines. In addition, a quantitative analysis-or reliability, availability, and maintainability (RAM) assessment-is made for Rolls-Royce’s Avon, RB211 and Trent aeroderivative engines.

## Results & Findings

Elements of aero-derivative technology developed in the 1970s form the basic design foundation of the aero-derivative type machines of today. These designs have been refined over time to provide proven, reliable, and maintainable designs while allowing the users the maximum degree of flexibility in plant designs or configurations. The aero-derivative's greatest asset is its modularity. With complete interchangeability of like modules and line-replaceable components, it relies on a maintenance philosophy called "repair by replacement.” High performance, high efficiency aero-derivatives are also fast starting and tolerant to cycling, characteristics that make them suitable for peaking power and distributed generation applications. There are some generic long-term problems associated with aero-derivatives, however, including bearings and seals that require monitoring and conditioning equipment, Dry Low Emissions (DLE) combustion systems that need refinement, and compressors sensitive to stall or surge.

The ultimate result of this report is a concise presentation of the design evolution of Rolls-Royce combustion turbines in the form of a pedigree matrix that allows risk to be assessed. The pedigree matrices identify design trends across all of a manufacturer's products that can be categorized as low, medium, or high risk. Some of the trends identified as high risk include (1) single crystal alloys and complex cooling schemes, (2) DLE combustion systems, and (3) proprietary Thermal Barrier Coatings (TBCs) and bond coatings exclusive to industrial turbine applications. Experience information includes site listings, O&M issues, and RAM-Durability fleet data to provide a comprehensive assessment of model maturity.

## Challenges & Objectives

Adapting aviation combustion turbine technology to power generation allows power companies to benefit from development efforts and costs already absorbed by commercial and military development programs. Computer-aided engineering and design programs and computer-aided manufacturing programs make it possible to rapidly develop and produce new turbines. However, this increased rate of change has increased the potential risk of new product introductions as design changes go from the ‘drawing boards’ into production testing at a customer’s site early in the learning curve. The absence of long-term experience with the technology raises issues of reliability and durability. For specific models and components, chronic durability problems could result in insurability issues potentially undermining a project’s financial structure.

## Applications, Values & Use

This report, along with EPRI’s previously published design evaluations for GE aero-derivative combustion turbines (EPRI report 1004220) and Pratt and Whitney aero-derivative combustion turbines (EPRI report 1004222), provide a context for the risk assessment of currently available aero-derived combustion turbine designs for power generation. This information is essential background to generation planning and equipment procurement decisions. Aero-derivative machines have been of particular interest due to their inherently short construction schedules, fast startup times, and ease of maintenance, particularly in simple cycle configuration for peaking and distributed generation service.

## EPRI Perspective

To help project developers, owners and operators manage the risks of new combustion turbine technologies, the durability surveillance report series supported by the EPRI New CT/Combined Cycle Design and Risk Mitigation Program provides a structured context for understanding design changes that drive these risks and related life cycle O&M costs. This information fully complements a machine selection process heavily based on first cost, efficiency, and delivery schedule. The multi-volume report series, along with regular updates, covers heavy-frame and aero-derivative turbine product lines manufactured by ALSTOM, General Electric, Pratt & Whitney, Rolls-Royce, Siemens Power Generation, and Mitsubishi Power Systems.

## Approach

The project team reviewed the design characteristics of the Rolls-Royce aero-derivative combustion turbine product lines (RB211, RB211 Uprate, and the Trent) to assess the technical risk associated with these advanced technology combustion turbine designs. Information was drawn from operations data and directly from the owners of machine fleet leaders operating in peaking, cycling or baseload service. The resulting pedigree matrix supplemented with reported experience consolidates information for each combustion turbine model into a format that allows the reliability status of the machines to be reviewed and major design changes or areas of potential risk to be evaluated. In addition, the team determined RAM statistics from the fleet of engines reporting to the Operational Reliability Analysis Program (ORAP) database.

## Keywords

Combustion Turbines
Aero-Derivative Gas Turbines
Reliability
Durability
Risk Assessment

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# INTRODUCTION

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The power generation market place and the combustion turbine market in particular are evolving at an ever-increasing pace. Market forces are driving the introduction of new technologies and advanced combustion turbines designs. The introduction of these technologies inherently involves risk. The economic pressure of a market moving towards deregulation intensifies this risk of new technologies. Whereas in the past new products were gradually introduced into the market, the demands of competing in an open market have driven the pace of incorporating new technologies to improve profitability on a $/kW basis. The intent of this report is to allow a qualitative assessment of the risks involved in the use of these new technologies to be made.

In reviewing the available information on the designs of the heavy-duty combustion turbines, several immediate observations can be drawn on the progression and evolution of the combustion turbine over the last several decades. The economic pressures in the market place have driven the pace of incorporation of military and commercial aviation combustion turbine technology (e.g. single crystal turbine blades) into the power generation market. This increased rate of design changes has also increased the potential risk of the new product introductions. This increased risk is incurred for several reasons but is primarily attributed to going from the ‘drawing boards’ into production testing at a customer’s site early in the learning curve before the design changes have been fully tested and proven over time.

In the past, the rate of incorporation of military and commercial aviation combustion turbine technology into industrial combustion turbines was slow due to limited production schedules (compared to military or commercial aviation) and largely limited to the under 50 MW class of industrial aeroderivative combustion turbines. In recent years, this technology is being incorporated into the new generation frame machines to create more efficient and powerful plants at lower costs by:

- Taking advantage of the development efforts and costs initially absorbed by the commercial and military development programs
- Availability of computer-aided engineering and design programs (CAE/CAD)
- Computer-aided manufacturing programs (CAM), and the current worldwide manufacturing capability

The advanced frame machines being produced today and the future Advanced Turbine System (ATS) machines sponsored by the U.S. Department of Energy are blending these technologies more quickly and producing hybrid combustion turbines with frame technologies, aero designed flow paths, aero designed cooling technologies, and industrial designed low $NO_x$ combustion systems. The advanced industrial machines have even surpassed the military and commercial turbines in combustion technology with dry low $NO_x$ and CO levels that are several orders of magnitude lower and meet land based pollution requirements in many geographic areas.

The enabling technology of today's advanced frame machines lies with the computer codes and manufacturing processes developed by the aviation combustion turbine industry. The application of these processes is inevitable under the pressure of the power generation industry to produce power at low cost with maximum efficiency, reliability, and availability.

The power generation combustion turbines have different operating demands than the aviation combustion turbines and the designers and developers have programs in place to advance the technology beyond the aviation programs. Manufacturers have extended the technology to more advanced industrial thermal barrier coatings (TBCs), oxidation resistant coatings, bond coat technologies, large size single crystal blade and vane manufacturing processes, single digit dry low NOx combustion systems, and integrated electronic digital control systems handling more than 4800 I/Os.

The trends by all the major manufacturers are similar with the adoption of the aviation technology into the flow paths, with corresponding advances in materials, cooling schemes, coatings, and clearance control. The basic approach, inherent in each manufacturer's design philosophy, is evident in their general combustion turbine designs (rotors, combustion systems, and proprietary technology) but the general trend to higher firing temperatures, pressure ratios, efficiency, low emissions, reliability (99%), and availability (96%) goals is similar. The overall approach to compete worldwide is based on cost per MW. Supporting the supplied equipment with long term maintenance contracts is the internal corporate incentive to provide reliable equipment and designs. With the merging of companies and aviation and industrial technologies to maintain competitiveness, the large frame combustion turbines are 'hybrids' absorbing technology that previously lagged by a decade before incorporation into industrial turbines. The industrial aero-derivative and some advanced frame combustion turbines are to the point of being the leading edge of technology in the overall combustion turbine environment in terms of efficiency, emissions, and advanced technology.

This strategy by the manufacturers is propelled in large part by advanced combustion turbines becoming the "only game in town" due to the current worldwide disfavor with nuclear and fossil boiler plants. The requirement to provide sited power quickly and cost effectively, with guarantees, is pushing these technologies forward at a rapid pace.

In order to understand the risk associated with new product introductions, the changes in the new products must first be understood. The design evolution of these machines have been reviewed and incorporated in a Pedigree Matrix. The pedigree matrix consolidates information for selected combustion turbine models into a format that allows the design evolution of the advanced machines to be reviewed and major design changes or areas of potential risk to be evaluated.

## Risk Trends

Based upon the review of the designs from all of the manufacturers, several trends are readily apparent. These trends in the development of advanced designs involve incorporation of current industrial combustion turbine technology, transfer of aircraft engine technology to industrial combustion turbines, and new technologies developed specifically for industrial combustion turbines. The subsections below discuss these trends in general terms and categorize the trends in terms of relative risk (Low Medium, or High).

### *Current Technology Trends Related to Industrial Combustion Turbines: Low Risk*

Elements of aero-derivative class technology developed in the 1970s form the basic design foundation of the aero-derivative type machines of today. These designs have been refined over time to provide proven, reliable, and maintainable designs while allowing the users the maximum degree of flexibility in plant designs or configurations. These design trends, which can be considered relatively low risk with respect to product reliability, include:

- High Degree of Modularity and Interchangeability
- Flight engine heritage provides for modular construction with separate sections completely interchangeable with other like modules.
- Compact size allows for ease of maintenance and allows for easy removal in sections or in its entirety with relatively common tools.
- Bolted on accessories and on-engine instrumentation that is accessible and designed for ease of removal and replacement.
- High degree of commonality with the flight engine to retain durability gains of proven hardware and retain lower costs due to higher production rates.
- Pre-tested packaged power units with small foot print for multiple units per site
- Fast starting and loading with tolerances to cycling duty.
- Easily adapted to cogeneration and combined cycle configurations.

### *Applied Aero Technology Trends Directly Transferred to Industrial Combustion Turbines: Low to Medium Risk*

Technology transfer with minimum risk to industrial aero-derivative and frame type combustion turbines based on proven designs from the military/commercial combustion turbine have been accomplished with CAE/CAD/CAM programs and analyses. The result is dramatic efficiency and airflow performance improvements (e.g. air and gas flow paths) without impacting the reliability or availability of the combustion turbine. Variable position compressor vanes have contributed to improved part load performance and are desirable for DLE combustion. Aerodynamic 2D and 3D designs have improved surge margins, compressor efficiency, and general operability ranges. The aero-derivative compressors are sensitive to the occurrence of surge and usually require a borescope inspection after a surge occurs to inspect for any abnormality in the flow path. Adoption of proven aviation technology has minimized leakage paths and has improved clearance control. These aviation to industrial transfer technology trends, which can be considered low to medium risk with respect to product reliability include:

- Advanced compressor designed flow paths
  - Controlled diffusion airfoils
  - Multiple circular arc airfoils
  - Double circular arc airfoils
  - 2D and 3D aerodynamics
  - Variable vanes
  - Shrouded stators with improved labyrinth seals
  - Increased surge margins
  - Exit (outlet) guide vanes
- Active and Passive Clearance and leakage control

### *Advanced Aero Technology Trends Transferred to Industrial Combustion Turbines: Medium to High Risk*

Hot end technology transferred to industrial turbines with firing temperatures in the 2300 $^o$ - 2600$^o$F (1260$^o$ – 1427$^o$C) range has been a challenge because of the duty cycle imposed on the land-based turbine. The advanced materials (e.g. single crystal [SC] castings), exotic cooling schemes, advanced coatings, and clearance control all had to be scaled to the sizes utilized in the larger frame sized combustion turbine. Designing the 3D aerodynamic flow path and providing adequate cooling for all the required blade and vane rows without exceeding base metal temperature was required while maintaining durability, acceptable stress levels, and vibratory characteristics.

The manufacturing of turbine blades and vanes with single crystal technology and the development of appropriate coatings and bond coatings for these materials is a challenge for the designers and manufacturers and currently should be classified as medium to high risk due to the current level of experience in the field. These advanced aviation to industrial transfer technology trends, which can be considered medium to high risk with respect to product reliability include:

- Turbine flow path
- 2D and 3D aerodynamics
- Advanced cooling technology*
  - Convection cooling schemes
  - Impingement cooling schemes
  - Film cooling schemes

  - Multi-pass serpentine cooling schemes
  - “Shower-head” cooling schemes
- Advanced materials
  - Directionally solidified alloys
  - Single crystal alloys*
  - Low sulfur alloys*
- Advanced coatings
  - TBCs*
  - Oxidation coatings*
- Clearance and leakage control
  - Passive
  - Active*
  - Abradable shrouds/labyrinth seals
  - Brush seals

* Higher risk technologies

### *Independently Developed Technology Applied to Industrial Combustion Turbines: Medium to High Risk*

Some technological advances require independent design and development for the conditions and environment the land based combustion turbines experience. The exhaust emission requirement is a prime example where current regulations require $NO_x$ emissions below 25 ppmv, with an increasing number of locations requiring single digits. The aviation industry has not yet addressed this challenge. The duty cycle of the aviation combustion turbine requires take-off temperature for 150 to 300 hours total during its overhaul cycle (operational time to depot repair) whereas the industrial land based turbine with DLE control, turndown requirements, inlet heating, and ambient temperature could conceivably operate at continuous rated power and rated firing temperature for the majority of its overhaul cycle. Since the time at temperature constraint is greater for the industrial combustion turbine, the TBCs, oxidation coatings, bond coatings, and materials must survive in a much harsher environment long-term than the commercial aviation equivalent combustion turbine. Reliability and durability of this technology is considered medium to high risk because much of the enabling technology has to be developed and proven. Existing advanced systems are complex and have yet to be proven for long term durability. Blades that have exotic coatings, in some cases, cannot be stripped and recoated, thus are non-repairable and may not achieve full design life for the combustion turbine design. This results in increased life cycle costs. Steam cooling for the combustion transition pieces, vanes, and/or blades is being developed by manufacturer, university and DOE/ATS development programs and is entering commercial use. Advanced industrial technology trends which are considered medium to high risk with respect to product reliability include:

- Dry low $NO_x$ Combustion systems*
- Cannular and annular designs with multiple fuel injection nozzles
- Exclusive industrial TBCs and bond coatings*
- Exclusive oxidation coatings*
- Closed loop steam cooling systems*
- External cooling air cooling systems
- Closed loop air cooling systems
- Staged combustion for high turndown capability

*Highest risk technologies

Rolls-Royce advanced aero technology is being applied to ALSTOM engines under a long-term technology transfer agreement (ref. *Diesel & Gas Turbine Worldwide* April 2002, p. 4). Very high temperature technologies, advanced aerodynamics, very high strength/high temperature materials and protective coatings will be applied to improve efficiency, power output and durability of ALSTOM's heavy duty combustion turbines. Note that a technology transfer agreement was in place with Westinghouse in the early 1990's to apply advanced technology to the frame 501F and G machines. Considering that Westinghouse and Mitsubishi Heavy Industries developed the 501F/G machines jointly, the same technology may have been incorporated into the 50 Hz 701F/G machines by MHI. Furthermore, Siemens subsequently acquired Westinghouse, presumably gaining access to that previous technology as well.

### *Other Risk Factors*

The transfer, development, and introduction of new hardware into the industrial power generation environment are part of the scope of a system that contributes to the life cycle cost picture. Hardware, first cost, and new advanced technology is misused if the integration of the whole system from "cradle to grave" is not addressed, because hardware is only a portion of the risk. Some elements of these "other risk elements" are summarized below. This is not intended to be a complete list of items. These items may have as significant an impact on the successful lifetime operation of the plant as the "advanced hardware" if not addressed adequately.

#### Users

- Experience/skill level
- Degree of training
- Cost reduction in O&M programs
- Heavy reliance on OEM's

- Single, large capacity units
- Minimum resources applied to Monitoring, Diagnostic, and Prognostic Programs

**Original Equipment Manufacturers**

- Integration of systems
- Competitive economics
- Corporate downsizing
- Sourcing compromises (country of sale or worldwide)
- Long term maintenance contracts (burden on OEMs) and extent shared with the suppliers

## The Use of Advanced Technology for Peaking Duty

The attraction of the new technology combustion turbines, as compared to what can be called "mature" technology combustion turbines, lies primarily in the increased thermal efficiency. Current "Advanced Class" combustion turbines (those with firing temperatures of 2300°F (1260°C) or greater) have simple cycle efficiencies that are approximately 2% better than their "mature" technology or earlier counterparts. This efficiency increase makes an enormous difference in operating costs over the life of the plant. Obviously, the more the plant operates, the bigger the advantage would be.

The aero-derivative combustion turbines also offer more flexibility of power when multiple units are at a single site. Fast starting and loading times means that multiple blocks of capacity can be quickly dispatched in cycling duty with added flexibility for the User.

For many, new technology would be the clear choice, all other things being equal. However, all other things are seldom equal. The other differences that must be evaluated are several. During system peaks, when power can be sold at steep premiums, having the ability to produce some fraction of plant total capacity (i.e. 4 of 6 RB211's operating) can have a very favorable impact on profitability versus one large frame unit down for an extended period of time.

New technology also pertains, separately, to environmental compliance and emissions performance. Indeed, the mature classes of combustion turbines may be forced to utilize new technology combustion systems to meet stricter emissions standards. Generally, higher $NO_x$ emissions would be produced at the higher firing temperatures and the turbines with the highest firing temperatures require the most sophisticated emission control technology. To control $NO_x$, and CO, manufacturers use complex combustion systems designed to precisely control the fuel/air mixture and the combustion process in general. There is clear evidence that these complex systems are not as robust as their simpler, low-tech counterparts. However, it is the site emissions requirements that dictate the selection of combustion systems.

Consequently, the advantages of new technology combustion turbines must be evaluated against the disadvantages. The cost of fuel will be a very important factor in the determination, as will the expected service time of the unit. If service time is low, and the cost of fuel is low, then the efficiency advantage of the new technology combustion turbine might not offset the increased maintenance costs. It is a difficult equation to solve, especially when trying to predict changes over the 20 to 30 year life of a typical plant.

## Insurers and Lenders Perspective

Technology risk is of interest not only to owners and operators but also to insurance companies and project lenders. Insurers protect owners and lenders from major financial loss due to costly but infrequent accidental events. In some cases, unproven technology and changes in design can lead to catastrophic failures and/or extended durations of unavailability. Insurers are therefore keenly aware of the introduction of new models and designs. Insurance for newly introduced “prototype” designs typically require very high financial responsibility on the part of the manufacturer until they have demonstrated several thousand hours of operation. At that point, the new model enters the category of “unproven” until typically one to three units leading the fleet have operated successfully for over 8,000 hours at rated conditions. During this period, some components may be excluded from coverage, as well as design and manufacturing defects. Depending on the results of this operating period, the insurer would then classify the model as “proven”, although they may take exception to insurance coverage for certain high-risk components until problems are resolved. In going from “prototype” to “unproven” to “proven”, deductible and premium amounts are reduced as the insurer perceives less risk. Extensive testing of the engines for reliability in a controlled environment such as a manufacturer facility is judged as being far superior to field testing to demonstrate performance and reliability.

Advanced technologies are perceived as having more risk mainly because they are being used in new applications and are being scaled up to larger capacities. Overall, insurers consider the following factors as significantly extending the risk of accident:

- New designs (typically highlighted by a change in model name)
- Higher firing temperature
- Higher capacity/output
- Higher compressor pressure ratio

Major insurance companies closely monitor and track performance of the combustion turbine suppliers and their specific models individually, and track their claim history for each model. Some insurers retain more in-house engineering expertise than others, but all have become more dependent upon OEM technical and marketing materials for information. Interestingly, some combustion turbine models are rated differently by different insurers; manufacturers are generally eager to get their models moved from “unproven” to “proven”, signaling more acceptance by insurers and therefore easing the sale of their model to the project developer. It appears that an insurer’s recent claim history and/or anecdotal evidence plays a major role in the models risk rating.

Insurers expect to profit from their activities by the receipt of premiums and their investments. However, their experience in the 1990’s was that insuring combustion turbines was a losing business. In 2001 and 2002, premiums were increased and deductibles were increased to try to compensate for their losses. Some companies concluded they would no longer participate due to the perceived risks, while others entered the market due to improving margins. In 2004 and 2005, the market again became “softer” and premiums decreased on a relative basis. The insurance market appears to be fundamentally based on supply and demand of its “product”, with volatility somewhat decoupled from quantified technical risk.

Project lenders are highly risk-averse to a multitude of risks, and require the project owner/ operator to carry insurance so that the cash flow to service the debt is secure. Typically, the owner/operator obtains their insurance coverage through a broker, who deals with a number of primary insurers to find the best financial arrangement for the insured. Although the primary insurers actually underwrite the risk, issue the policies, and settle claims, they in turn pass along much of their risk along to one of several reinsurance companies. In essence, the primary insurers themselves are risk-averse and the primary insurance risks are aggregated by the re-insurers.

The main type of insurance that is impacted by technical risk is Boiler and Machinery Insurance (or Machinery Breakdown Insurance). This insurance covers direct damage from sudden and accidental breakdown of mechanical, electrical or pressure vessel equipment, such as turbines, boilers, generators, motors, pumps, transformers and switchgear. Deductible amounts are typically set to be higher than the maximum loss that could be typically expected over the course of the normal life, i.e. an amount that would be typically budgeted as an allowance for unplanned maintenance, and that the project could sustain without jeopardizing its financial health. Deductible amounts of $500,000 to $3,000,000, depending on project size, would not be uncommon.

Business Interruption Insurance is sometimes also required, depending on the project. This insurance covers the revenue lost due to the lack of generation i.e. unavailability, over an extended period of time caused by an event covered under the Boiler and Machinery Insurance. In this case, the deductible is typically expressed as a number of days, i.e. the maximum normal number of days to obtain parts and install them if required to return the unit to service, typically 45-60 days, although longer periods result in lower premiums.

When insurers are quoting coverage level for a particular project and the annual premiums and deductibles, many factors are considered. Besides the many aspects of uncertainty and costs related to potential risks, insurers also consider the general marketplace for their products, the degree of competition, and their ability to gain additional business associated with the power project. Technology risk is one part of the equation

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# 2

# ROLLS-ROYCE AERO-DERIVATIVE COMBUSTION TURBINE BACKGROUND

## Summary

Rolls-Royce's aero-derivative heritage goes back more that forty years with an active role in establishing the combustion turbine in marine application with such units and the Proteus, Gnome, Tyne Spey, and Olympus combustion turbine propulsion units. Rolls-Royce has more than 975 marine installations with over 6 million operating hours. Many units are still operating today.

The Proteus (2.7 MW/4,000 hp) and Avon (14MW/19,000 hp) combustion turbines were used in industrial applications for electrical generation and mechanical drive applications since 1964. These two units have more than 1200 units installed base with more 48 million operating hours.

The acquisition of Allison engines in 1994 added additional scope and experience in the 2-9 MW range with various models of the Rolls Allison 501, 601, 570, and 571. The Rolls Allison family of combustion turbines adds an additional 2200 units and 75 million operating hours of experience.

Initial designs for the aero-derived industrial RB211 began in 1965 with the first installation in 1974 in pipeline service. The first DLE production RB211 was delivered in October of 1994 to Pacific Gas Transmission Company in pipeline service. The RB211 has more than 410 units and an installed base with more than 15 million hours of operation, with over 50 customers in 20 countries. The RB211 has over 220 onshore and 120 offshore installations. There are more than 70 DLE units with well over 1,000,000 hours of operation, with the lead unit at over 45,000 hours.

The industrial Trent began initial design work in 1988 and became operational at the Whitby Cogeneration Project in 1996. The industrial Trent is the world's largest aero-derivative combustion turbine at 51.2 MW and 41.6% efficiency at ISO conditions. The new water-injected Trent can achieve 58 MW.

## RB211 Background Information

The RB211 has evolved since its introduction in 1974. The RB211 was a successful follow-on to the highly successful Avon used in utility, industrial power generation, cogeneration, mechanical drives, and gas compression. The RB211 has a two-spool gas generator with a seven-stage low pressure compressor (LPC), six-stage high pressure compressor (HPC) driven by a single-stage high pressure turbine (HPT), and a single axial stage, low pressure turbine (LPT) which drives the LPC via an inner coaxial shaft, for a total of 5 pre-balanced modules. The RB211 for power generation is derived from the three-spool aero RB211 flight engine in which a final three-stage turbine drives a single-stage wide-chord fan.

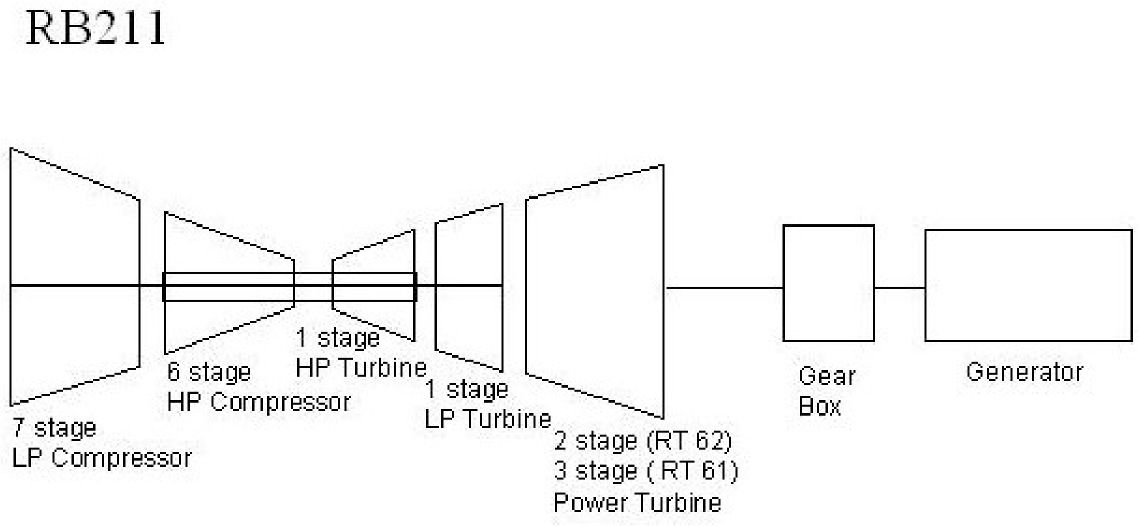

**Figure 2-1**
**Industrial RB211: Gas Generator and Free Power Turbine**

The standard combustor is a single, fully annular, combustion chamber with eighteen air-spray burners with atomizing fuel nozzles for liquid fuel. The DLE combustion system was introduced in 1994 that resulted in a radical design change to the combustion module. The design change includes nine reverse-flow radial combustors. Each combustion chamber contains a two-stage combustion assembly with the air and fuel divided between the series-staged combustors. The combustion module has the same physical dimensions as the standard module and is completely upgradeable for all RB211 units without incurring a major overhaul. Combustors can be configured for gas, liquid or dual fuel capability.

The RB211 incorporates an industrial type, free power turbine on a large pedestal base that supports both the power turbine and the gas generator. The power turbine (for earlier models RT 56 and RT 62) is a two-stage free power turbine that uses journal bearings and mineral oil for lubrication. Aimed at the pipeline/compressor drive application (oil and gas market) the power turbine is design to rotate at 4800 to 4880 rpm. The RB211 is a hot end drive. For utility applications, a reduction gearbox is required to reduce the speed to 1500 or 1800 rpm to drive a four-pole generator for 50 and 60 hertz utility applications.

The new three-stage RT61 free power turbine, based on the aero Trent 800 engine's turbine, is designed for improved efficiency and is used with the uprated RB211. The new design incorporates a three-stage, free power turbine but is lighter in weight with modular construction for ease in maintainability. This unit also requires a reduction gearbox in electrical utility applications.

Several significant upgrades are available for RB211-24C and -24G gas generators which are generally included in the RB211-24GT:

- DLE "short style" combustor for premix natural gas firing. The new "short style" reduces acoustic resonance and dynamic pressure pulsations compared with the previous "long style" DLE burner. The DLE retrofit can achieve less than 25 ppm of $NO_x$ and CO. There are over 80 units with over 1.5 million hours experience with the DLE combustor (may includes all DLE styles). The DLE burner generally requires no manual tuning in the field.
- Dual fuel conversion for diffusion flame combustion of natural gas or fuel oil includes the swirler burner for improved liquid fuel firing, as well as improved gas firing when it contains condensable liquids
- Gas generator RB211-24G from -24C. Includes replacement of the HP turbine assembly, including new directionally solidified blades with improved cooling. Either the user can choose to maximize power and efficiency, or extend creep life of components by up to 50% by derating the firing temperature 25 F (14 C).
- IP Compressor life improvement. A new stage 7 stator design and new stage 5 and 6 components reduce frettage due to aerodynamic excitation that ultimately could cause stator breakup and downstream damage.
- Power turbine upgrade of either RT56 or RT62 for use with higher temperatures from the RB211-24G gas generator. The upgrade generally includes blades, vanes, casings and diffusers.

### RB211 Horsepower Ratings

| Engine type | Horsepower | Designation |
|---|---|---|
| -22 | 26,400 | Coberra 264 |
| -24A | 29,600 | Coberra 6256 |
| -24C | 34,000 | Coberra 6456 / 6462 |
| -24G | 39,600 | Coberra 6562 |
| -24G DLE | 40,500 | Coberra 6762 |
| -24GT | 45,000 | Coberra 6761 |

| | |
|---|---|
| **RT 56 –** | (Cooper Bessemer) 56” Diameter, two stage, Reaction Turbine.<br>**For the –22, -24A and –24C engines** |
| **RT 62 -** | (again Coopers) 62” Diameter, two stage, Reaction Turbine.<br>**For the –24G and –24G DLE engines** |
| **RT 61 -** | (based on the Trent 800 aero engine) 61“ Diameter, three stage, Reactive Turbine<br>**For the –24GT or uprated engine** |

### *RB 211 Maintenance Approach.*

The time line for RB 211 maintenance, based on over 25 years of operating experience, is as follows:

- 2,000 hour Inspection and Compressor soak wash
- 8,000 hour Inspection and borescope inspection
- 25,000 hour Mid Life Inspection & 04 Module Overhaul
- 50,000 hour Full Overhaul of the engine

  *(Inspection/overhaul details and workscope are described in the Appendix).*

Both the 2,000 and 8,000 hour Inspections are carried out with the engine remaining in place. The 2,000 inspection and soak wash can be accomplished in 4 to 6 hours, whereas the 8,000 hour inspection with the borescope will need 8 to 10 hours of downtime. The standard turnaround time for the RB211 gas generator is roughly 40-50 days.

For the Mid Life Inspection, the engine has to be removed from the berth but may be overhauled at the site or depot. If spare 04 Module and IP Compressor Stator assemblies or access to ‘pool’ units is available, the work can be done on site. Otherwise, the engine is dispatched to the Vendor’s overhaul shop to carryout this operation.

The Modular design of this engine allows for the swap of any Module once the engine is ‘bulk stripped’ to its individual Modules. In the case of the 25,000 hour Mid Life, the 04 Module has to be changed out. With the Vendors repair crew of two / three men, along with their tooling, this task can be accomplished in three to four days, depending on client’s downtime window. Two cranes (3 Tonne & 5 Tonne) with a lift height of 14 meters is a minimum requirement.

Historically, there are two areas in the RB 211 that have been life-limiting features. First, the rubber dampening used in the inner shrouds of the **I.P. Compressor Stage 5, 6 Stator** assemblies and the **Stage 7 Stator or Outlet Guide Vane** assembly degrades. This allows the vanes to ‘flutter’ and leads to high cycle fatigue. Thus far, these assemblies have to be inspected at 25,000 hours. Secondly, the **‘Z’ notch of the H.P. Turbine Blade outer shrouds** suffers from heat erosion and need to be repaired at this juncture. Failing that, the erosion will progress to a point where the blades are beyond repair limits.

Once the engine is removed from the berth, it can be placed on its transportation stand. At this point the I.P. Turbine assembly can be uncoupled from its curvic coupling and removed. Then, by use of the two cranes, the engine can be lifted into the vertical position and be placed nose down on the lifting fixture. This allows for the removal of the 05 and the 04 Modules.

At this point the 01, 02 and 03 Modules are lifted and turned such that the assembly is now resting on the 03 Module casing. This allows for the removal of the 01 and 02 Modules. Once the 02 Module is removed the half casings can then be split, allowing access to the Stage 5 and 6 Stator assemblies for replacement.

The Stage 7 or OGV Ring assembly is the front part of the 03 module and can be replaced with the spare assembly or ‘pool’ unit.

Rebuilding the engine is basically the reverse of the above procedure.

The 04 Module, along with the I.P. Stage 5,6 and 7 Stators, are then taken back to the overhaul shop for full refurbishment to the latest Mod standard, to be placed back in the ‘pool’ or returned to the Customer, if they were his spare assemblies.

One thing that should be emphasized here is that this experience is based on base load operation, using gas fuel. Deviations from this scenario i.e. prolonged running with the bleed valves open, will alter the inspection criteria. Other than these inspections **clean fuel** and **clean air** are a must, to help prolong the life of the engine.

### Turnaround Time and Costs

- As mentioned above, a Mid Life can be accomplished in the field with two men in 3 to 4 days.
- The 04 module will take approximately 40 days to fully recondition in the overhaul shop. In the case of the IP Stage 5, 6 and 7 Stator assemblies, it will take 21 days to accomplish their repair.
- Average cost of a Mid Life on the above components has been running in the region of $ 345,000 to 375,000 US.
- For a full engine overhaul, the turntime is averaging 95 days and the costs are in the region of $850,000 US.

### Parts Life Upgrades

As discussed in the section - Maintenance Approach, the parts life issue was detailed. In the case of the I.P. Compressor Stator assemblies, here are the latest Modifications these parts should be refurbished to.

**I.P. Stage 5 Stator:** to Mod. 1205. This will put hard facing on the vane feet and the assembly will be re rubbered with machine injected, RTV 851 dampening medium.

**I.P. Stage 6 Stator:** to Mod. 1159, as above

**Stage 7 (OGV Ring):** to Mod. 1190, as above

**Note:** A redesigned OGV Ring was introduced thru Mod. 1249. This assembly cannot be reworked from Mod 1117 or Mod 1190 assemblies. The redesigned vanes in this standard, feature full width vane feet, hard facing and the RTV 851 rubber. New engines will have this latest standard.

**H.P. Turbine Blades:** To combat the 'shroud erosion' extra cooling air and a better protective coating was introduced to the blades.

**Mod 1217:** This introduced rear outer discharge nozzle (RODN) slots in the package 1 combustor that delivered cooling air to the outer shroud of the blades.

**Mod 1131:** H.P. Turbine Blades in MAR M002 material and coated with Sermaloy 'J'

**Mini Flare Erosion:** Burning and erosion of the Combustion Liner 'mini flares', although not a life limiting feature, it will eventually cause problems to the fuel nozzle head section.

These 'mini flares' are changed at the 25,000 hour refurbishment of the 04 Module. Any minor flaking of the thermal barrier coating (TBC) in the combustor can also be repaired at this time.

**05 Module 'Coking':** Another area of risk in the RB 211 has been oil 'coking' in the scavenge and vent lines in the 05 module. This is cause by 'crash' stops, where the latent heat causes the residual oil in the bearing cavity to coke up. Over time this coke completely blocked the main oil scavenge line and oil was forced out the bearing cavity vent lines.

There are two ways to solve this problem.

First, review the unit's shutdown experience and determining what can be classed as a 'cool' stop. A 'cool' stop is where the engine is brought down to idle RPM and remains at that speed for 5 to 8 minutes, before being shutdown. This gives the engine, and the close coupled Power Turbine, a chance to 'cool' considerably from their running temperature. On actual field tests it was found that on a crash stop the bearing cavity can see temperatures in excess of 400 degrees in the ninety minutes following a crash stop. Whereas, on a cool stop that cavity temperature only got up to just over 275 degrees. No oil in the world can stand the former temperature, without laying down some coke.

Secondly, to allow for the emergency stops – fire, gas in the building etc. modifications were incorporated to get cool air into the 05 Bearing Cavity after such an event. A Davis valve (Mod 1136) has shop air connected to one inlet. When the engine suffers a crash shutdown, the valve opens allowing shop air to pass, via the vent lines, into the bearing cavity thus keeping it cool. Mod 1135 was also introduced to allow a double vent of this cavity, and Mod 1123 fits a new connection on the 05 module that a pressure gauge can be installed to set the shop air pressure to the bearing cavity.

Service experience has shown that the combination of these modifications has greatly reduced the amount of oil 'coking' seen in this bearing cavity.

**H.P. Compressor – Stage 5 Vanes:**
There have been incidents of High Cycle Fatigue cracking on Stage 5 H.P. Compressor Vanes. It has been associated with Operators who experience extremely cold ambient conditions. It has also occurred when the bleed valves have been way out of their schedule, or the bleed valve controller has seized.

Mod 1275 introduces the 'spade foot' stator to overcome this problem.

**DLE Combustor Noise:** Mod 1313 has gone a long way toward reducing the 'noise' in the DLE combustor. This modification introduces Asymmetric Fuel Injectors in the Primary combustion area.

However, 30% of the engines still had unacceptable levels of noise. Asymmetric or split Secondary Fuel Injectors are now being introduced

## Trent Background Information

The industrial Trent design uses much of the aero Trent 800 engine core with the addition of a new two-stage low-pressure compressor (LPC) in lieu of the high-bypass wide-chord fan on the aero Trent. The main difference is the radical change to the DLE combustion system with eight can-type combustors that are reverse-flow combustion design, radially mounted, perpendicular to the axis of rotation. The DLE concept has been designed in the industrial Trent upfront. Initially, the unit had difficulty meeting 25 ppm $NO_x$ emissions. A Wet Low Emission (WLE) version has been developed and has been running in the UK. On-line emissions monitoring controls water usage to meet emission levels for changes in power demand and ambient conditions.

The 8-stage intermediate pressure compressor (IPC) and the 6-stage high-pressure compressor (HPC) are identical to the Aero Trent 800. The HPT and IPT are also single stages and identical to the Aero 800 Trent. The low-pressure turbine LPT incorporates five stages, of which the first three stages are identical to the Aero 800 Trent. The last two stages have longer blades because the low-pressure shaft system is a direct drive system rotating at lower speed than the aero and the expansion ratio is higher. This increase in expansion ratio is due to the need to extract all the available energy for power production in the industrial turbine while the aero version retains some of this kinetic energy to provide thrust.

Like GE's LM6000, the low-pressure spool rotates at 3600/3000 rpm and is directly coupled to the generator. No reduction gearbox is required. For 50-Hertz operation, the stagger angle on the low-pressure compressor blades are changed slightly and the LPC rotates at 3000 rpm. The industrial Trent is unique in that it is the largest aero-derivative combustion turbine in the world at 51.2 MW and incorporates the three-shaft arrangement in both the compressor and turbine sections. The industrial Trent is a hot end drive.

The three-shaft arrangement provides for better stage matching and performance since each spool is optimized and allows for more efficient operation than an equivalent 2-spool turbine. This design results in fewer stages, fewer airflow regulating provisions such as variable stators and bleeds, a shorter turbine, and a high degree of modularity with its attendant benefits during maintenance.

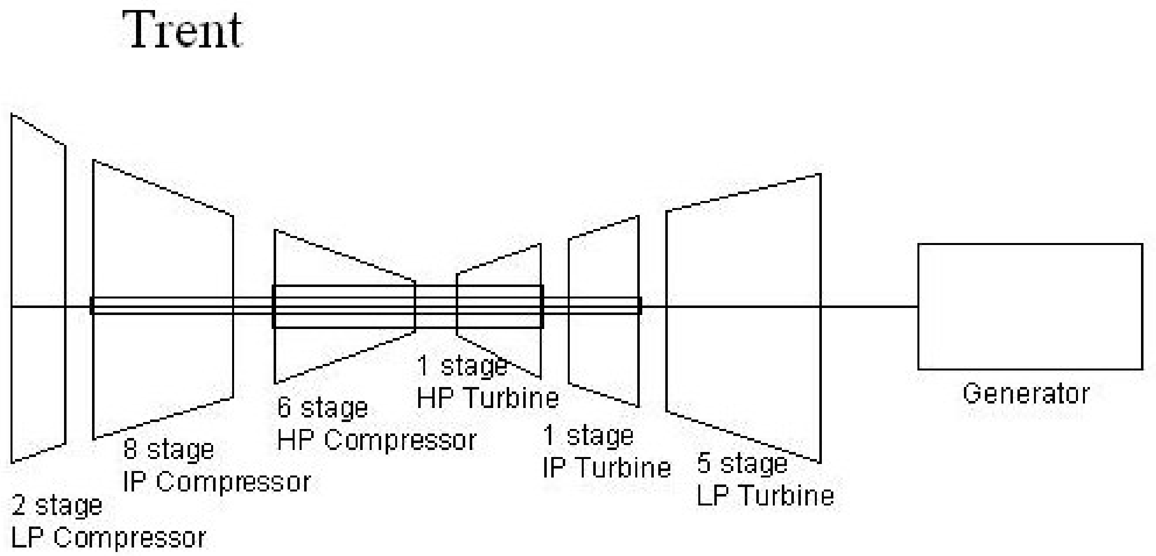

**Figure 2-2**
**Industrial Trent**

The fundamental feature of the aero-derived turbine is its modularity. The industrial Trent consists of 6 prebalanced and interchangeable modules. A module can be removed and replaced with a module from the module pool and operations resumed without any other work being necessary. This offers considerable benefits to a user in terms of reduced spares inventory, increased availability, and the ability to defer refurbishment costs. Some users might choose to send the entire engine back to a repair depot where the module changes can be made more easily.

There are over 10 units currently operating in power generation service, with at least 5 of those in combined-cycle service. Other Trent engines have been sold for gas compression duty. At about 40-42% efficiency, the Trent engine is currently the most efficient engine in its size category of 50-58 MW.

The engine requires a 12 hour cool down cycle. It may use an External Heat Exchanger for cooling air to blades and vanes.

### *Trent Maintenance Approach*

As with the RB211, the industrial Trent engine package is designed for ease of maintenance. Currently, all Trent engines are maintained under long-term maintenance contracts. Scheduled maintenance occurs as follows:

- <u>4,000 Hour (or 6 month) Intermediate Maintenance</u>: boroscope inspection of hot section components
- <u>8,000 Hour (or annual) Annual Maintenance</u>: boroscope inspection, plus functional checks of gas turbine package systems and safety checks of equipment and control system
- <u>25,000 Hour HP/IP Core Replacement</u>: includes annual maintenance, plus refurbishment/replacement of worn parts and re-coating of parts as required.
- <u>50,000 Hour Whole Engine Replacement</u>: includes annual maintenance, plus a total engine strip and refurbishment of all parts, which extends engine life through a second 50,000 hour interval.

Modules can be swapped out in the field in as little as 72 hours. The unit can be easily split into 3 portions: the LP compressor, the HP/IP core, and the LP turbine.

## Avon Background Information

The industrial Avon engine, introduced in 1964, has seen more than a 44% increase in power rating and improvement of over 14% in efficiency in the last 40 years. The current model, the Avon-2656, produces 15.6 MW at 30.3% efficiency. Cumulatively, the Avon in its various applications has more than 1,200 installed units with over 53 million operating hours. In electrical power generation, there are approximately 529 units with over 11 million operating hours. A recently announced upgrade will provide an additional 6-8% capacity and about 3 percentage points higher efficiency.

The 17 stage gas generator provides a compression ratio of 8.8:1 and is driven by a 3 stage turbine. The 2 stage power turbine drives a 4-pole generator at 1500-1800 rpm, similar to the RB211.

Although some new units are sold each year, the product line appears to be phasing out for electrical generation applications. Rolls-Royce provides continuing support for the relatively large existing fleet. Furthermore, several upgrades have been implemented: the swirler burner for improved handling of liquids in otherwise gaseous fuel (similar to the upgraded diffusion burner for the RB211), and improved components for increased power and efficiency. Even though a DLE combustor was previously announced for the Avon, that work is apparently not going forward. Although standardized skid-mount packages are being developed for the RB211 and Trent, the effort for a highly-engineered Avon package is not anticipated.

Unlike the maintenance schedule for the RB211 and Trent engines, the Avon is refurbished at roughly 30,000 and 60,000 hours, while undergoing a comprehensive overhaul at 90,000-100,000 hours. The standard turnaround time is 40 days.

## Pedigree Matrix for the RB211 and Trent 60 Engines

This section provides a review of the Pedigree Matrix developed for the Rolls-Royce RB211 and Trent industrial combustion turbine product line currently relevant for new electrical generation projects. The Pedigree Matrix is structured to show the distinguishing characteristics of the selected models, and the significant or major design changes from each model.

The Pedigree Matrix for the Rolls-Royce RB211-6562, RB211-6761 (Uprate), and the Trent 60 current production industrial units is provided in the following table. Items with gray background highlight areas of significant design changes compared with previous designs from the manufacturer.

## Table 2-1
## Pedigree Matrix: Rolls-Royce RB211-6562, RB211-6761, Trent 60 (DLE and WLE) Engine Design Characteristics

| Design Characteristic | RB211 – 6562 (RB211-24G Gas Generator with RT62 Power Turbine) | RB211 – 6761 (RB211-24GT Gas Generator with RT61 Power Turbine) | Trent 60 DLE (Derivative of AERO 800 on Boeing 777 and Airbus A330) | Trent 60 WLE (Derivative of AERO 800 on Boeing 777 and Airbus A330) | Reliability, Maintainability, Durability Comments |
|---|---|---|---|---|---|
| Distinguishing Features | **Standard Annular Combustor (Non - DLE) 5 Modules, Free Power Turbine, External Gearbox** | **DLE Combustor Option More efficient Power Turbine** | **DLE Combustor, 3 Spools with 6 Modules , LP Turbine drives Generator and LP Compressor Directly** | **Std. Diffusion Combustor with Water Injection, 3 Spools with 6 Modules , LP Turbine drives Generator and LP Compressor Directly** | Fully interchangeable modules with advanced condition monitoring techniques allows high levels of availability with a minimum of downtime. |
| Year of Introduction | 1993 (DLE option in 1994)<br>Original RB211 Model 1980<br>RB211-6556 Model 1990 (-24C GG with RT56 PT) | 2000<br>RB211-6762 Model (-24G Gas Generator and RT62 Free Turbine) 1999 | 1997<br>(was initially named Trent 50) | 2002 | |
| Approximate Fleet Size | 240 RB211-24G<br>Total of 400+ RB211 incl. 260+ mech. drive and 80+ Power Generation | 68 DLE engines.<br>All Existing Units can be Retro-Fitted<br>New "short style" DLE reduces dynamics | 10+ Total Operating<br>1 in Ontario, Canada<br>5 in the UK<br>1 in Denmark<br>5 Ordered for Power Generation | 1<br>Four (4) development engines running | Designed for maintenance with full modular features and five interchangeable modules<br>Designed with condition monitoring system and multiple borescope ports<br>Modules are light weight and easily transportable |
| Output, ISO, Gas Fuel | 28.8 MW (50 Hz or 60 Hz)<br>27.5 MW (DLE) | 32.1 MW (50 Hz or 60 Hz) | 51.5 MW (50 Hz)<br>51.7 MW (60 Hz)<br>(58 MW max.) | 58 MW (50 Hz)<br>58 MW (60 Hz) | Utilized on 220 onshore applications and 120 offshore applications |
| Heat Rate, ISO, LHV | 9,226 Btu/kWh (9,734 kJ/kWh)<br>9,415 Btu/kWh DLE (9,933 kJ/kWh) | 8,680 Btu/kWh (9,158 kJ/kWh) | 8,104 Btu/kWh (8,488 kJ/kWh) 50 Hz<br>8,138 Btu/kWh (8,530 kJ,/kWh) 60 Hz | Approx. 8,400 BTU/kWh (8,900 kJ/kWh) | |
| Firing Temperature | 2128 °F<br>1164 °C | 2250 °F<br>1232 °C | HPT Inlet 2250 °F<br>1232 °C | HPT Inlet 2250 °F ?<br>1232 °C ? | |
| Thermal Efficiency, ISO, Gas Fuel | 36.2% | 39.3% | 42.1% | 41.0% | Industry leading efficiency and reliability are achieved by incorporating the latest technological advances proven in the flight engine.<br>Efficiency and flexibility makes this design also well-suited for pipeline operation |

| **Design Characteristic** | **RB211 – 6562 (RB211-24G Gas Generator with RT62 Power Turbine)** | **RB211 – 6761 (RB211-24GT Gas Generator with RT61 Power Turbine)** | **Trent 60 DLE (Derivative of AERO 800 on Boeing 777 and Airbus A330)** | **Trent 60 WLE (Derivative of AERO 800 on Boeing 777 and Airbus A330)** | **Reliability, Maintainability, Durability Comments** |
|---|---|---|---|---|---|
| Exhaust Flow, ISO, Gas Fuel | 208.7 lb/sec<br>94.5 kg/sec | 207.4 lb/sec<br>94.0 kg/sec | 351 lb/sec<br>159 kg/sec | 358 lb/sec<br>163 kg/sec | |
| Exhaust Temperature, ISO, Gas Fuel | 916 F<br>492 C | 941 F<br>505 C | LPT Outlet Temp 801 F<br>427 C | LPT Outlet Temp 813 F<br>434 C | |
| Compression Ratio - Compressor Discharge to Inlet | 20.8:1 | 21.0:1 | 35.0:1 | 35.5 : 1 | |
| Output End (Drive End) | Hot End Driven by RT 62 power turbine through reduction gearbox @ 4880/1800/1500 | Hot End RT61 Power Turbine driven through reduction gearbox 4800/1800/1500 | Hot End directly driven by LPT at 3600/3000 (Stagger on LPC blades changed for 3000 rpm operation) | Hot End directly driven by LPT at 3600/3000 (Stagger on LPC blades changed for 3000 rpm operation) | |
| Compressor Stages | 7 stage LP/IPC<br>6 stage HPC | 7 stage LP/IPC<br>6 stage HPC same as Aero Trent 700 | LPC 2 Stages<br>IPC 8 Stages<br>HPC 6 Stages | LPC 2 Stages<br>IPC 8 Stages<br>HPC 6 Stages | |
| Extractions | Bleed Valves Rear IPC<br>Bleed Valves Center HPC | | LPC 18 Exit Bleed Doors<br>IPC 4 Bleed Doors Stage 8<br>HPC 3 Bleed Doors Stage 3 | LPC 18 Exit Bleed Doors<br>IPC 4 Bleed Doors Stage 8<br>HPC 3 Bleed Doors Stage 3 | |
| Accessories | Gas / Air or hydraulic starters are available | Anti-Icing feature deleted. Continuous pulse air filter used to minimize icing.<br>Gas / Air or hydraulic starters are available | Gearbox mounted main lubrication oil pump and the starter/clutch assembly drive shafts<br>Speed probes and manual rotation feature | Gearbox mounted main lubrication oil pump and the starter/clutch assembly drive shafts<br>Speed probes and manual rotation feature | The inlet contains two rings of 20 nozzles each; the inboard ring is used for off-line water wash and the outboard ring is used for on-line water washes. |
| Bearings, Number and Type. (all) Continuously Lubricated | IP Rotor 3 Bearings<br>HP Rotor 3 Bearings<br>Thrust Bearing Double Ball (Duplex) | IP Rotor 3 Bearings<br>HP Rotor 3 Bearings<br>Thrust Bearing Double Ball (Duplex) | 3 Thrust (Ball) Bearings<br>5 Roller (Cylindrical Roller Bearings | 3 Thrust (Ball) Bearings<br>5 Roller (Cylindrical Roller Bearings | Uses aircraft anti-friction rolling element bearing lubricated by synthetic fluids. The industrial power turbine uses mineral oil and requires separate oil system |
| Starting Times:<br>to breaker closure<br>to full load<br>Total time | 8 Minutes to purge and warm-up<br>2 minutes to baseload<br>10 Minutes Total for Start | 8 Minutes to purge and warm-up<br>2 minutes to baseload<br>10 Minutes Total for Start | 16 minutes including Purge and Warm-up;<br>10 minutes to Baseload<br>25-30 minutes Total for Start | 10 minutes fast start to full load<br>(no life limitation) | |

| **Design Characteristic** | **RB211 – 6562 (RB211-24G Gas Generator with RT62 Power Turbine)** | **RB211 – 6761 (RB211-24GT Gas Generator with RT61 Power Turbine)** | **Trent 60 DLE (Derivative of AERO 800 on Boeing 777 and Airbus A330)** | **Trent 60 WLE (Derivative of AERO 800 on Boeing 777 and Airbus A330)** | **Reliability, Maintainability, Durability Comments** |
|---|---|---|---|---|---|
| Starting Means | Hydraulic Starter via radial drive gearbox on HPC | Hydraulic Starter via radial drive gearbox on HPC | Hydraulic Starter (250 kW motor) | Hydraulic Starter (250 kW motor) | |
| Compressor Variable Stages | 1 stage of 34 VIGV's | 1 stage Solid Variable Inlet Guide Vane (VIGV)<br>Revised VIGV Control RVDT (Rotary Variable Diff. Transformer) | IGVs in Front of the LPC<br>IPC has Stage 1 VIGV's<br>IPC has 2 rows of VSVs<br>HPC has no variable stators | IGVs in Front of the LPC<br>IPC has Stage 1 VIGV's<br>IPC has 2 rows of VSVs<br>HPC has no variable stators | |
| Compressor Blades | LPC Titanium Blades coated with Sermetel "W"; HPC Blades Stage 1 Ti, Stg 2-6 Stainless Steel | | LPC Blades-Titanium<br>IPC Blades-Titanium<br>HPC Blades 1,2 - Titanium<br>HPC Blades 3,4,5 - Nimonic | LPC Blades-Titanium<br>IPC Blades-Titanium<br>HPC Blades 1,2 - Titanium<br>HPC Blades 3,4,5 - Nimonic | |
| Compressor Vanes | First stage (34) VIGV's, Stages 2 thru 7 fixed on IP Compressor. 6 fixed stages of stators in the HP Compressor | Redesigned Stage 5 stator, Hard-faced stage 6 stator, First stage (34) VIGV's, Stages 2 thru 7 fixed on IP Compressor. 6 fixed stages of stators in the HP Compressor Revised OGV ring ( Stage 7) fitted to IP Compressor. | LP - 1 variable 2 fixed<br>IP 2 Variable 7 fixed HP 8 fixed | LP - 1 variable 2 fixed<br>IP 2 Variable 7 fixed HP 8 fixed | |
| Compressor Rotor | IPC Welded Drum SS & Ti<br>HPC Welded Drum Ti | Trent 800 HPC Compressor | LPC Operates at 3600 or 3000 RPM without the need for a reduction gear. The LPC blades are changed for 50 Hz Operation.<br>LP - 2 Stage IP - 8 Stage HP - 6 stages | LPC Operates at 3600 or 3000 RPM without the need for a reduction gear. The LPC blades are changed for 50 Hz Operation.<br>LP - 2 Stage IP - 8 Stage HP - 6 stages | |
| Compressor Casings | Air Intake Al Alloy Casting<br>IPC Casing Al Alloy Casting<br>HPC 12% Cr SS | Single Skin Inlet Bullet-nose with the elimination of anti-icing (-24G and -24GT) | LPC Outer Case is Split to Access the LPC Stators | LPC Outer Case is Split to Access the LPC Stators | |
| Turbine Casings | Turbine Casing Nimonic PE. 16 | Single Piece Frame Turbine Support | | | |

| **Design Characteristic** | **RB211 – 6562 (RB211-24G Gas Generator with RT62 Power Turbine)** | **RB211 – 6761 (RB211-24GT Gas Generator with RT61 Power Turbine)** | **Trent 60 DLE (Derivative of AERO 800 on Boeing 777 and Airbus A330)** | **Trent 60 WLE (Derivative of AERO 800 on Boeing 777 and Airbus A330)** | **Reliability, Maintainability, Durability Comments** |
|---|---|---|---|---|---|
| Turbine Vanes - HP | Mar-M-002, Sermaloy J coating, air-cooled | Mar-M-002, Sermaloy J coating, air-cooled | MarM002, Pt-Al coating, air-cooled<br>Identical to the Aero 800 except for minor film cooling modification | MarM002, Pt-Al coating, air-cooled<br>Identical to the Aero 800 except for minor film cooling modification | Typically performs Hot Gas Path Inspections at 25,000 fired hours and turbine overhauls at 50,000 fired hours |
| Turbine Vanes - IP | C1023, Sermaloy J coating | C1023, Sermaloy J coating | MarM002, Pt-Al coating<br>Identical to the Aero 800 | MarM002, Pt-Al coating<br>Identical to the Aero 800 | |
| Turbine Vanes - LP | (see Power Turbine description) | (see Power Turbine description) | LPT-1,2 MarM002<br>LPT-3 C1023<br>LPT-4, 5 IN738LC | LPT-1,2 MarM002<br>LPT-3 C1023<br>LPT-4, 5 IN738LC | |
| Turbine Blades - HP | HPT-1 CMSX4 DS, Sermaloy 1515 coating, air-cooled (upgrade from RB211 -24C) | Identical to the Aero RB211-524G/H-T<br>HPT-1 CMSX4 Single Crystal,<br>Sermaloy J Coating, air-cooled<br>(was MarM002 with Pt-Al for -24G prior to upgrade) | Identical to the Aero 800 - Air Cooled<br>HPT Blades CMSX4, Single Crystal<br>Platinum-Aluminide Coating<br>(cooling air from HPC-6) | Identical to the Aero 800 - Air Cooled<br>HPT Blades CMSX4, Single Crystal<br>Platinum-Aluminide Coating<br>(cooling air from HPC-6) | Uses blades directly from Trent 800, minor changes in the film cooling pattern on the HP Nozzle |
| Turbine Blades - IP | Stage 1 LPT Blades CMSX4 (Directionally Solidified), Coated with Sermaloy 1515 (upgrade from RB211 -24C) | Stage 1 LPT Blades CMSX4 (Directionally Solidified), Coated with Sermaloy 1515 | Identical to the Aero 800 - Uncooled<br>IPT Blades RR3000, directionally-solidified (proprietary nickel-based super-alloy)<br>Platinum-Aluminide Coating | Identical to the Aero 800 - Uncooled<br>IPT Blades RR3000, directionally-solidified (proprietary nickel-based super-alloy)<br>Platinum-Aluminide Coating | |
| Turbine Blades - LP | (see Power Turbine Description) | (see Power Turbine Description) | The first three stages of the LPT are identical to Aero 800; the last two stages have increased expansion ratio to extract all of the available energy from the gas stream for power production, having larger gas path area and a lower exit Mach Number than the Aero 800<br>LPT-1 MarM002 LPT-2,3 IN713 LPT-4, 5 IN718 | The first three stages of the LPT are identical to Aero 800; the last two stages have increased expansion ratio to extract all of the available energy from the gas stream for power production, having larger gas path area and a lower exit Mach Number than the Aero 800<br>LPT-1 MarM002 LPT-2,3 IN713 LPT-4, 5 IN718 | |

| **Design Characteristic** | **RB211 – 6562 (RB211-24G Gas Generator with RT62 Power Turbine)** | **RB211 – 6761 (RB211-24GT Gas Generator with RT61 Power Turbine)** | **Trent 60 DLE (Derivative of AERO 800 on Boeing 777 and Airbus A330)** | **Trent 60 WLE (Derivative of AERO 800 on Boeing 777 and Airbus A330)** | **Reliability, Maintainability, Durability Comments** |
|---|---|---|---|---|---|
| Turbine Rotor | (see Power Turbine Description) | (see Power Turbine Description) | HPT 1 Stage, IPT 1 Stage<br>LPT 5 Stages with aft 2 stages functioning as a Power Turbine | HPT 1 Stage, IPT 1 Stage<br>LPT 5 Stages with aft 2 stages functioning as a Power Turbine | |
| PT Free Power Turbine (Industrial Type) | RT62 Introduced 1982;<br>Two stage PT with industrial thrust & journal bearing | RT61 Introduced in 1997;<br>Three Stage PT unit with industrial thrust and journal bearings | (see LP Turbine Description) | (see LP Turbine Description) | |
| PT Casings | Pedestal base that supports both PT & GG assemblies<br>Strutless inlet & exhaust diffusers | Lighter weight unit with modular construction (5) | (see LP Turbine Description) | (see LP Turbine Description) | |
| PT Nozzle Vanes | Stage 1 vanes Rene' 80<br>Stage 2 vanes U - 500 | 46 First Stage Nozzle Vanes Rene' 80<br>60 Second Stage Nozzle Vanes U-500<br>60 Third Stage Nozzle Vanes N-155 | (see LP Turbine Description) | (see LP Turbine Description) | |
| PT Rotor | Shaft AISI 4340 high tensile Ni Cr Mo Alloy Steel<br>(Overhung design) | Shaft AISI 4340 high tensile Ni Cr No Alloy Steel<br>(Overhung design) | (see LP Turbine Description) | (see LP Turbine Description) | |
| PT Rotor Blades | 1st stage blades: Rene' 80<br>(83 count)<br>2nd stage blades U-500<br>(83 count) | 1st Stage Blades:Rene' 80 (83 count)<br>2nd Stage Blades U-500 (79 count)<br>3rd Stage Blades N-155 (71 count)<br>Interlocking, shrouded blades with honeycomb tip seals | (see LP Turbine Description) | (see LP Turbine Description) | |
| PT Rotor Disks | Both disks INCO 901 Ni Co Base Alloy | Disks are joined with Curvic Couplings<br>Inco 901 | (see LP Turbine Description) | (see LP Turbine Description) | |
| PT Bearings & Seals | Kingsbury type Thrust Bearing (1)<br>Tilting Pad type Journal Bearings (2)<br>Labyrinth Seals (SS) | Kingsbury Type Thrust Bearing (1)<br>Tilting Pad Type Journal Bearings (2)<br>Labyrinth Seals (SS) | (see LP Turbine Description) | (see LP Turbine Description) | |

| **Design Characteristic** | **RB211 – 6562 (RB211-24G Gas Generator with RT62 Power Turbine)** | **RB211 – 6761 (RB211-24GT Gas Generator with RT61 Power Turbine)** | **Trent 60 DLE (Derivative of AERO 800 on Boeing 777 and Airbus A330)** | **Trent 60 WLE (Derivative of AERO 800 on Boeing 777 and Airbus A330)** | **Reliability, Maintainability, Durability Comments** |
|---|---|---|---|---|---|
| Distinguishing Features (from earlier models) | RT62 Power Turbine | Single Crystal Turbine Blades (HPT & IPT)<br>Radial Can-Annular DLE Combustor | The Radial DLE combustor is a radical departure from the aero version with DLE designed in up front | Phase 5 annular combustor (similar to Aero Trent) | |
| Number of Combustors | Single fully annular combustor with steel outer casing and NIMONIC 263 liner<br>Eighteen fuel nozzles | Series Staged 9 Can Type DLE radially mounted pre-mix lean burner chambers with a single fuel injector for each can | 8 Can Type DLE with reverse flow Perpendicular to the Axis of Rotation<br>3 stage lean burn DLE Combustor Materials-INCO 625 and Haynes 230 | 24? fuel burners on standard Phase 5 Combustor<br>Dual Fuel Capable | |
| Emission Capabilities | 170+ ppmv $NO_x$ @ 15% $O_2$ | DLE 25 vppm NOx on gas<br>42 vppm $NO_x$ on liquid fuel with water injection<br>25 ppm CO | 25 ppmv NOx, 25 ppmv CO at 15% O2 on gas<br>Water injection is required for LF operation | $NO_x$ - 25 vppm<br>CO < 32 vppm<br>(diffusion burner with water injection) | DLE combustor uses 2 stages with precise control of the fuel flow division rather than trying to control the air flow<br>RB211 has over 250,000 DLE fired hours of operation |
| Emission Abatement Configuration | Standard combustor - DLE retrofit available? | DLE Combustion System - Standard Combustor Available? | DLE Combustion System | Water injection thru combined fuel / water injectors | RB211 uses WI for NOx control on LF |
| Control System | Flexitrend by En-Tronic | Flexitrend by En-Tronic | Woodward | Woodward | Utilizes time proven control systems with digital electronics<br>Proven operation in remote areas with operator-less control and protection. |
| Options | | Integrated auxiliary drive fro lube oil, seal oil and hydraulic systems | | | |

# 3

# RELIABILITY, AVAILABILITY AND MAINTAINABILITY

## Data Analysis: Rolls-Royce Aero-derivative Engines

This chapter provides statistical evaluation of the Reliability, Availability, and Maintainability (RAM) performance of the Rolls-Royce Avon, RB211, and Trent machines in power generation applications. The fleet is represented by units that report to the Operational Reliability Analysis Program (ORAP) managed by Strategic Power Systems (SPS). RAM data is reported to ORAP on a voluntary basis and therefore not all units in a particular fleet are represented. To the extent that the data is based on a substantial number of the fleet units in a particular category, the results are representative statistical sampling of that fleet. See Appendices for details about ORAP and RAM statistics.

Simple cycle plant statistics are provided in this report because the focus is on the combustion turbine. The impact of the combustion turbine and its interaction with the operation and maintenance of the plant is considered the prime issue. Other studies examine the balance of plant RAM for combined cycles, including the HRSG and steam turbines.

For most models, the majority of the units reporting in the ORAP database are baseload electric or cogenerators, although the smaller capacity models also have a substantial number of units in simple cycle mode for peaking duty. The units currently performing cycling duty formerly were baseloaded units and have recently transitioned to cycling duty. At a site with a single unit the tendency of the cycling unit is to shutdown for the weekend. At sites with multiple units the tendency of the cycling units is shutdown on a rotating schedule. Some of the units run for longer fired hours per start, then shutdown on the third night and restart in the morning to minimize the total number of on-off cycles.

The maintenance philosophy implemented by the OEMs and Users has a direct impact on RAM and is the leading cause of a plant's unavailability. The demand and use of a combustion turbine greatly influences these decisions but unavailability is a User/OEM controlled parameter of when and how scheduled and unscheduled maintenance is performed. For instance, plants that are simple cycle peakers may have less incentive to minimize the time required to perform scheduled maintenance, and therefore have lower availability than baseload units of the same model. For peakers, reliability and availability are most critical during seasons in which electricity prices are at a premium.

This report contains a summary of RAM statistics available at the time of publication. More detailed statistics, including future annual updates, are available to current project 80.002 funders via electronic download from www.epri.com. Login is required. Proceed to Program 80 in the

Generation area, Strategic Generation Options and go to Newsletters/ Program Updates under the Research Area Updates section in the left sidebar.

### *RAM Statistics: Avon, RB211 and Trent - All Duties*

Data from the Operational Reliability Analysis Program (ORAP) was utilized to provide statistics on Rolls-Royce engines. The following table summarizes the characteristics for the Rolls-Royce fleet as represented by the units reporting to ORAP. The statistics are for all units reporting that meet SPS criteria for inclusion in the database for a particular year. As such, they are a subset of Rolls-Royce entire operating fleet. 2005 is the first year in which Rolls-Royce data is available in ORAP; therefore trending over time is not available.

**Table 3-1**
**RAM Statistics: Fleet Characteristics for Avon, RB211, and Trent**

| | **Avon** | **RB211** | **Trent** |
|---|---|---|---|
| Time Period | 1 Year: 2005 | 1 Year: 2005 | 2 Years: 2004, 2005 |
| No. of Units | 6 | 10 | 4, 8 |
| Unit-Years | 4.2 | 8.1 | 11.1 |
| Period Hours | 36,790 | 70,960 | 97,240 |
| Fired Hours | 29,700 | 45,250 | 18,860 |
| Service Factor | 81% | 64% | 19% |

Units that report for less than 100% of the time period result in partial unit-year data. Units reporting less than 70% of a calendar year are typically excluded from the data set. Note that this data set represents a limited sampling of engines in each model type and therefore the RAM statistics may not accurately represent the larger fleet.

The following table summarizes the combined duty RAM statistics for the Rolls-Royce fleet reporting to ORAP.

### Table 3-2
### RAM Statistics for Roll-Royce Avon, RB211 and Trent Engines – All Duties

| Model & Year | Availability (%) | Reliability (%) | Service Factor (%) | Service Hours/Start | Starting Reliability (%) | Average Load (MW) | Forced Outage Factor (%) | Scheduled Outage Factor (%) | Unscheduled Outage Factor (%) | Mean Time Between Failure (Hours) | Mean Time To Repair (Hours) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Avon 2005 | 97.5 | 99.4 | 81 | 215 | 93 | N/A | 0.6 | 1.7 | 0.2 | 423 | 3 |
| | | | | | | | | | | | |
| RB211 2005 | 83.4 | 86.8 | 64 | 159 | 97 | 20 | 13.2 | 2.9 | 0.5 | 285 | 453 |
| | | | | | | | | | | | |
| Trent 2004 | 82.1 | 86.1 | 24 | 28 | 82 | 47 | 13.9 | 3.9 | 0.1 | 59 | 18 |
| Trent 2005 | 75.0 | 88.7 | 17 | 14 | 87 | 46 | 11.3 | 4.9 | 8.8 | 38 | 35 |

Average values compiled from Operational Reliability Analysis Program (ORAP). 2005. MTBF and MTTR include both forced and unscheduled Maintenance hours. High MTBF of RB211 due to a single event requiring 4,416 hours before restored to operation.

### *Additional RB 211 Operating Statistics*

The following table provides average Reliability and Availability statistics for a limited number of RB 211 engines based on a one-year operational study. Statistical values are from sources other than ORAP and have not been verified.

**Table 3-3**
**Additional RB 211 Operating Statistics**

| Type # | Number of Units | Service Factor | Availability % | Reliability % |
|---|---|---|---|---|
| 24 A | 9 | 56.4 | 90.2 | 98.3 |
| 24 C | 21 | 61.07 | 90.2 | 98.6 |
| 24 G | 13 | 52.26 | 98.0 | 99.5 |
| 24G DLE | 16 | 71.8 | 95.9 | 99.8 |
|  |  | Avg. of Fleet | 93.6% | 99.0% |
|  |  | Avg. of -24G & DLE | 97.0% | 99.8% |

## RAM Assessment

The typical benchmark for mature heavy-duty and aero-derivative engines is 99% reliability, 94% availability and 95% starting reliability, on average. The Avon exceeds these minimum expectations; however, the RB211 and Trent machines, as represented by these particular fleets reporting to ORAP, do not meet benchmark values. Furthermore, the Trent does not meet expectations for starting reliability. Since the Trent engines in this sample appear to be in peaking service, starting reliability is a critical factor as well. Again, caution is advised since the number of units in the ORAP statistical sample is relatively small, particularly for the Avon and RB211 engines. The single year operational study data on RB211 engines shows more favorable availability and reliability statistics, particularly for the later sub-model type G.

## Conclusion

The aero-derivatives are generally classified as “under 50 MW”. The industrial Trent breaks that barrier and is the word’s largest aero-derivative combustion turbine at 51.2 MW. The heritage of the aero-derivatives leads to the inherent development of flexible, high power density, and highly efficient industrial combustion turbines. By their very nature they are generally more complex and more exotic than the frame type (heavy duty) industrial combustion turbine. The frame type industrial combustion turbine, however, is adopting much of the aero technology to the point that there is a similarity of the flow paths cooling schemes, coatings, and combustion technologies. The limiting factor is not the transfer of technology but in the manufacturing of frame size components from the aero size components.

The review of the frame pedigree matrices in a previous EPRI Report TR-114081, "Gas Turbine Design Evolution and Risk" clearly shows a high degree of commonality between the design of a frame unit and an aero-derivative unit. But at the same time, they are extremely different. One cannot operate a frame unit like an aero-derivative and visa versa. Also, the modularity with small sizes and lighter weights promote "repair by replacement" philosophy as part of the aero-derived heritage. The User must accept the "repair by replacement" philosophy and understand the inherent design features of the aero-derivatives. The prime features are multi-spools and multiple main rolling element shaft bearings. The lubrication system uses synthetic lubricating fluid and the turbine requires high degree of purity and cleanliness. The aero-derivative combustion turbine with more variable geometry, control devices, and accessories experiences approximately twice the number of forced outages as the frame units. But, because of the aero-derivative's inherent maintenance features, the turbine can generally be restored to operation in half the time as a similar frame outage. Therefore, the net downtime is the same for aero-derivatives and frame turbines (i.e. the Forced Outage Factors (FOF) are roughly equivalent). The main difference is the downtime associated with major outages requiring disassembly and repair of the frame units on site.

The inherent design of the aero-derivative industrial combustion turbine is generally more complex and exotic and has more parts and more moving parts to fail. The aero-derivative industrial combustion turbine also has more instrumentation to allow for designed control and protection. Due to its heritage, it is easier to repair and return to service.

The aero-derivative's greatest asset is its modularity. With complete interchangeability of like modules and line replaceable components, it relies on a maintenance philosophy called "repair by replacement". The Rolls-Royce aero flight engines have a long history of being the world's most powerful and reliable turbines. The industrial versions of these engines are continuing that tradition and are some of the world's most powerful and reliable industrial turbines.

The features outlined below represent the major differences between aero-derivatives and frame units, other than their power density:

- Modularity, promoting repair by replacement
- Aircraft heritage for fast starting and tolerance to cycling
- Ease of maintenance
- High performance and efficiency

Some long-term problems associated with aero-derivatives include:

- Bearing and seals requiring monitoring and conditioning equipment
- DLE combustion systems requiring refinement to meet stringent objectives
- Compressor sensitivity to stall or surge

Lastly, the repair cycle and actual costs to achieve high availability must be accounted for in life cycle evaluations. The cost of membership into a lease program, the cost of leased turbine usage, and the cost of repair to the Users turbine has to be considered and assessed by the Users.

# 4
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# A

# KNOWN ISSUES

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**Table A-1**
**Listing of Known Issues for Rolls-Royce Units**

| Issue | Symptom | Comments |
|---|---|---|
| Ancillary Package Design | Numerous Deficiencies | Cooper Bessemer, now part of Rolls-Royce, packaged the unit as a Coberra 6256 and then, with the higher powered machines, the Coberra 6562 unit. The troublesome Lube Oil skid problems have now been resolved.<br>Westinghouse also offered a package design known as the EconoPac concept. While the turbine performed very well, there were problems with some aspects of the initial package design, which were corrected by RR. |
| Digital Control System Upgrade | Software and card problems | The new Entronics, (now part of Rolls-Royce), control system required software and card changes with introductory units (as with any new product introduction that has not yet been widely tested) |
| DLE Combustion | Acoustics | Initially the DLE technology produced unacceptable acoustic problem within the DLE combustion system. Modifications and testing are being introduced to eliminate these problems. |
| DLE Combustion - Trent | NOx Emissions | The Trent DLE has had difficulty meeting 25 ppm $NO_x$ emissions guarantees. A new DLE design is expected in 2003 to resolve the issue. |
| Combustor Module Casing - Trent | Gas Leakage – Maximum Power Derating | A revised casing for the Trent DLE combustor module is expected in 2003 to resolve this issue. Until then the maximum pressure ratio during cold day operation is limited. |
| General - Trent | Numerous Deficiencies | Numerous problems occurring on the lead machine (Whitby Cogen) in 1996-1999 – resolutions indicated. Details unknown. |

# B

# RB 211 MAINTENANCE SCOPE

## RB 211 - 2,000 Hour Inspection

- Carry out a soak wash of the engine's compressor.
- On completion of the above;
  - Inspect the Intake Flare for any cracks or damage
  - Examine the Variable Intake Guide Vanes (VIGV's) and visible
  - Compressor Blades for nicks, dents and foreign object damage.
  - Clean up the floor and ensure items are removed from the plenum.
- Remove and inspect the oil scavenge block Magnetic Chip Detectors.
  - Refer to the RB 211 Maintenance Manual for go and no go limits on any metallic contamination.
- Fit new 'O' rings to the mag plugs before reinstalling same. (Service Bulletin # 108)
- Remove and clean the gas generator mounted lube oil filters (if installed).
- Check the security of all accessible connections, clamps, brackets, locking devices and nuts.
- Check all external pipes, conduit, and electrical leads for evidence of frettage or wear. Gas fuel 'flex' pipes are very susceptible to this problem.
- Examine the exterior of the engine casings for signs of air or oil leaks. Also check for cracks, dents distortion and hot spots.
- Check the level of the oil in the lube oil reservoir tank. Replenish as required.
- Ensure the static seal of the VIGV Master Ram has sufficient oil in it.
- Remove a sample of lube oil and send it for analysis and oil acidity reading.

## RB 211 - 8,000 Hour Inspection

- Ensure that all applicable Service Bulletins and Service Information Letters are carried out on both the Gas Generator and the Lube Oil Console.
- Carry out all the 2,000 hour inspections, including a soak wash of the engine compressor.
- Check the Nose Bullet as per Chapter 6 of the Maintenance Manual (M/M) Vol. 1.

- Conduct a full internal borescope examination of the engine. Refer to the M/M Volume 1, Chapter 6. for reference and allowable limits of any nicks, dents or other foreign object damage found.
- Examine all borescope blanking plugs, which extend into the gas generator, for frettage and wear. Any major frettage should be investigated and the plug changed.
- Examine the rubber flexible joint seal between the Intake Flare and the engine flange.
- Check the variable inlet guide vane (VIGV) operating mechanism for freedom of movement and security of linkages. Inspect the VIGV bushes for wear.
- Check the security and condition of the VIGV high and low speed stops.
- Remove and check the Blow Off Valve (BOV) Control Solenoid. Refer to the M/M Vol.1, Chapter 6 and Service Bulletin # 54.
- On RB 211 – 24'A' & 'C' engines, visually inspect and service the VIGV Master Ram assembly, as per the M/M Vol.1, Chapter 6, Paragraphs 11 & 12.
- On the Master Ram assembly, remove the P2 air splitter housing and carefully clean the needle valve and seat. **Do not adjust the Ram.**
- Remove and clean the HP 3 air filter.
- Remove and check the discharge rate of the Igniter Plugs. Change one or both as required.
- If it is still installed, remove and clean the gas generator mounted lube oil filter. Reference should be made to Service Bulletin # 55.
- Check the functioning and calibration of the Vibration Monitoring equipment. The M/M Vol. 1, Chapter 6 details this check. Replace any components as required.
- A DC resistance and insulation test should be carried out on all of the engines electrical components.
- Check and service the Davis Vent valve. The seal replacement is detailed in Service Bulletin # 104. Valve connections are detailed in M/M Chapter 2.
- Check the Gas Starter and associated pipework for any evidence of oil leaks.
- Change the Main Lube Oil Skid mounted Filters. Refer to the Maintenance and Parts Manual Off-Engine Parts, Vol. 1A, Part 1A, Chapter 4.
- On the Mark 2 Console, clean or replace the in line filter to the Pegasus Valve.
- On the Mark 3 Console, clean or replace the in line filter to the MOOG Valve.
- Check the inert gas pressure of the lube oil system accumulator.
- Replace the inlet filter to the fuel valve actuator.
- Perform a function check on the high-speed shut-off cock in the fuel skid.
- It is recommended that a check of all pressure switches, solenoids, heaters, thermostats, and electrical equipment, mounted off engine, be carried out as per the manufacture's

instructions. These instructions and checks are to be found in the Maintenance and Parts Manual, off-engine parts, Volume 1A, Part 1A, Chapter 3 and Chapter 3 of Part 2A.

- On re-start of the engine, carryout an airflow control system check. Chapter 7, paragraph 4 in the Maintenance Manual gives the full details.

## RB 211 - Midlife Workscope

To conducted schedules maintenance of the engine and overhaul of the 04 Module plus the I.P. Stage 5, 6 and 7 (OGV Ring) Stator Vane assemblies at approximately 25,000 operating hours.

This work to be carried out at Customers premises if 'POOL' assemblies are available. The same workscope would apply for a shop visit.

### *On Removal*

- Conduct Engine Inspection, include external visual inspection and record any damage to the engine accessories.
- List and report any missing parts or other visual abnormalities/conditions observed.
- Ensure rotating assemblies are free of rubs and/or stiffness.
- **Bulk strip engine into modules.**

**01 Module:**

- Visually inspect, in the bulk strip condition, Front Roller Bearing, Abradable Seals, Variable Inlet Guide Vanes, Actuating Ring and IGV ram.
- Electrically check the N1 Magnetic Speed Sensors and electrical connector.
- Visually Inspect Diaphragm Seal, Cylinder and Cover Abradable Seals.

**02 Module:**

- Remove the I.P. Compressor Half Casings from the Assembly
- Remove Stage 5 and 6 Stator Assemblies. Prepare these components for shipping to Vendor for full overhaul to latest mod. Standard.
- Visually Inspect Compressor Half Casings and Stage 1 to 4 Stators in the Bulk Strip Condition (i.e. Check Blade Path Linings, Stators and Inner Shrouds).
- Inspect the IPC Rotor as an Assembly.
- Rebuild the 02 Module using 'POOL' Assemblies.

**03 Module:**

- Remove the Stage 7 Outlet Guide Vane (OGV) Ring assembly. Prepare the component for shipping to Vendor for full overhaul to the latest mod. Standard.

- Visually inspect the remainder of the module in the bulk condition (i.e. Curvic Coupling, thrust bearings).
- Electrically check the N2 Magnetic Speed Sensors and electrical connectors.
- Fit the ‘POOL’ OGV Ring Assembly

**04 Module:**

**Prepare the 04 Module for shipping to Vendor. At Vendor Premises, the module will be fully overhauled to this workscope.**

- Overhaul in accordance with accepted standards.
- Dismantle to detail, clean and inspect.
- Visually and dimensionally, inspect the Burner Sealing Liners.
- Dimensionally inspect ALL of the abradable linings, renew where required.
- Comply with the following Repair Notes and Overhaul Information Alerts:

| | |
|---|---|
| RN5003 | Replacement of HP compressor curvic coupling joint bolts |
| RN5009 | Renew HP compressor bolts in Jethete material at every Ex-service strip |
| RN5016 | Engine components life limitation data |
| RN5017 | Log book cyclic life information |
| RN5020 | Reduced cyclic life of specific HP compressor rotor Stages to 2 disc assembly |
| RN5022 | Restricted usage of Nimonic 80A fasteners |
| RN5024 | HP turbine blade check procedure |
| RN5033 | Fatigue failures of compressor, turbine rotor blades and stator vanes |
| RN5036 | Inspection of HP Compressor Stage 3 disc for corrosion and cracking (at 48,000 hours) |
| RN5039 | Inspection standard for HP turbine blades |
| 0IA005 | HPT blades for thermal cracking |
| 0IA032 | Stage 5 stator vane feet frettage |
| 0IA035 | Stage 5 stator vane failure |
| 0IA037 | Stage 5 stator vane platform gaps proforma |
| 0IA043 | Revised HP Turbine honeycomb seal clearances |
| TI30029 | Re-protect the outer casing with Sermetal ‘W’ |

### Compressor Rotor HP (Section 1664)

- Inspect the HP compressor rotor path linings and incorporate modifications 1115 and 1189, if required. Reprotect if necessary.
- Incorporate Mod 1167 - Improved bolt material on combustor.
- Replace the curvic coupling bolts in accordance with RN5003, if required.
- Inspect the HP compressor rotor blades, stators, and repair as necessary.
- Crack test the following components and reprotect if satisfactory:

### Stage 1-2 HP Compressor Disc

Stage 3 HP Disc (RN5036)

Stage 4, 5 and 6

Stage 1-6 HP Blades

Stage 1-5 HP Compressor vanes

### Combustion Liners (Sections 1092 – 1092/A – 1092/B)

- Consign the Front combustion Liner for condition assessment and overhaul.

### Turbine Rotor Discs and Shaft HP (Sections 1071-1071/A)

- Dimensionally inspect the Panel Support and Rotor Disc Location.
- Subject the following components to crack testing.

### HP Turbine Disc

HP Turbine Blades

Panel Support

HP Turbine Bearing Inner Race

Conical Shaft

- Visually inspect the remaining components.
- Renew the thermal barrier coating on the rear combustion liner.

### Nozzle Case and Nozzle Vanes HP (Section 1081)

- Strip to detail.
- Inspect the HP Seal Segments, repair and renew the Honeycomb seals as necessary.
- Consign the HP NGV’s for repair, as required, and reprotection with Sermaloy ‘J’ coating in accordance with Mod 1110.

Rebuild the Module to the Rolls-Royce overhaul specification, fits and clearances etc. and ship back to the Customer or replace in the ‘POOL’.

**05 Module:**

- Carry out dimension check of IPT Rotor setting.
- Inspect the IP Turbine Casing Assembly in the Bulk Condition, including Seal Segments, IP NGV’s, HP and IP Roller Bearings and Static Abradable Seals.
- Inspect the IP Turbine Rotor Assembly in the Bulk condition. Check wear on IP
- Turbine blade ‘Z’ notch, turbine disc, shaft, coupling and IPT bearing.
- Insure no ‘coking’ in oil scavenge or vent lines in the ‘spider’.
- Carry out the following Repair Notes and Overhaul Information Alerts:
  - RN5018 HP/IP support internal pipe inspection/test
  - RN5037 IP Turbine Blade inspection criteria
- Embody the following modifications:
  - Mod 1123 Revised vent connection, if required

**06 Module:**

- Visually Inspect all accessories, including Air and Oil Piping, Nose Bullet and P2 Air Filter.
- Electrically check Thermocouple Harness.
- Remove HP and IP Bleed Valves and Overhaul.
- Replace Seals in Davis Valve.

### Rebuild

Using the Customers spare 04 Module, rebuild the engine to the Rolls-Royce Overhaul build specification and fits/clearance limits.

## RB 211 - Overhaul Workscope

This overhaul workscope is conducted as schedule maintenance at approximately 50,000 Operating Hours, providing the engine had a midlife inspection repair at 25,000 hours.

### *On Receipt of Engine*

- Take pictures of engine on the inbound truck (i.e. tie down straps etc.)
- Inspect and report condition of engine transportation stand and bag.
- Open bag and photograph all four sides of the engine especially engine components or parts that are damaged or missing.
- Carry out full “booking in” inspection of the engine, checking that the rotating assemblies are free of rubs and stiffness.
- Any missing parts/components or other visual abnormalities should be immediately reported to the Customer.
- Remove the Nose Bullet, “A” Frame, Intake Extension Ring etc. and prepare the engine for a vertical lift.
- Carry out an airflow check of the 01, 03 and 05 module oil lines and record findings.
- Place the engine on the “pot” vertically for removal of all the 06 module components (i.e. all pipes, harnesses etc.)
- Bulk strip the engine into its five (5) modules.

**01 Module:**

**Air Inlet and Front Bearing Support (Section 1020)**

- Detail strip the module – wash, NDT and inspect all components.
- Replace the I.P. Roller Bearing.
- Incorporate MOD 633 on IP front static seal.
- Inspect anti-icing manifold, check for damage, cracks or other defects. Ensure MOD 961 is embodied.
- Inspect anti-icing sleeve for wear. NOTE: Discuss with Customer deletion of Anti-Ice System (Mod 1051) where applicable.
- Inspect nose bullet for dents, cracks and other defects. Incorporate IRBT1120.
- Inspect support frame assembly. Incorporate IRBT1120.
- Inspect actuating ring check for free movement.
- Inspect bearing, housing, repaint if necessary.

- Inspect VIGV's, crack test, measure inner and outer journals. Inspect threads.
- Measure and inspect inner and outer bushes.
- Embody the following Repair Notes (RN):
  - RN 5002 – Wear of VIGV Trunnions and associated parts
  - RN 5035 – Acceptance Standard for VIGV Vespel Bushes
- Inspect IGV arm assembly, re-protect if necessary.
- Inspect air intake casing assembly, locally crack test, repaint if necessary.
- Renew metco on all static seals (MOD 830, MOD 1044).
- Inspect all remaining parts.
- Overhaul Master & Follower (2) Inlet Guide Vane Rams.
- Inspect and electrical check RPM indicator system

It is recommended to incorporate MODs 1104, 1054, 1081, 1044, 1164, if not already incorporated. These Mod's, and all other modifications, should be discussed and agreed to by the customer.

**02 Module:**

### Compressor Casing and Vanes IP (Section 1665)

- Detail strip the module – wash NDT, inspect and record/embody the following Overhaul Information Alert (OIA):
- OIA 014 – Inspection of IP Vanes Stages 5 & 6.
- Main Casing: Inspect general condition and report – repaint casing and incorporate Mod 734.
- Inspect shrouds Stage 1 through 6, overhaul process.
- Inspect liners for serviceability, replace if necessary.
- Inspect and overhaul process Stage 1 through 4 vanes.
- Overhaul process Stage 5 and 6; incorporate Mod 1159 (Stage 6) or Mod 1205 (Stage 5). Incorporate MODs 734, 1101, 1036 if applicable.

It is recommended to incorporate the latest mod standard on the IP Stage 5 and 6 Stator Vane Assemblies.

Latest MOD Standard – Stage 5 to MOD 1205
Stage 6 to MOD 1559

**Customer should be advised as to what MODs can be incorporated.**

- Rebuild the casings as per standard procedure.

### Compressor Rotor IP (Section 1666)

- Detail strip the Rotor. Wash, NDT, inspect and record/embody the following:
  - RN 5015 – Cyclic Lives of Critical Group A Components
  - RN 5016 – Engine Component Life Limitation Data
  - RN 5023 – Inspection/Crack testing of Stage 6 Disc for Corrosion
  - OIA 017 – Log Book Cyclic Information
- Inspect all rotor drums and seals.
- Inspect IP compressor stub shaft and curvic coupling for wear.
- Inspect all blades Stage 1 through 7, overhaul process. Incorporate MODs 701, 984, 794. It is also recommended to incorporate MODs 1044 and 1159.
- Rebuild and balance the rotor assembly as per standard procedure.

### 03 Module:

### Internal Gearbox (Section 1010)

- Detail Strip, Clean and Inspect.
- Embody the following:
  - RN 5005 – Acceptance Standard for Bevel and Spur Gears
  - RN 5025 – Inspection of Helical Spines
  - RN 5034 – Corrosion Acceptance Standard for IP Compressor Rear Stub Shaft
  - CTS 1154 – Centrifugal Clutch Carrier Assembly – Spin test
  - MOD 1017 – Oil Seals: Kalrez material
  - MOD 1161 – Oil Seals: Kalrez material
- Crack test the starting mechanisms.

### HS Gearbox Drive Quill and Fittings (Section 1045)

- Detail Strip, Clean and Inspect.

### RPM Indicating System HP (Section 1420)

- Detail Strip, Clean and Inspect.
- Embody the following:
  - RN 5016 – Engine Component Life Limitation Data, Magnetic Speed Sensor
  - OIA 030 – Wire Locking of HP/IP Probes
  - OIA 044 – Fitting Procedure of HP Speed Probe LW18358

  - MOD 1231 – Revised HP Speed Probes

### Compressor Intermediate Case (Sections 1661/1661A)

- Detail Strip, Clean and Inspect.
- Re-protect the Compressor Intermediate Case.
- Replace Thread Inserts on the Starter Mounting Flange, Borescope Ports and BOV Mounting Flange.

It is recommended that the Outlet Guide Vane Ring (OGV) be modified up to the latest applicable MOD standard i.e. 1249 (1190)

NOTE: Lower standards of OGV ring can only be upgraded to MOD 1190. MOD 1249 is incorporated through replacement only. Again customer should be advised/and agree to what MODs can be incorporated.

### HP and IP Compressor Location Bearings (Section 1668)

- Detail Strip, Clean and Inspect.
- Replace the HP Thrust Bearing (MOD 1183 Standard) and IP Thrust Bearing (MOD 899 Standard).
- Crack Test the following components:
  - Rear Stub Shaft
  - Sleeve Inner IP Bearing
  - Sleeve Locking
  - Coupling IP Shaft
- Dynamic Balance the Rear Stub Shaft during build.
- Rebuild all sub assemblies then rebuild 03 as per standard procedure.

### 04 Module:

### Attachment Fittings HP Turbine Rotor (Section 1069)

- Detail Strip, Clean and Inspect.

### Turbine Rotor Discs and Shaft HP (Sections 1071 – 1071/A)

[If required – carry out a “porcupine check” before strip as per RN5024]

- Detail Strip, Clean and Inspect.
- Embody the following:
  - RN 5016 – Engine Components Life Limitation Data

  - RN 5017 – Log Book Cyclic Life Information
  - RN 5024 – HP Turbine Blade Check Procedure
  - RN 5033 – Fatigue failures of Compressor, turbine rotor blades and stator vanes
  - RN 5039 – Inspection standard for HP turbine blades
  - OIA 005 – HPT blades for thermal cracking
  - MOD 1167 – Single life bolts
- Dimensionally inspect the Panel Support and Rotor Disc Location.
- In conjunction with the OEM and Customer, review the HP turbine creep life.
- Consign HP turbine blades for weld repair of the outer shroud abutment and non-abutment faces to MOD 1130 & 1131 Sermaloy 'J' Coating.
- Overhaul process HP Turbine Disc and front rear cones.
- Inspect rear bearing track and seals.
- Inspect all rotating seals.
- Visually inspect all Remaining Components.
- Rebuild and rebalance the HP Turbine Rotor as per standard procedures.

### Nozzle Case and Nozzle Vanes HP (Section 1081)

- Detail Strip, Clean and Inspect.
- Embody the following:
  - RN 5012 – Acceptance standard of the cooling tube in HP NGV's.
  - RN 5022 – Restricted usage of Nimonic 80A fasteners.
  - RN 5033 – Fatigue failures of compressor, turbine rotor blades and stator vanes.
  - OIA 043 – Revised HP Turbine honeycomb seal clearances.
- Inspect the HP Seal Segments, repair and renew the Honeycomb seals as necessary.
- Consign the HP NGV's for repair, as required, and re-protection with Sermaloy 'J' coating in accordance with MOD 1110.
- Rebuild the HP Nozzle cases as per standard procedures.

### Attachment Parts and Fittings Combustion Liners (Section 1088)

- Detail Strip, Clean and Inspect.

### Attachment Fittings Combustion Outer Case (Section 1089)

- Detail Strip, Clean and Inspect.

### Combustion Outer Case (Section 1090-1090/A)

- Detail strip, clean and inspect.
- Re-protect the outer casing with Sermetal "W" coating

### Combustion Liner (Sections 1092-1092A-1092B)

- Detail Strip, Clean and Inspect.
- Embody the following:
  - OIA 040 – Debris in front combustion liner
  - OIA 043 – Revised HP Turbine honeycomb seal clearances
- Consign the Front Combustion Liner for condition assessment then overhaul process.

### Combustion Outer Case Fittings (Section 1093)

- Detail Strip, Clean and Inspect.

### Compressor Casing and Vanes HP (Section 1662)

- Detail Strip, Clean and Inspect.
- Visually inspect all casings, cones and inner shrouds. Replace 'Metco' and 'Feltmetal' linings and repaint. Inspect integrity of all rivets, trap nuts, alignment pins and borescope plug locations plates.
- Inspect all Stators and route for overhaul process.
- Rebuild as per standard procedure and machine casing assembly to the appropriate machine instruction drawing.
- Embody the following:
  - OIA 032 – Stage 5 stator vane feet frottage
  - OIA 035 – Stage 5 stator vane failure

### Compressor Rotor HP (Section 1664)

- Detail Strip, Clean and Inspect.
- Remove all blades, visually inspect and overhaul process.
- Strip HP compressor rotor to overhaul process Stage 1 and 2 Disc assembly, Stage 3 Disc and rear Compressor Shaft.
- Inspect locking plates Stages 1 through 4.
- Incorporate MOD 1167 – Improved bolt material on combustor.
- Embody the following:
  - RN 5003 – Replacement of HP compressor curvic coupling joint bolts.

  - RN 5009 – Renew HP compressor bolts in Jethete material at every service strip.
  - RN 5020 - Reduced cyclic life of specific HP compressor rotor Stages 1 to 2 discs Assembly
  - RN 5033 – Fatigue failures of compressor, turbine rotor blades and stator vanes
  - RN 5036 – Inspection of HP Compressor Stage 3 disc for corrosion and cracking (48,000 hours)
- Crack test all rotating components.
- Rebuild and balance the rotor assembly.
- Rebuild the 04 module assembly as per standard procedure.

**05 Module:**

### Turbine Rotor Discs and Shaft IP (Sections 1072 and 1072/A)

- Detail Strip, Clean and Inspect.
- Subject the Turbine Assembly to swash and concentricity checks and comply with RN 5021.
- Embody the following:
  - RN 5016 – engine component life limitation data
  - RN 5017 – Engine component records and component life marking
  - RN 5021 – Interlock blades, acceptance standard
  - RN 5025 – Inspection of IP shaft splines (crack test)
  - RN 5037 – IP Turbine Blade inspection criteria
  - MOD 1186 – IP Turbine disc rim, increasing cooling
  - OIAGEN 010 – IP Turbine blade fitment
  - OIAGEN 019 – Taper Bolt discoloration
- Strip, crack test and inspect the following components and O/H process:
- IP Turbine Disc
  - IP Turbine Inner Bearing Race
  - IP Turbine Shaft (RN 5025/20)
  - Metering Plate
- IP Turbine Blades re-protect with Sermaloy “J” (MOD 1187).
- In conjunction with the OEM and customer, review the IP turbine creep life.
- Rebuild and balance as per standard procedure.

### Nozzle Case and Nozzle Casings (Sections 1080 – 1080A)

- Detail Strip, Clean and Inspect.
- Embody the following:
    - RN 5018 – HP/IP support internal pipe inspection/test
    - RN 5029 – Replace thread inserts
    - OIA 027 – IP Turbine Blade Tip clearance check
    - OIA 033 – Debris Ingress
    - OIA 036 – Oil feed pipe crack detection
    - MOD 1181 – IP Bearing retainer improved abradable/clearance (1181/121)
- Strip coating and crack test the IP NGV's. If satisfactory, re-protect with Sermaloy "J" in accordance with MOD 1110.
- Replace the IP and HP roller bearings.
- Renew the 'Metco" on HP and IP bearing retainers.
- Inspect HP and IP bearing support as follows:
  X-Ray to ensure integrity of all internal tubes and brackets
- Inspect all panels and seals.
- Visually inspect main IP casing for any discrepancies.
- Renew honeycomb seal on IP seal segments; incorporate MOD 1141 if applicable on original part number.
- Inspect all remaining components.
- Replace the inserts at theT6 thermocouple locations.
- Incorporate MODs 1084 and 1129. It is recommended to incorporate MODs 1123, 1135 and 1136.
- Rebuild as per standards procedure.

**06 Module:**

- Wash and inspect all pipes.
- Visually and electrically inspect harnesses and thermocouple harness.
- Overhaul the fuel burners in accordance with the Rolls-Royce Overhaul Standard.
- Recondition all accessories as such IP and HP bleed valves and bleed valve controller.
- Electrically check HP3 transducer.
- Inspect accelerometers or vibration pick-ups.
- Pressure test burner feed pipes.
- Strip and clean scavenge block assembly.

- Visually inspect starter or as advised by customer.
- Visually inspect all remaining components and recondition as necessary.
- Incorporate MOD 1149.

It is recommended to incorporate MODs 1135, 1136, 1164, 1078, 1054, 1071, 1124 and 1266

### Non-Engine Components

- Inspect transportation stand for serviceability.
- Inspect transportation bag for serviceability.

### Engine Test

Conduct performance test in accordance with Rolls-Royce CTS 1165.

# C

# RAM TERMS AND DEFINITIONS

| Term | Definition |
|---|---|
| Availability (%) (Avail) | $\left(1 - \frac{\text{Forced Outage Hours} + \text{Scheduled Outage Hours}}{\text{Unit Period Hours}}\right) \bullet 100$<br>where Scheduled Outage Hours = Maintenance Unscheduled Outage Hours + Maintenance Scheduled Outage Hours |
| Reliability (%) (Reliab) | $\left(1 - \frac{\text{Forced Outage Hours}}{\text{Unit Period Hours}}\right) \bullet 100$ |
| Forced Outage Factor (%) (FOF) | $\left(\frac{\text{Forced Outage Hours}}{\text{Unit Period Hours}}\right) \bullet 100$ |
| Scheduled Maintenance Factor (%) | $\left(\frac{\text{Maintenance Schedule Outage Hours}}{\text{Unit Period Hours}}\right) \bullet 100$ |
| Unscheduled Maintenance Factor (%) | $\left(\frac{\text{Maintenance Unschedule Outage Hours}}{\text{Unit Period Hours}}\right) \bullet 100$ |
| Service Factor (%) (SF) | $\left(\frac{\text{Service Hours}}{\text{Unit Period Hours}}\right) \bullet 100$ |
| Starting Reliability (%) (SR) | $\left(\frac{\text{Number of Successful Starts}}{\text{Number of Attempted Starts}}\right) \bullet 100$ |
| Service Hours per Start (SH/Start) | $\left(\frac{\text{Service Hours}}{\text{Successful Starts}}\right)$ |
| Average Load | $\left(\frac{\text{Gross Megawatt Hours Generated}}{\text{Service Hours}}\right)$ |
| Mean Time Between Failure (MTBF) | $\left(\frac{\text{Service Hours}}{\text{Trips from a State of Operation}}\right)$ |
| Mean Time To Repair (MTTR) | $\left(\frac{\text{Outage Hours Resulting from Trips}}{\text{Trips from a State of Operation}}\right)$ |
| Mission (Running) Reliability | $e^{-\lambda t}$<br>where $\lambda$ = Failure Rate and<br>t = Mission Time (SH/Start) |

The above equations adhere to IEEE Standard 762: Standard Definitions for use in Reporting Electric Generating Units Reliability, Availability, and Productivity

| **Unavailability Types** | | |
|---|---|---|
| SPS ORAP$^{®}$ System | | IEEE 762 Equivalent (1987) |
| ***Forced Outage Types*** | | |
| FOA | Forced Outage - Automatic Trip: While the unit was operating a component failure or other condition occurred which caused the unit to be shut down automatically by the control system. | Unplanned Outage (UO)<br>UO Class 1 |
| FOM | Forced Outage - Manual Shutdown: While the unit was operating a component failure or other condition occurred which resulted in a decision by the appropriate person (or persons) to manually trip the unit from service. | Unplanned Outage (UO)<br>UO Class 1<br>UO Class 2<br>UO Class 3 |
| FS | Failure to Start: A signal was given to start the unit but the starting sequence was not fully completed (unit did not synchronize with system) within the required time period. Sequential failures to start caused by a single problem are to be counted as one failure to start event, unless corrective action is performed or a successful start is achieved in the interim. | Unplanned Outage (UO)<br>UO Class 0 |
| FU | Forced Unavailability:<br>1. The unit was available in the Reserve Shutdown (standby) state, but a component failure or other condition caused it to be reclassified as "Unavailable".<br>2. An extension of a planned maintenance action due to additional component failure/repair. | Unplanned Outage (UO)<br>UO Class 1 |
| ***Scheduled Outage Types*** | | |
| MU | Maintenance - Unscheduled: Maintenance that is required, but has not been specified in the maintenance plan. This outage type can be a result of a unit shutdown (when the unit is not required or outage time has been scheduled) to facilitate repairs to the unit. | Unplanned Outage (UO)<br>UO Class 4 |
| MS | Maintenance - Scheduled: Maintenance that is pre-planned, well in advance of the outage, as part of the maintenance plan. | Planned Outage (PO) |
| ***Other Outage Types*** | | |
| DR | Derating: A component failure or limitation causes a decrease in the output of the unit. | Planned Derating<br>Unplanned Derating |
| NC | Non-Curtailing Event - A redundant component fails, but does not impact the intended operation of the equipment. | (No outage code exists in IEEE Std. 762) |
| CM | Concurrent Maintenance: Maintenance is performed while downtime is charged to another component or while the unit is operating on-line or is available to start off-line (in reserve shutdown). | (No outage code exists in IEEE Std. 762) |

# D
# INSTALLATION LISTS

The following tables provide a representative listing of installation sites for Rolls-Royce RB211, Trent and Avon models in electrical generation applications. Mechanical drive and off-shore applications in the oil and gas industry are not included. For instance, there are over 240 units in mechanical drive applications (29,000 to 38,000 hp each), with over 40 having DLE combustors. Sites are sorted by commercial operating date (COD) in inverse chronological order, when known. Source: INTURB database (www.eprictcenter.com/inturb).

Legend:
CC = Combined Cycle
Cogen = Cogeneration Only
SC = Simple Cycle
NG = Natural Gas
DO = Distillate Oil

### Table D-1
### RB211 Sites

| Company | Site | City | State | Country | Model | Cycle Type | Number of CTs | Fuel | MW rating | COD |
|---|---|---|---|---|---|---|---|---|---|---|
| PT PLN Persero | Jakarta | Jakarta Area | Jakarta | Indonesia | RB211 6562 | Cogen | 1 | NG | 23 | 2004 |
| Electricidade de Portugal SA (EDP)<br>EDP Energen | Fafen Energia Cogen | Camacari | BA | Brazil | RB211 6761 | CC/Cogen | 3 | NG | 134 | 2003 |
| Rolls-Royce Power Ventures (RRPV)<br>Rolls-Royce Power Ventures Ltd | Ankara Bilkent (University) | Ankara | | Turkey | RB211 | Cogen | 1 | NG | 37 | 2003 |
| E.ON AG<br>Powergen CHP Ltd | Mersey Docks | Liverpool | | UK/England & Wales | RB211 | Cogen | 1 | Unknown | 30 | 2002 |
| Electricidade de Portugal SA (EDP)<br>EDP Cogeracao | Carrico | Carrico | | Portugal | RB211 6562 | Cogen | 1 | Unknown | 25 | 2002 |
| Direccion Provincial de Energia (DPE) | Mataderos | Ushuaia | Tierra Del Fuego | Argentina | RB211 | SC | 1 | Unknown | 27 | 2001 |
| Abengoa SA | Curtis Ethanol | Curtis | Galacia | Spain | RB211 | Cogen | 1 | Unknown | 25 | 2001 |
| Bilkent Holding AS | Bilenerji Cogeneration | Ankara | | Turkey | RB211 | CC/Cogen | 1 | NG, DO | 37 | 2000 |
| Wolverine Power Supply Coop Inc | George Johnson (Hersey) | Johnson | MI | USA | RB211 | SC | 4 | DO | 50 | 2000 |
| PT PLN Persero | Tanjung Batu | Samarinda | East Kalimantan | Indonesia | RB211 | CC/Cogen | 2 | Unknown | 50 | 1999 |
| Elf | Elgin | Elgin | | UK | RB211 | SC | 2 | NG | 54 | 1998 |
| Ertisa SA | Heulva Ertisa | Heulva | | Spain | RB211 | SC | 1 | Unknown | 27 | 1997 |
| Union Fenosa SA<br>Union Explosivos Rio Tinto SA | Huelva Refinery | Huelva | | Spain | RB211 | Cogen | 1 | NG, LPG | 26 | 1997 |
| Perusahaan Umum Listrik Negara Co | Samarinda | East Kalimantan | Borneo | Indonesia | RB211 | SC | 2 | NG | 54 | 1996 |
| TransCanada Corp<br>TransCanada PipeLines Ltd | Kapuskasing | Kapuskasing | ON | Canada | RB211 | CC/Cogen | 1 | NG | 26 | 1996 |
| TransCanada Corp<br>TransCanada PipeLines Ltd | North Bay | North Bay | ON | Canada | RB211 | CC/Cogen | 1 | NG | 26 | 1996 |

| Company | Site | City | State | Country | Model | Cycle Type | Number of CTs | Fuel | MW rating | COD |
|---|---|---|---|---|---|---|---|---|---|---|
| Statoil | Heidrun OS | | | Norway | RB211 | SC | 3 | NG | 56 | 1994 |
| AGIP SpA<br>AGIP (UK) Ltd | Tiffany OS | | | UK | RB211 | SC | 3 | NG | 75 | 1992 |
| BP | Bruce Field | | North Sea | UK | RB211 | SC | 2 | NG | 50 | 1992 |
| Norsk Hydro A/S | Oseberg A OS | | | Norway | RB211 | SC | 5 | NG | 50 | 1992 |
| Shell Oil Co<br>Shell Exploration and Production Company | Gannet OS | | | UK | RB211 | SC | 3 | NG | 50 | 1992 |
| TransCanada Corp<br>TransCanada Power LP | Nipigon | Nipigon | ON | Canada | RB211 | CC/Cogen | 1 | NG | 26 | 1992 |
| Formosa Plastics Corp | Ol Plant | | | Taiwan | COB6462 | SC | 1 | Unknown | 32 | 1991 |
| BP | Miller OS | | | UK | RB211 | SC | 3 | NG | 75 | 1990 |
| Osaka Petrochemical Co | Osaka | Osaka | | Japan | RB211 | SC | 1 | NG | 25 | 1989 |
| BP<br>BP Production Co | Anschutz Ranch | Evanston | WY | USA | RB211 | SC | 2 | NG | 43 | 1987 |
| BP<br>BP Production Co | Anschutz Ranch | Evanston | WY | USA | RB211 | Cogen | 2 | NG | 41 | 1987 |
| BP<br>BP Production Co | Wasson ODC Unit | Denver City | TX | USA | RB211 | SC | 1 | NG | 21 | 1987 |
| Shell Oil Co<br>Shell Exploration and Production Company | Tern OS | | | UK | RB211 | SC | 2 | NG | 51 | 1987 |
| Marathon Oil (UK) Limited | Brae B OS | | | UK | RB211 | SC | 3 | NG | 77 | 1986 |
| ExxonMobil Corp<br>Mobil North Sea Limited | Beryl B OS | | | UK/England & Wales | RB211 | SC | 2 | NG | 45 | 1983 |
| Brown & Root Houston | South China Sea | | South China Sea | Philippines | RB211 6562 | SC | 1 | Unknown | | |
| SPO Oslavany AS | Oslavany | Cz-66412 Oslavany | | Czech Republic | RB211 | SC | 1 | Unknown | 28 | |
| Aker Maritime Kiewit-Husky Energy | White Rose Field | Jeanne D'Arc Basin | | Canada | RB211 | SC | 3 | NG | 90 | |

## Table D-2
## Trent Sites

| Company | Site | City | State | Country | Model | Cycle Type | Number of CTs | Fuel | MW rating | COD |
|---|---|---|---|---|---|---|---|---|---|---|
| TransCanada Corp<br>TransCanada PipeLines Ltd | Bear Creek Cogen | Grande Prairie | AB | Canada | Trent | CC/Cogen | 1 | NG | 80 | 2003 |
| Rolls-Royce Power Ventures (RRPV)<br>Rolls-Royce Engineering | Croydon Powre Facility | Croydon | | UK/England & Wales | Trent | SC | 1 | NG | 50 | 2001 |
| Energi E2 A/S | Avedore Power Station | Dk-2650 Hvidovre | | Denmark | Trent | CC/Cogen | 2 | Unknown | 140 | 2001 |
| Rolls-Royce Power Ventures (RRPV)<br>Rolls-Royce Power Ventures Ltd | Ansty Factory | Ansty (Coventry) | | UK/England & Wales | Trent | Cogen | 1 | Unknown | 49 | 2001 |
| Rolls-Royce Power Ventures (RRPV)<br>Rolls-Royce Engineering | Bristol Cogeneration | Bristol | | UK | Trent | SC | 1 | NG | 50 | 2000 |
| Rolls-Royce Power Ventures (RRPV)<br>Rolls-Royce Engineering | Exeter Power Facility | Exeter | Southwest England | UK | Trent | SC | 1 | NG, FO#6 | 50 | 2000 |
| Rolls-Royce Power Ventures (RRPV)<br>Heartlands Power Ltd | Fort Dunlop (Heartlands) | Warwickshire (Birmingham) | | UK/England & Wales | Trent | SC | 2 | NG | 100 | 1999 |
| Rolls-Royce Power Ventures (RRPV)<br>Rolls-Royce Engineering | Viking Power Facility | Seal Sands on Teesside | Durham | UK/England & Wales | Trent | SC | 1 | NG | 50 | 1999 |
| RWE Group<br>Rolls-Royce Power Engineering | Derby Cogeneration | Derbyshire | | UK/England & Wales | Trent | CC/Cogen | 1 | NG | 60 | 1999 |
| Northern Electric plc | Newcastle-Upon-Tyne | Newcastle Upon Tyne | | UK/England & Wales | Trent | Cogen | 1 | Unknown | 52 | 1998 |
| Calpine Corp | Whitby Mill Cogeneration | Whitby | ON | Canada | Trent | Cogen | 1 | NG | 50 | 1996 |
| Rolls-Royce Power Ventures (RRPV)<br>Rolls-Royce Power Ventures Ltd | Altwater WWTP | Montreal | QC | Canada | Trent | SC | 1 | NG | 53 | |

### Table D-3
### Avon Sites

| Company | Site | City | State | Country | Model | Cycle Type | Number of CTs | Fuel | MW rating | COD |
|---|---|---|---|---|---|---|---|---|---|---|
| Pakchina Fertilizer Ltd | Haripur Pakchina | Haripur | | Pakistan | Avon | Cogen | 1 | Unknown | 14 | 1997 |
| Schon Power Generation Ltd | Pakchina Haripur | Haripur | | Pakistan | Avon | SC | 1 | Unknown | 15 | 1997 |
| Electricite de France (EDF)<br>Electricite de France - Guyane | Kourou | Kourou | | French Guiana | Avon | SC | 2 | Unknown | 31 | 1990 |
| Korea Petrochemical Industries Co | Onsan | | | South Korea | Avon | SC | 1 | Unknown | 15 | 1990 |
| Tokyo Metropolitan Government | Azuma | Tokyo | | Japan | Avon | SC | 1 | Unknown | 16 | 1990 |
| Tokyo Metropolitan Government | Shinozaki Wwtp | Tokyo | | Japan | Avon | SC | 1 | Unknown | 16 | 1990 |
| Honam Petrochemical Corp | Yeochon Plant (HPC) | Yeochon | | South Korea | Avon | SC | 1 | Unknown | 19 | 1988 |
| Yemen Hunt Oil Co | Marib Hunt | Marib | | Yemen | Avon | SC | 3 | Unknown | 39 | 1988 |
| Public Electricity Corporation (PEC) | Alif | | | Yemen | Avon | SC | 3 | Unknown | 47 | 1987 |
| Elsam A/S | Studstrup | Dk-8100 Arhus C | | Denmark | Avon | SC | 1 | Unknown | 13 | 1986 |
| General Petroleum Co | SPC GT | | | Syria | Avon | SC | 1 | Unknown | 17 | 1986 |
| Nippon Telegraph and Telephone Corp (NTT) | Tokyo NTT | Tokyo | | Japan | Avon | SC | 1 | Unknown | 17 | 1986 |
| Petroleum Development Oman (PDO) | Yibal Gas Plant | Yibal | | Oman | Avon | SC | 3 | Unknown | 38 | 1983 |
| Tarong Energy Corp Ltd | Tarong | Nanango | QLD | Australia | Avon | SC | 1 | Unknown | 15 | 1983 |
| CRA/Barrack House Group | Jurien Bay | | | Australia | Avon | SC | 1 | Unknown | 16 | 1982 |
| Empresa Electrica Guaracachi SA | Karachipampa | Potosi | | Boliva | Avon | SC | 1 | Unknown | 16 | 1982 |

| Company | Site | City | State | Country | Model | Cycle Type | Number of CTs | Fuel | MW rating | COD |
|---|---|---|---|---|---|---|---|---|---|---|
| Abu Dhabi Gas Industries Ltd (ADGAS) | Bu Hasa (ADGAS) | | Abu Dhabi | United Arab Emirates | Avon | SC | 4 | Unknown | 45 | 1981 |
| General Electric Co of Libya | Abu Kamash | | | Libya | Avon | SC | 2 | Unknown | 29 | 1981 |
| General Electric Co of Libya | Misurata Steel Works | Misurata | | Libya | Avon | SC | 1 | Unknown | 11 | 1981 |
| E.ON AG<br>PowerGen plc | Ince | Cuerdley | Warrington | UK/England & Wales | Avon | SC | 2 | Unknown | 50 | 1979 |
| Dallah Establishment | Ads Jeddah | | | Saudi Arabia | Avon | SC | 1 | Unknown | 17 | 1978 |
| Maritime Electric Co Ltd | Borden | Port Borden | PE | Canada | Avon | SC | 1 | DO | 15 | 1978 |
| National Iranian Oil Co (NIOC) | Pazanan Field | | | Iran | Avon | SC | 2 | Unknown | 29 | 1978 |
| Zambia Consolidated Copper Mines (ZCCM) | Luanshya Nchanga | Luanshya | | Zambia | Avon | SC | 3 | Unknown | 44 | 1977 |
| BHP Co Ltd<br>BHP Minerals | Mount Newman | Newman | WA | Australia | Avon | SC | 1 | Unknown | 14 | 1976 |
| NRG Asia-Pacific Ltd | Gladstone Comalco | Gladstone | QLD | Australia | Avon | SC | 1 | Unknown | 14 | 1976 |
| Premier Power Ltd | Ballylumford A | Larne | County Antrim | UK/Northern Ireland | Avon | SC | 2 | Unknown | 120 | 1976 |
| British Energy plc<br>Bruce Power Inc | Bruce | Tiverton | ON | Canada | Avon | SC | 8 | DO | 133 | 1974 |
| ExxonMobil Corp<br>Exxon Mobil Australia | Longford Gas Plant | Longford | VIC | Australia | Avon | SC | 1 | Unknown | 14 | 1974 |
| SWB AG | Mittelsburen | Bremen | HB | Germany | Avon | SC | 1 | Unknown | 88 | 1974 |
| Vattenfall AB | Hallstavik | Hallstavik | | Sweden | Avon | SC | 2 | Unknown | 116 | 1974 |
| Vattenfall AB | Lahall | | | Sweden | Avon | SC | 4 | Unknown | 232 | 1974 |
| Abu Dhabi National Oil Co (ADNOC) | Asab | Asab | Abu Dhabi | United Arab Emirates | Avon | SC | 3 | Unknown | 44 | 1973 |
| E.ON AG<br>E ON Energie AG | Audorf | | | Germany | Avon | SC | 1 | Unknown | 88 | 1973 |

| Company | Site | City | State | Country | Model | Cycle Type | Number of CTs | Fuel | MW rating | COD |
|---|---|---|---|---|---|---|---|---|---|---|
| Fingrid Oyj | Huutokoski | Fin-79620 Huutokoski | | Finland | Avon | SC | 6 | Unknown | 174 | 1973 |
| Power and Water Authority | Berrimah | Darwin | NT | Australia | Avon | SC | 1 | Unknown | 14 | 1973 |
| Vattenfall AB | Gothenburg | | | Sweden | Avon | SC | 1 | Unknown | 58 | 1973 |
| Wolverine Power Supply Coop Inc | George Johnson (Hersey) | Johnson | MI | USA | Avon | SC | 2 | DO | 54 | 1973 |
| Electricity Supply Board (ESB Ireland) Coolkeeragh Power Ltd | Coolkeeragh | Maydown | County Londonderry | UK/Northern Ireland | Avon | SC | 1 | Unknown | 60 | 1972 |
| Imperial Chemical Industries Ltd (ICI) | Middlesborough | | | UK/England & Wales | Avon | SC | 1 | Unknown | 15 | 1972 |
| Scottish and Southern Energy plc Scottish Hydro-Electric plc | Arnish Lewis | | | UK/Scotland | Avon | SC | 2 | Unknown | 29 | 1972 |
| Burlington Electric Dept (VT) | Lake Street Gas Turbine | Burlington | VT | USA | Avon | SC | 2 | DO | 28 | 1971 |
| Delta Electricity | Munmorah | Doyalson | NSW | Australia | Avon | SC | 1 | Unknown | 12 | 1971 |
| E.ON AG<br>E ON Energie AG | Itzehoe Pe | | | Germany | Avon | SC | 1 | Unknown | 88 | 1971 |
| EnBW Energie-Versorgung Schwaben AG | Marbach | D-71672 Marbach | | Germany | Avon | SC | 1 | Unknown | 77 | 1971 |
| ESEBA Generacion | Bragado | Buenos Aires | | Argentina | Avon | SC | 1 | Unknown | 13 | 1971 |
| ESEBA Generacion | Pehuajo | | Buenos Aires | Argentina | Avon | SC | 1 | Unknown | 13 | 1971 |
| Fingrid Oyj | Kristiina | Kristiinankaupunki | | Finland | Avon | SC | 2 | Unknown | 58 | 1971 |
| London Underground Ltd | Greenwich | Greenwich | | UK/England & Wales | Avon | SC | 8 | Unknown | 116 | 1971 |
| Macquarie Generation | Liddell | Muswellbrook | NSW | Australia | Avon | SC | 2 | Unknown | 44 | 1971 |
| Qatar Fertilizer Co (QAFCO) | Mesaieed (QAFCO) | Mesaieed | | Qatar | Avon | SC | 7 | Unknown | 102 | 1971 |

| Company | Site | City | State | Country | Model | Cycle Type | Number of CTs | Fuel | MW rating | COD |
|---|---|---|---|---|---|---|---|---|---|---|
| Vattenfall AB | Gotland Vattenfall | | Gotland | Sweden | Avon | SC | 2 | Unknown | 116 | 1971 |
| Virgin Islands Water & Power Authority | St. Thomas | Charlotte | VA | USA | Avon | SC | 1 | Unknown | 26 | 1971 |
| Australian Newsprint Mills Ltd | Boyer | Boyer | | Australia | Avon | SC | 1 | Unknown | 14 | 1970 |
| CS Energy Corp Ltd | Mica Creek Power Station | Mount Isa | QLD | Australia | Avon | SC | 1 | NG | 14 | 1970 |
| CS Energy Corp Ltd | Middle Ridge | Toowoomba | QLD | Australia | Avon | SC | 1 | Unknown | 60 | 1970 |
| Edison International<br>Edison Mission Energy | Fiddlers Ferry | Cuerdley | Warrington | UK/England & Wales | Avon | SC | 4 | Unknown | 116 | 1970 |
| Papua New Guinea Electricity Commission | Moitaka | Port Moresby | | Papua New Guinea | Avon | SC | 1 | Unknown | 20 | 1970 |
| RWE Group<br>Innogy Holdings plc | Didcot | Didcot | Oxfordshire | UK/England & Wales | Avon | CC/Cogen Multishaft | 4 | Unknown | 572 | 1970 |
| Sithe Energies Inc | Framingham Power Plant | Framingham | MA | USA | Avon | SC | 3 | DO | 43 | 1970 |
| Sithe Energies Inc | West Medway Power Plant | West Medway | MA | USA | Avon | SC | 3 | DO | 135 | 1970 |
| Boston Generating LLC | Mystic Station | Everett | MA | USA | Avon | SC | 1 | DO | 14 | 1969 |
| CS Energy Corp Ltd | Swanbank Power Station | Ipswich | QLD | Australia | Avon | SC | 1 | Unknown | 30 | 1969 |
| International Power plc | Rugeley B | Rugeley | Staffordshire | UK/England & Wales | Avon | SC | 2 | Unknown | 50 | 1969 |
| London Electricity plc | Cottam | Cottam Near Retford | Nottinghamshire | UK/England & Wales | Avon | SC | 4 | Unknown | 25 | 1969 |
| Sithe Energies Inc | Edgar Power Plant | North Weymouth | MA | USA | Avon | SC | 2 | DO | 28 | 1969 |
| E.ON AG<br>PowerGen plc | Kingsnorth | Rochester | Kent | UK/England & Wales | Avon | SC | 4 | Unknown | 72 | 1968 |
| Esso<br>Esso UK plc | Milford Haven Refinery | Milford Haven | | UK/England & Wales | Avon | SC | 1 | Unknown | 14 | 1968 |
| Newfoundland Power Inc | Salt Pond | Burin Bay Arm | NF | Canada | Avon | SC | 1 | DO | 14 | 1968 |

| Company | Site | City | State | Country | Model | Cycle Type | Number of CTs | Fuel | MW rating | COD |
|---|---|---|---|---|---|---|---|---|---|---|
| Shell Oil Co | Carrington Shell | | | UK/England & Wales | Avon | SC | 1 | Unknown | 14 | 1968 |
| TXU Corp<br>TXU Europe Group plc | West Burton | Retford | Nottinghamshire | UK/England & Wales | Avon | SC | 4 | Unknown | 72 | 1968 |
| E.ON AG<br>E ON Energie AG | Emden | D-6725 Emden 1 | | Germany | Avon | SC | 1 | Unknown | 52 | 1967 |
| Newfoundland and Labrador Hydro | Holyrood | Holyrood | NF | Canada | Avon | SC | 1 | DO | 14 | 1966 |
| RWE Group<br>Innogy Holdings plc | Thorpe Marsh | Doncaster | South Yorkshire | UK/England & Wales | Avon | SC | 2 | Unknown | 56 | 1966 |
| ScottishPower plc | Clydes Mill | | | UK/Scotland | Avon | SC | 1 | Unknown | 55 | 1965 |
| Stadtwerke Dusseldorf AG | Flingern | Dusseldorf | | Germany | Avon | SC | 1 | Unknown | 77 | |

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