ABSTRACT
The industrial Trent is the largest aeroderivative gas turbine available, at 50+ MW, and the most efficient gas turbine available to industrial and marine operators, at 42%. Its Dry Low Emissions combustion system embodies the features of the similar combustor on the industrial RB211, which is enjoying very successful service experience.

Its design features and derivation from the aero engine are reviewed, together with an assessment of the maintenance aspects of the engine.

The current status of the engine validation programme is discussed, covering both component rig testing and progress on the full engine testing being carried out in Montreal, Canada.

The applications of the industrial Trent are considered by reviewing the major markets and examining its suitability, both technically and economically, for several existing and emerging sectors.

Launched as a power generation machine, the industrial Trent is shown to be well suited to those sectors which have resulted from the growing deregulation of this industry worldwide. In addition it is shown to be attractive for certain applications in the oil and gas industry and, in the marine market, for some large high speed vessel concepts.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>Btu</td>
<td>British Thermal Unit</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>CO</td>
<td>Carbon Monoxide</td>
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<tr>
<td>DLE</td>
<td>Dry Low Emissions</td>
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<tr>
<td>HP</td>
<td>High Pressure</td>
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<td>Hz</td>
<td>Hertz</td>
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<td>h</td>
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<tr>
<td>kg</td>
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<td>Kilonewton</td>
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<tr>
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<td>VIGV</td>
<td>Variable Inlet Guide Vane</td>
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<tr>
<td>rpm</td>
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<tr>
<td>s</td>
<td>Second</td>
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<tr>
<td>vppm</td>
<td>Volume Parts per Million</td>
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<tr>
<td>°C</td>
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INTRODUCTION
The industrial Trent gas turbine takes aeroderivative machines through the 50 MW threshold for the first time (Figure 1) bringing the characteristic benefits of aeroderivatives to a further group of operators and applications.

In performance terms the Trent leads its class in both simple cycle and combined cycle heat rate, and offers excellent low ambient temperature characteristics. This last feature makes the Trent eminently suitable for intake refrigeration, offering a realistic solution to the problems of performance reduction at high intake temperatures.

Simple cycle performance data is provided in Appendix 1 and combined cycle performance data in Appendix 2.

In keeping with the aeroderivative approach to engineering validation the industrial Trent has been subjected to an extensive modelling, simulation and testing exercise. This is in addition to the exhaustive Trent aero engine certification programme, thus assuring that all components are known to be operating within their technological limitations. As a result of this comprehensive development process a confident entry into service is anticipated.
PEDIGREE

The industrial Trent derives from the aero Trent (Figure 2), itself an extension of the highly successful RB211 family of three-shaft engines which has powered both narrow and wide-bodied aircraft since the 1970's.

The aero Trent 800 was the first aero engine to be certificated at 90,000 pounds (400 kN) thrust for the Boeing 777. Of these aircraft ordered to date, 35% are Trent powered. Further growth versions of the Trent are being engineered to satisfy the demands of stretch variants of the aircraft. These growth versions of the aero Trent will in due course bring even higher output versions of the industrial Trent.

The industrial Trent and the aero Trent 800 both share extensive commonality also with the Trent 700, which has been in service since early 1995 on the Airbus A330. Of these aircraft ordered to date, 38% are Trent powered.

In practice, these various Trent members of the same family all contribute to, and benefit from, service experience, leading to accelerated embodiment of product improvements common to all.

FEATURES

The broad derivation of the industrial Trent design from the aero Trent engine has been covered elsewhere by Buxton and Thoman (1) and a detailed review of the concept optimisation process has been presented by Jackson (2).

In summary, the main differences (Figure 3) from the aero-engine are:-

1) A new LP Compressor
   In order to maintain conditions at entry to the IP compressor substantially similar to those provided by the fan of the aero engine, the industrial Trent uses a two-stage LP compressor delivering a pressure ratio up to around 1.7:1.

   In fact, two LP compressor configuration standards are available, between which different blade stagger angles are employed for the rotor stages. These two standards accommodate efficient synchronous operation at either 3,000 rpm or 3,600 rpm, endowing the industrial Trent with the unique ability to drive a synchronous alternator without a gearbox, in either 50 Hz or 60 Hz electrical systems.

   The inherent modular capability of the industrial Trent, which it shares with the whole RB211/Trent family, would even permit, by change of LP compressor module, in-field conversion from 50 Hz to 60 Hz configuration, in the unlikely event of that ever being needed. Of course, the main benefit of having the two versions is to achieve maximum performance for customers in both markets at the minimum production cost and lead time.

2) A modulated LP air bleed system
   During the start up cycle and low power operation (normally in the transient periods when load is being added or removed), the LP compressor operating at synchronous speed delivers air in excess of the IP compressor swallowing capacity, even accounting for the VIGV systems of the LP and IP compressors.

   To accommodate this flow discrepancy, a set of hydraulically operated bleed doors are employed to spill controlled levels of excess air via a duct to atmosphere.

3) A dual-fuel DLE combustion system
   Rolls-Royce has already established reliable and successful operation of dry low emissions combustion systems on the industrial RB211 engine. By employing this technology on the Trent, emissions levels of below 25 ppm of both NOx and CO have been demonstrated on natural gas fuel.

   The uncompromising, series-staged layout of the premixed lean-burn combustion system has shown itself well able to meet operators' needs for low emissions performance not only at the design point, but over the wide combustor operating range associated with turndown, or with varying ambient temperatures in the -40°C to +40°C band.

   Mixed operation on natural gas and distillate throughout the power range, in dual fuel mode, is also available.

   The industrial Trent demands performance from its DLE system at advanced levels of cycle parameters, and in addition it embodies the capability to operate in a non lean-burn mode on distillate fuels when necessary. Mitigation of emissions on liquid, or part liquid fuel is achieved by the use of well proven water injection technology which typically involves a water to fuel ratio of around 1 to 1.

   Also, Rolls-Royce having established the principles of dry low emissions on liquid fuel, the industrial Trent combustor concept is configured for adaptation to such technology, and this will be available to customers in due course.

   Lighting of each combustor is by a small gas-fuelled torch which provides highly reliable starting and eliminates any need for cross-firing between combustors.

4) A revised LP turbine including power delivery hub coupling
   Whilst the industrial Trent uses a five-stage turbine like the aero Trent, only the first three stages are common.

   The last two stages have been redesigned for larger flow area to reduce exit velocities to aerodynamically acceptable levels in the interests of efficiency, and to ensure the mechanical integrity of the blading itself as well as other exhaust system components.

   In the interests of retaining conservative load levels in the internal shafting systems of the engine, the industrial Trent offers only an exhaust-end drive configuration and this is provided by a robust output drive coupling mounted on the turbine rotor hub.

5) A new control system
   The industrial Trent embodies a number of advanced
technology features to provide operators with state-of-the-art performance over a wide operating range, and these features are under the control of a microprocessor-based Engine Management System.

The equipment is supplied by Woodward Turbomachinery Controls, and its application to the industrial Trent has been developed jointly by the Rolls-Royce and Woodward engineering teams.

A listing of the EMS functions is superfluous here, and will be reported elsewhere for specialist interest.

MAINTAINABILITY
In common with other Rolls-Royce aeroderivatives, comprehensive inspection and condition monitoring facilities are available on the Trent.

Figure 4 for example, shows the range of boroscope access, which allows extensive inspection of the gas path for assessment of deterioration or damage.

Boroscope access, coupled with vibration monitoring, bearing debris monitoring, and increasingly sophisticated performance trend analysis, permit continuing judgements to be made on an engine's ongoing serviceability.

When excessive deterioration is indicated, then the modularity of the engine minimises the need to return the complete Trent to an overhaul shop. Drawing on the very successful modular experience of the whole aeroderivative RB211/Trent family, the Trent can be readily disassembled on site (Figure 5).

It is anticipated that repair or overhaul of the LP systems will rarely be required, so these modules will normally be left on site, and the "gas generator" exchanged for a spare or lease pool unit. Should it be judged that only one or two of the gas generator modules needs rectification, then this is also easily achieved on site.

The dimensions of the Trent gas generator are in fact very similar to those of the RB211 gas generator, and it is shippable by air transport in a standard wide-bodied freighter.

Should either of the LP systems need repair, then these are also of suitable dimensions for similar air shipment.

A variety of component replacements are of course possible with the Trent installed in its working position. In particular, the individual combustion chambers and their turbine entry ducts (transition pieces) can be exchanged in situ.

ENGINEERING DEVELOPMENT & VALIDATION PROGRAMME
The overall project programme for the industrial Trent is shown in Figure 6 and involves a team of engineers at Rolls-Royce Gas Turbine Engines (Canada) Inc. in Montreal working closely with both the aero Trent engineering group in Derby (UK) and the engineering and business management of Rolls-Royce Industrial and Marine Gas Turbines at Ansty (UK).

With the aero engine certification programme providing the fundamental validation of the core of the engine, the task for the RRGTE team has been:

a) to check the common aero components ability to operate at the industrial engine conditions.

b) to prove that the industrial specific components (and software) perform their designated function.

The mission of the development programme is to confirm:
- integrity and safety
- performance - power/heat rate/emissions
- systems integration and operability (hardware and software)
- durability
- maintainability

This mission is achieved on a progressive basis by:
- design to meet a specified project requirement
- detailed component and systems analysis
- systems simulation and modelling
- component rig testing
- full engine testing

Whilst this paper is not intended to provide a comprehensive review of the whole development programme, it is worth summarising the tasks undertaken to ensure confidence in the main industrial design features:

LP Compressor
- conservative design by existing Rolls-Royce codes, with aerodynamic characteristics within existing experience
- full compressor characteristic "mapping" during engine trials.
- extensive instrumentation during engine trials to ensure satisfactory stresses, vibration characteristics, etc.

LP air bleed system
- model testing to ensure airstream disturbances during operation are within acceptable parameters for LP and IP compressors, followed by instrumentation during engine trials
- control system software verification both by simulation and full engine testing

DLE combustor system
- extensive design analysis, using state-of-the-art CFD processes
- flow visualisation techniques
- fuel/air mixing trials
- low pressure combustor rig testing
- high pressure combustor rig testing
- ongoing interchange with RB211 DLE engineering team
LP turbine
• extensive instrumentation during engine testing to ensure safe blade stresses, temperatures, vibration characteristics, etc.

Engine Control system
• full back-to-back simulated operation against an electronic model of the engine incorporating full feature replication of all the major engine components.

FULL SCALE ENGINE TESTING
A comprehensive series of full scale development tests has been an intrinsic feature of all Rolls-Royce’s engine validation programmes since introduction to service of the aeroderivative industrial and marine gas turbine nearly forty years ago.

Whilst the Trent is reaching power levels where the major cost of such testing has to be considered carefully, it is the Rolls-Royce view that there is no substitute if service entry is to be achieved with few problems.

Furthermore, whilst experience has shown that the close tolerance manufacture of the components in RB211 and Trent engines allows production engines to be built with the confidence that their assembly will be fault-free, it is also the company’s policy to test each production engine to its full rating prior to despatch to the customer.

Rolls-Royce has therefore established in Montreal a full power test bed dedicated to the industrial Trent, with its development testing activity during 1995, 1996 and 1997 giving way progressively to production engine pass-off testing as the programme increases.

This test facility has the capability to absorb the full power output of the Trent at either 50Hz or 60Hz operation. An electrical generator driven by the Trent’s output shaft, produces power at 13,500 volts which is transferred to load banks on the roof.

An overall sketch of the test bed is shown in Figure 7, with photographs at Figures 8 and 9 revealing the scale of operation.

APPLICATIONS

Power Generation

The power industry is currently subject to a high rate of change world-wide, with privatisation, deregulation and functional separation characterising the mood.

In this economic environment, with its focus on profit, competition and risk mitigation, attention is increasingly turning to independent, rather than interdependent, power systems.

The economies of scale no longer dominate the thinking, but the economies of smaller integrated energy systems (electricity, steam, chilled water) are increasingly acknowledged.

In this setting, the fundamentally beneficial performance of the industrial Trent make it suitable for a wide range of power generation applications from simple cycle standby and peaking operations, through mid-merit duties, to full baseload service in cogeneration and combined cycle.

In typical standby and peaking duties, the Trent brings the features of operational flexibility, including reliable starting, rapid loading and unloading, peak rating capability and capital cost/heat rate characteristics which make it economical at fairly low operating hours whilst also providing some insurance against volatility of fuel prices.

For mid-merit operation, particularly whilst fuel prices remain relatively low, the efficiency of the Trent makes it suitable for operation over 4000/5000 hours per annum, with much lower operator attention than the use of older power stations which is the otherwise common approach for this function.

Perhaps above all the Trent meets the requirements of operators looking for cogeneration or combined cycle performance in the 50 to 150 MW range, a power station size which is increasingly common.

Figure 10 demonstrates the steam production capability of the Trent, whilst the resultant combined cycle performance is given in Appendix 2.

For cogeneration and combined cycle duties, the industrial Trent provides additional benefits including excellent off-design performance (under turndown or differing ambient temperatures) through the use of its VIGV systems and bleed-free series-staged combustors.

The ambient temperature characteristics of the industrial Trent, where maximum power (around 60 MW) is available around 0°C, permit conventional inlet refrigeration systems to be employed in capitalising on the inherent flow capacity of the machine.

In all applications, maximum continuing availability is achieved through the ability to exchange turbine units or modules within a few working shifts.

Gas and Oil Industry

The aeroderivative gas turbine has dominated the offshore gas and oil industry in sizes above 10 MW for many years, as a result of its compact size and high availability, supported by its ease of operation and efficiency.

The industrial Trent extends these capabilities into a new power range which will extend the present available choice on large platforms where either very large electrical power demands may now be met by a smaller number of units, or where gas processing compressor drive horsepower requirements are very large.
A typical case of the latter opportunity is the Natuna gasfield project, where waste gas compression power requirements are in the industrial Trent range.

Whilst the industrial Trent is well able to operate over the power/speed laws typical of a compressor drive, in fact the majority of applications in this power range will run at the fairly constant power levels associated with typical gas processing plant. The industrial Trent, with its flexible operating features controlled by the broad capability of its EMS, should be well able to cover any anticipated operating range.

Marine Projects

At this point, marine applications of the industrial Trent are limited, but there are already projects under discussion for high capacity, high speed transoceanic transport which could use its power.

In particular, one project envisages a fleet of Atlantic vessels carrying high value cargo between Europe and the USA. For such a project, regular scheduling is essential and large, powerful craft are being considered to minimise the impact of variable weather. Such craft would use five Trents driving waterjets for propulsion.

As for mechanical drive duties in the gas and oil industries, the flexibility of the Trent makes it ideally suited to this task.

REFERENCES

(1) Buxton, R.D and Thoman, R. J., 1994
"Trent Econopac Development Initiated"
Power Gen Conference, Orlando, Florida

(2) Jackson, A.J.B. October 1995
"The Industrial Trent Engine"
Canadian Gas Association,
11th Annual Symposium on Industrial Gas Turbines
Banff, Alberta
APPENDIX 1

INDUSTRIAL TRENT - SIMPLE CYCLE PERFORMANCE

<table>
<thead>
<tr>
<th></th>
<th>BASE LOAD RATING</th>
<th>PEAK LOAD RATING</th>
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<tr>
<td><strong>POWER OUTPUT</strong></td>
<td>51,190 kW</td>
<td>55,310 kW</td>
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<tr>
<td><strong>HEAT RATE</strong></td>
<td>8,660 kJ/kWh</td>
<td>8,550 kJ/kWh</td>
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<tr>
<td></td>
<td>(8,210 Btu/kWh)</td>
<td>(8,105 Btu/kWh)</td>
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<tr>
<td><strong>THERMAL EFFICIENCY</strong></td>
<td>41.6%</td>
<td>42.1%</td>
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<td><strong>EXHAUST FLOW</strong></td>
<td>159.4 kg/s</td>
<td>163.0 kg/s</td>
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<td>(351 lb/s)</td>
<td>(359 lb/s)</td>
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<tr>
<td><strong>EXHAUST TEMPERATURE</strong></td>
<td>426°C</td>
<td>438°C</td>
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<td></td>
<td>(800°F)</td>
<td>(820°F)</td>
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<tr>
<td><strong>ELECTRICAL FREQUENCY</strong></td>
<td>50/60 Hz</td>
<td>50/60 Hz</td>
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**NOTES:**

NATURAL GAS FUEL, SEA LEVEL, ISO CONDITIONS, 60% RELATIVE HUMIDITY

NO INSTALLATION LOSSES

HEAT RATE BASED ON LHV (LOWER HEATING VALUE) OF FUEL
## APPENDIX 2

### INDUSTRIAL TRENT - COMBINED CYCLE PERFORMANCE

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<td>NET POWER OUTPUT</td>
<td>62,680 kW</td>
<td>125,500 kW</td>
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<tr>
<td>HEAT RATE</td>
<td>6,969 kJ/kWh</td>
<td>6,963 kJ/kWh</td>
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<tr>
<td></td>
<td>(6,606 Btu/kWh)</td>
<td>(6,600 Btu/kWh)</td>
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<tr>
<td>NET PLANT EFFICIENCY</td>
<td>51.7 %</td>
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<tr>
<td>ELECTRICAL FREQUENCY</td>
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</table>

### NOTES:

1 + 1 = 1 TRENT WITH 1 STEAM TURBINE

2 + 1 = 2 TRENTS WITH 1 STEAM TURBINE

NATURAL GAS FUEL, SEA LEVEL, ISO CONDITIONS, 60% RELATIVE HUMIDITY

DOUBLE PRESSURE STEAM CYCLE

100 mm (4 in) WATER INLET AND 250 mm (10 in) WATER EXHAUST LOSSES

HEAT RATE BASED ON LHV (LOWER HEATING VALUE) OF FUEL
Industrial Trent

Output power (MW)

- Peak rating
- Base rating

Ambient temperature (°C)

Efficiency (%)

- Peak rating
- Base rating

Inlet temperature (°C)

ROLLS-ROYCE INDUSTRIAL & MARINE POWER LIMITED

Figure 1
Rolls-Royce Trent

Figure 2
Industrial Trent derived from aero Trent 800

- New compressor replaces fan
- LP bleed added for low speed operation
- Dry low emissions combustor replaces aero annular can
- Last two stages of LPT and exhaust redesigned
- Rear drive added
- New control system incorporates closed loop emissions control
Trent gas turbine borescope access
Industrial Trent maintenance options

1. Gas turbine changeout

2. Gas generator changeout

3. Module changeout

Figure 5
### Industrial Trent development programme

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**Notes:**
- Trent 700
- Trent 800

**Figure 6**
Industrial Trent
Montreal test facility
Industrial Trent
Montreal test facility
Industrial Trent on test

Figure 9
Trent steam raising capability
- Meets a wide range of heat/power requirements at high efficiency

- For 40 bar steam at 385°C Single Pressure boiler 50 mbar condenser pressure Refiring limit 650°C

Increasing level of refiring

Trent envelope of optimum capability i.e. GT operating at base rating

Increasing level of pass out from steam turbine

All steam to process with maximum refiring (no steam turbine)

All steam to process (no steam turbine)

Pure combined cycle with maximum refiring (no process steam)

Pure combined cycle (no process steam)

Figure 10