DEVELOPMENT OF THE RB211-Gzero AFTERMARKET POWER UP-RATE

by

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RB211-Gzero upgrade

- Retrofit for RB211 –C and –G
- +10% power, no hot end mods
- Maintained efficiency

- Applied at scheduled overhaul
- “Plug and play” engine swap
- Maintained reliability & operability

RB211-Gzero product released in 2013

Existing RB211-G hot end

Upgraded Gzero cold end
Agenda

- Product rationale
- Design features
- Engine Development Program
- Verified product attributes
- Conclusions
Rolls-Royce aero-derivative GT

Industrial RB211
- Over 32 Million hrs accumulated to date
- Many upgrades and improvements since initial introduction in 1970’s
RB211 / Trent product families

Aero thrust

Trent 8104 Demonstrator (114K lb)

Output Power (MW)


Power growth

RB211-Gzero PhII RT62
Uninstalled, Sea Level, 60% RH, Typical Natural Gas, New and Clean engine

+ 10% from –G
+ 31% from –C

Shaft power output [ MW ]

Ambient temperature [ °C ]
RB211 modular architecture

- Only front-end modules modified by the Gzero upgrade
- Increased core flow capacity
- Power increase achieved without hot end modifications
Engine cold end upgrade

- Stage Zero
- 3 Stage VIGV / VSVs mechanism
- IP Compressor Casing Stage 1-6 stators
- RB211-GT Rotor 2 Blade
- RB211-GT IP OGV
- Stg 0/1 Drums
- RB211-G Stage 2-7 Drum & Blades

New Parts
Donor Engine
Existing Design

Engine length unchanged
Module 01- Air Inlet Casing

- CFD-optimized inlet strut profile
- Machine finished gas path surfaces
- Engine front bearing housing unchanged
- VIGV location features
- Integrated front extension
- Wash spray nozzle ports
- Integrated engine front mount

Single casting incorporating all features
IP Compressor – rotor assembly

- Rotor 1 disc replaced with new 0 & 1 stage drum assembly
- Titanium discs and blades to maintain optimal rotor dynamics
- Discs and blades of rear stages (2-7) left unchanged

Rotor 0 and 1 blades

- No change to IPC front stub shaft
- Rotor 0 & 1 drum replacing rotor 1 disc between existing interfaces
- No change to rotor 2-7 drum assembly
IP Compressor – blades & vanes

- Titanium blades (0 & 1), SS vanes
- Blades have Elliptical Leading Edge, optimized by CFD for high efficiency
- Bench tested for HCF strength
- Three variable geometry stages
IPC design optimization

- Aerodynamics optimized by 1D, 2D and 3D CFD using latest tools for increased IPC flow and efficiency, and preserved surge margin
- Vibration response of all blades & vanes to pressure forcing from upstream & downstream stages simulated with proprietary tool
- Stator incidence angles optimized to minimize vibration response
- Stress analysis completed with 3D FEA tools
- Avoided need for complex on-engine strain gauge testing
Variable geometry actuation

- 3-stage variable geometry
- System design based on aero Trent 900
- Actuation & controls already proven in Ind. RB211 & Trent
Package and Power Turbine modifications

- Power Turbine Inlet Guide Vane ("hot match")
- Additional Bleed-Off Valve ducting as per the RB211-GT
- Power turbine thrust bearing upgrade
- Gas generator mounting bolt change
- Cyclone separator
Gzero Development Engine Timeline

Feb 2012 – All H/W in store

May 2012 – Development Engine Build Complete
Gzero Engine in Montreal Test Bed

Jun 2012 – Sep 2012: Gzero Engine Development Program
Engine Instrumentation

More than 1200 parameters recorded:

- Inter-stage instrumentation (temperature and pressure survey) in new IP Compressor for full characterization
- “Blade Tip Timing” laser probes to measure the vibration response of the new IP compressor blades while running
- Inlet air meter for accurate measurement of core flow
- Fast response dynamic pressure probes to detect the onset of compressor stall
- Capacitance probes for real-time monitoring of Compressor blade Tip Clearances
- Accurate position measurement of new variable geometry stator vanes
- Strain gauges / accelerometers
- …and more
Gzero Engine Development Program

F1A Testing – 3 independent VSV stages
- Mapping of new IP compressor (performance, surge margin)
- Optimization of VSV schedule
- Schedule robustness

F1b Testing – Production standard VSV system
- Final verification with production crank shaft
- Fast transient response

<table>
<thead>
<tr>
<th>2011</th>
<th>2012</th>
<th>2013</th>
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<tbody>
<tr>
<td>Jan</td>
<td>Feb</td>
<td>Mar</td>
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</table>

F0 (24G Datum)
(Strip & upgrade to Gzero)

F1A
VSV schedule optimized for performance & operability

F1B
Finalized VSV crank shaft for F1B testing

X-cal
(Strip inspection & re-build)

ESN424 Gzero EDP Vehicle

<table>
<thead>
<tr>
<th>24G</th>
<th>Gzero</th>
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<tbody>
<tr>
<td>Customer service</td>
<td>F0 Test</td>
</tr>
<tr>
<td>Hrs</td>
<td>100,031</td>
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<tr>
<td>Cycles</td>
<td>777</td>
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Demo Engine available for despatch

(Pre-roughed set of crank shafts for quick turnaround)
On-engine IPC mapping tests

1. Low power surge line mapping, VSV schedule optimization

2. High power clearance of surge margin to clear (no actual surge points)

Fast stop with bleeds forced closed

Operational worst case (margin to clear)

Normal IPC working lines purposely raised with calibrated end nozzles

Normalized IP pressure ratio

Corrected mass flow
Test results – IPC performance

- CFD prediction
- Test matched data
- Pre-test scale-back

**Gzero**
- Gzero design point
- Efficiency (+3%)

** IPC flow function**

- 24G design point
- 24G
Compressor blade vibration

- Blade response to engine forcing monitored real time with “tip timing” optical probes across entire range
- Data processed to calculate “endurance ratios” of blade response vs. HCF strength
- Max response less than half the HCF initiation threshold
- Pre-test analysis confirmed – HCF not an issue
## Verified technical attributes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Target</th>
<th>Result</th>
<th>Data</th>
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<tbody>
<tr>
<td>Power growth</td>
<td>+ 10% or more</td>
<td>✓</td>
<td>Slightly better than expected. Opportunity to grow beyond initial 10%.</td>
</tr>
<tr>
<td>Surge margin</td>
<td>To clear operational worst case</td>
<td>✓</td>
<td>IPC stack-up cleared by extensive testing. HPC surge margin maintained.</td>
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<tr>
<td>Efficiency</td>
<td>No less than 24G</td>
<td>✓</td>
<td>Higher than 24G.</td>
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<tr>
<td>Gas Generator Exit Temperature (TGT)</td>
<td>No higher than 24G</td>
<td>✓</td>
<td>Lower than 24G.</td>
</tr>
<tr>
<td>Operability</td>
<td>No worse than 24G</td>
<td>✓</td>
<td>Fuel transfers OK, no auto-ignition. Load step capability maintained.</td>
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Conclusions

- Gzero provides 10% power increase for existing RB211 without hot end modifications
- Focused introduction of today’s best technology into a proven engine core
- “Plug-and-play” aftermarket upgrade
- Product attributes verified by extensive testing
- Novel analysis & test techniques successfully utilized to reduce development risk & lead time
- Verification program complete, Demonstrator Engine available
THANK YOU