**Institution: 10007822**

**Unit of Assessment: 12**

**Title of case study:**

**Thermal barrier coatings: improved performance of Rolls-Royce aero-engines**

## 1. Summary of the impact (indicative maximum 100 words)


New low thermal conductivity (low K) barrier coatings, developed at Cranfield, reduce specific fuel consumption by over 1%. Commercial variants are now implemented on the Trent 1000, used to power the Airbus 380, and the Trent XWB, the new engine to power the Boeing Dreamliner aircraft.

Our thermal barrier coating (TBC) systems have improved thermal efficiency in gas turbines. Low-K TBCs will save 14Mt$CO_2$e over the 20 year life of the engine. Adjustment for the effect of emissions at high altitude increases the calculated benefit to 26.6Mt$CO_2$e. In fuel costs, this saves operators £1.8 billion over the REF14 period considered and £3.4 billion over the engine lifetime.


## 2. Underpinning research (indicative maximum 500 words)

In 1997, the Advisory Group for Aerospace Research and Development (AGARD) organised a specialist workshop to review thermal barrier coating (TBC) technologies where Professor Nicholls presented his ideas and concepts aimed at lowering the thermal barrier coating's ceramic thermal conductivity [P1].

The methods proposed involved engineering phonon and photon scattering centres into the ceramic coating through control of the deposition process; research ideas later supported by funding from the EU [G1], EPSRC [G3, G4] and industry [G2, G5]. This was achieved by modifying evaporation rates [G1, G2] and deposition temperature [G5], used in electron beam physical vapour deposition (EB-PVD), by adding tertiary and quaternary Lanthanide group additions [G3, G4] and layering the TBC during deposition to scatter/reflect photons [G5].

Figure 1: *An aerofoil coated with a low K thermal barrier doped with Erbia at Cranfield*

In 1997, the thermal conductivity of an EB-PVD thermal barrier coating was reported as 1.8-2.0W/mK. Cranfield's research into improved manufacturing methods, particularly the EB-PVD process route, and the microstructure and chemistry of the coatings produced, saw this drop to 1.65W/mK for a 200µm thick TBC [G1, G2, P1]. This was achieved through control of deposition temperature and bond coat surface roughness [G4], both of which directly affected the microstructure produced, plus elaboration of deposition models applicable to the deposition of zirconia ceramic. Control of the microstructure allowed control of the vacancy concentration introduced and thus phonon scattering within various depths of the zirconia TBC microstructure. Later, research into various Lanthanide additions, including Erbium, Ytterbium, Neodymium, and Gadolinium, and the combined use of multiple Lanthanide group oxides saw this reduce to 1.2W/mK, through tertiary and quaternary element size effects further altering phonon and photon scattering within the ceramic layer, thus lowering the thermal conductivity (figure 1) [G3,G4,P2-4].

Recently, Cranfield developed periodically layered TBCs, using a multiple source with jumping beam electron beam evaporation methods, through the modification of the nanostructure. This has resulted in a further reduction in thermal conductivity, now achieving 0.9-1.0W/mK [G5]. This coating method has been developed to a capability of pilot plant coating manufacture that meets manufacturing performance criteria suitable for testing in test-bed operational gas turbine engines.

The most recent extension to this work uses the phosphorescent properties of Lanthanide oxides when in a suitable host lattice such as Zirconia. This has permitted the development of 'self diagnostic' TBC systems [P5, P6, G6]. These smart TBCs have the ability of measuring their operating temperature in-situ. It can be read externally and remote from the material surface allowing a direct measurement of temperature on a rotating turbine blade. This latest innovation has been recognised through two technical prizes; the 'Charles Sharpe Beecher' prize of the Institution of Mechanical Engineers for 2002 [P5] and the 'Best Technical Paper Award' of the American Society of Mechanical Engineers for 2008 [P6].

## 3. References to the research (indicative maximum of six references)

***Evidence of quality – Peer reviewed journal papers***

P1 J Nicholls, K Lawson, D Rickerby and P Morrell 'Advanced Processing of TBC's for Reduced Thermal Conductivity' AGARD, R823, paper 6, 1-9, 1998. ISBN 92-836-1073-3 [http://ftp.rta.nato.int/public/PubFullText/AGARD/R/AGARD-R-823/06chap06.pdf](http://ftp.rta.nato.int/public/PubFullText/AGARD/R/AGARD-R-823/06chap06.pdf) (accessed Nov. 2013)

P2* J R Nicholls, K J Lawson, A Johnstone and D S Rickerby, 'Methods to Reduce the Thermal Conductivity of EB-PVD TBCs', Surface and Coatings Technology, **151-152**, pp. 383-391, 2002. DOI: 10.1016/S0257-8972(01)01651-6

P3 J. R. Nicholls 'Advances in Coating Design for High Performance Gas Turbines' MRS Bulletin **28** (9), pp. 659-670, 2003. DOI: 10.1557/mrs2003.194

P4* Nicholls, J R, Simms, N J, Chan, W, Evans, H E, Smart overlay coatings - concept and practice, Surface & Coatings Technology **149**(2-3) pp. 236-244, 2002. DOI: 10.1016/S0257-8972(01)01499-2

P5 J.P. Feist, A.L. Heyes and J.R. Nicholls, 'Phosphor Thermometry in an EB-PVD Produced TBC, doped with Dysprosium', Proc. Inst. Mech. Eng. Part G – Journal of Aerospace Engineering, **215** (6), pp. 6333-6342, 2001. DOI: 10.1243/0954410011533338

P6* R Steenbakker, J Feist, J Nicholls and R Wellman, 'Sensor TBCs: Remote In-situ Condition Monitoring of EBPVD Coatings at Elevated Temperatures', Journal of Engineering For Gas Turbines and Power, **131** (4) p. 041301 (9 pages), 2009. DOI: 10.1115/1.3077662

* 3 identified references that best indicate the quality of the research

***Further evidence of quality – underpinning research grants***

G1 J.R. Nicholls and K.J. Lawson, EU FP5 GRD2-2000-30211. 'HIPERCOAT, High Performance Coating Systems'; £192,187 2002-2005.

G2 J.R. Nicholls and K.J. Lawson, Rolls-Royce plc et al, 'EB-PVD of Modified PYSZ TBCs'; £141,300 1998-2002.

G3 J.R. Nicholls, H.E. Evans and A. Atkinson, EPSRC GR/R03440. 'Modelling the Performance of Advanced Coatings'; £188,332 2001-2003.

G4 A. Atkinson, E.P. Busso and J.R. Nicholls, EPSRC GR/T07336/01. 'Luminescence Piezo-Spectroscopy for Life Assessment and Improvement of TBCs'; £214,465 2005-2008.

G5 J.R. Nicholls Rolls-Royce plc/5001073324. 'SILOET – Development of Low K TBCs'; £242,500 2010-2011.

G6 B.A. Charnley and J.R. Nicholls, TSB TS/G000255/1, Sensor Coating System – SeCSy, £167,012, 2008-2011 with Southside Thermal Services Ltd, RWE npower, LAND Instruments

| Key Researchers | Post details | Dates involved | Research |
|---|---|---|---|
| K.J. Lawson | Coating Services Manager | 1998 – 2009 | EB-PVD Deposition of Ceramics [G1-G3] |
| Dr R.G. Wellman | Lecturer | 2002 – 2005 | Erosion Performance of TBCs [G1] |
| Dr K. Long | Research Fellow | 2002 - 2010 | CVD of Bondcoats [G3, G4] |
| Dr L. Chirivi | Research Fellow | 2005 - present | Surface Finish, TBC Cyclic Oxidation Lifetime [G4, G5] |
| Dr C. Chalk | Research Fellow | 2009 - present | EB-PVD of Ceramics, CVD of Bondcoats [G5] |
| Prof J.R. Nicholls | Professor | 1998 – present | All the above [G1-G5] |
| B.A. Charnley | Lecturer | 2004 - 2012 | Phosphorescence |

**4. Details of the impact** (indicative maximum 750 words)

Advanced thermal barrier coating systems (TBCs) made at Cranfield have improved the thermal efficiency of large civil aero-gas turbines [P1-3, C1]. Specific fuel consumption (SFC) has been reduced by over 1% [P2, P3] with consequent $CO_2$ reduction, by introducing doped TBCs, involving the incorporation of Lanthanide-based oxides.

TBC technology has allowed Rolls-Royce to not only maintain, but increase its market share for large civil aircraft engines [C2]. To support the introduction and application of advanced thermal barrier coatings in the Trent family of engines, Rolls-Royce plc entered a joint venture with Chromalloy (UK) Ltd, to build a new coating facility in Nottinghamshire, UK. The facility, Turbine Surface Technologies Ltd., will undertake all coating manufacture with these advanced compositions, ensuring the I.P. is protected for the UK [C3]. The adoption of 'power by the hour' (availability based) services further protects this technology by ensuring only Rolls-Royce plc approved contractors undertake any engine maintenance.

Through the adoption of Cranfield's 'low K' thermal barrier coating technologies, the thermal conductivity of such EB-PVD TBCs is reduced from 1.8-2.0W/mK to 1.0-1.2W/mK, permitting a 170°C temperature drop across the 200µm thick EB-PVD TBC. Commercial variants of these new low-K thermal barrier coatings are now specified and implemented on the Rolls-Royce Trent engine series, the most powerful of the Rolls-Royce engines [C3, C4]. Further, a net result of adopting this new technology will be the growth in Rolls-Royce market share of the large civil engine market. This is accepted by Rolls-Royce [C4] but its value is commercially sensitive.

A series of new multi-layered coatings for engine test have been produced by Cranfield and have been run in Rolls-Royce development engines [G5, C3], proving the technology for incorporation in future high performance Trent family (Trent 1000 and Trent XWB) engines.

The 'Carbon Brainprint' case study [C1, 5], quantified the long-term impact of Cranfield's thermal barrier coating research for two Rolls-Royce engines used in large civil aircraft:

- Trent 700, introduced 1995, used on about half the Airbus A330 aircraft currently in service;
- Trent 500, introduced 2002, used on all Airbus A340-500 and A360-600 aircraft.

In fuel costs alone, the whole-life saving amounts to £3.4 billion to the aircraft operators, in addition to saving 14Mt$CO_2$e in greenhouse gas emissions over the 20 year life of these engines. Using the data from the 'Carbon Brainprint' case study [C1,5] an estimate of the commercial benefits over the time frame of REF'14 has been made. First, the level of greenhouse gas emissions has been considered, in order of magnitude: carbon dioxide from combustion of the fuel, emissions during extraction and refining of the fuel, and emissions of the other greenhouse gases during combustion. The best estimates of the current emissions [P6] for individual aircraft were as follows:

| | A330 | A340-500 | A340-600 | Total fleet |
|---|---|---|---|---|
| t$CO_2$e/year | 1016 | 1574 | 1646 | 568,000 |

Thus over the period Jan 2008 to July 2013, for these two engines on three aircraft platforms, the savings is already 3.12Mt$CO_2$e (in fuel cost terms, a £750 million saving to the fuel bill).

Looking to the future, including all the aircraft on order, the prospective emissions reduction is 833kt$CO_2$e/year. Assuming a service life of 20 years, then the total saving is approximately 17Mt$CO_2$e or saving £1.15 billion in fuel cost terms. Two adjustments are made:

- a *reduction* in effectiveness of 18%, assuming that older engines do not and will not benefit from the improvement to thermal resistance as a result of this technology;
- but the effect of emissions at high altitude would *increase* the calculated benefits to 26.6Mt$CO_2$e, over the period considered in REF'14, a total saving £1.8 billion in fuel cost.

The phosphorescent 'self diagnostic' TBCs are marketed by Southside Thermal Science (STS) Ltd, a spin-out company based at Imperial College [C6]. With the TBS technology it is possible to measure remote, real-time, non-contact on-line temperatures in harsh conditions such as through flames, without disrupting gas flow, which could not be done with traditional methods. The accuracy is better than 5°C. The method allows industrial users of high temperature processes new ways of monitoring, controlling and tuning their burners and flow paths. In a further cooperative development with RWE npower, LAND Instruments and Cranfield University, temperature measurements were carried out at Cranfield in a Viper engine on nozzle guide vanes, in a combustion chamber and on rotor blades rotating up to 13,500 rotations per minute, [C6-8]. STS in collaboration with Cranfield was granted a worldwide patent for the method [C9].

**5. Sources to corroborate the impact** (indicative maximum of 10 references)


C1 D. J. Parsons, J. Chatterton and J. R. Nicholls, Carbon Brainprint Case Study: Ceramic Coatings for Jet Engine Turbine Blades. Report published 31/7/2011, http://edoqs.com/pdf/carbonbrainprintcasestudy-ceramic-coatingsfor-bjetb-bengineb-_fdb80ab638b877664e747d681d79ee06 (accessed November 2013)

C2 F Haselbach & R Parker, 2012, Hot end technology for advanced, low emission large civil aircraft engines, http://www.icas.org/ICAS_ARCHIVE/ICAS2012/PAPERS/306.PDF (accessed November 2013)

C3 Contact: Head of Surface Engineering, Rolls-Royce plc., Derby, UK.

C4 Contact: Director of Materials and Mechanical Behaviour, Rolls-Royce plc., Derby, UK.

C5 HEFCE, Quantifying the impact of universities on carbon reduction - http://www.carbonbrainprint.org.uk/ (accessed November 2013)

C6 Contact: Managing Director, Southside Thermal Services Ltd., London, UK.

C7 Southside Thermal Services Online measurement system: http://www.stscience.com/products-and-services/online-measurement-system (accessed November 2013)

C8 Inside a jet engine - measuring temperature through flames – video of testing at Cranfield http://www.youtube.com/watch?v=_jLWNkYYr8U (accessed November 2013)

C9 Measurement, coating and monitoring system and method, Patent WO 2007023292 A3