Institution: University of Sussex		
Unit of Assessment: 12 – Engineering		
Title of case study: Design Information for Improved Disc Life and Clearance Control		
Period when the underpinning research was undertaken: 2000 – 2014		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
A. Alexiou	Research Fellow	1995 – 2002
N. R. Atkins	Lecturer	2007 – 2009
P. R. N. Childs	Professor	1987 – 2008
D. D. Coren	Research Fellow	2002 – 2010
N. J. Hills	Senior Research Fellow	1998 – 2005
V. Kanjirakkad	Lecturer	2011 – present
C. A. Long	Reader	1982 – 2015, 2017 – present
M. Puttock-Brown	Lecturer	2011 – present
A. B. Turner	Professor	1983 – 2005
Period when the claimed impact occurred: Aug 2013 – Dec 2020		
Is this case study continued from a case study submitted in 2014? Y		

1. Summary of the impact

Research at Sussex on two separate projects studying the flow and heat transfer in gas turbine cooling and sealing systems has led to the following impacts:

- It allowed GE Aviation to make direct savings of circa £8M in avoiding the use of two separate engine tests.
- The high quality of data acquired has led to improved confidence in design methods.
- Over the typical life of all (around 3300 units) the relevant engines, it is estimated that, as a result of the improved designs resulting from the research, approximately 300,000 tonnes of fuel and 800,000 tonnes of CO_2 have been saved.

2. Underpinning research

The rotor blades in an axial compressor or turbine are attached to the periphery of highly stressed and expensive discs. Disc life is limited by the magnitude and frequency of thermal and inertial stresses. Inertial stresses are relatively easy to predict. However, the thermal stress depends on the distribution of surface temperature, which depends on the local heat transfer coefficients, which in turn are governed by the flow physics [R1]. The flow in the rotating cavities between adjacent compressor discs is time-dependent, three-dimensional, with a mix of forced and free convection [R2, R3]. Although Computational Fluid Dynamics (CFD) can be used to predict these flows, their complex nature requires computational resources that limit use for engine design. Instead, engine manufacturers use empirical one-dimensional methods using data from experimental rigs [R2, R3, R4] and (expensive) engine tests.

The Multiple Cavity Test Facility

The Multiple Cavity facility is an engine-representative test rig used to examine flow and heat transfer in the internal air system of a typical high-pressure compressor. The key insight leading to its design was in recognising that these flows are significantly affected by geometric features and engine architecture. This facility has had acknowledged academic success in this field [R1, R2, R3 and R4] and attracted significant funding (ICASGT1, ICASGT2, NEWAC). It has also provided the gas turbine community with valuable insight into the complex behaviour of flow and heat transfer in disc cavities, and generated design data for engine manufacturers to use in their empirical models. From 2013, this facility attracted funding from GE Aviation to acquire data to improve modelling methods of high-pressure compressor cavities.

The Turbine Rim Seal Test Facility

This test facility emulates a complete turbine stage, with rotating and stationary blades and discs, mainstream and secondary flows. The key insight leading to its design was that the presence of an external flow and blading significantly affects the flow inside the rotor-stator cavity. Prior to 2012, it was used (funded by ICASGT1, ICASGT2 & MAGPI) to investigate the interaction between the main gas path flow with the internal air system flows that escape into it. Once used, air from these cooling and sealing flows is ejected into the mainstream flow and this can have a detrimental effect on overall thermodynamic efficiency. That research led to:

1) Measurements of sealing effectiveness over a range of cooling flows and for different configurations of cooling hole design [R5, R6].
2) Quantification (by CO_2 tracer gas) of ingestion, reingestion and interstage seal flows [R5, R6].

Since 2013, this test facility was modified to represent GE Aviation designs, who provided funding to acquire information to support improved modelling methods of high-pressure turbine stages.

3. References to the research

University of Sussex staff at the time the research was carried out are in **bold**. All other authors, with the exception of Childs in [R5], are (or were) employees of other organisations.

[R1] **Illingworth J. B., Hills N. J.,** Barnes C. J. (2005) '3D fluid - Solid Heat Transfer Coupling of an Aero Engine Pre-Swirl System'. *Proceedings of the ASME Turbo Expo*, 3 PART A, pp. 801-811. http://dx.doi.org/10.1115/GT2005-68939

[R2] **Long, C. A.** and **Childs, P. R. N** (2007) Shroud Heat Transfer Measurements Inside a Heated Multiple Rotating Cavity with Axial Throughflow. International Journal of Heat and Fluid Flow, Vol. 28, pp. 1405-1417. http://dx.doi.org/10.1016/j.ijheatfluidflow.2007.04.009

[R3] **Atkins, N. R.** (2013). Investigation of a Radial-Inflow Bleed as a Potential for Compressor Clearance Control Paper No. GT2013-95768, Proceedings of ASME Turbo Expo 2013, June 3-7, 2013, San Antonio, USA. https://doi.org/10.1115/GT2013-95768

[R4] **Alexiou, A., Hills, N. J., Long, C. A., Turner, A. B., Wong, L - S** and Millward, J. A. (2000) Discharge Coefficients for Flow Through Holes Normal to a Rotating Shaft. *International Journal of Heat and Fluid Flow, Vol. 21, pp. 701-709.* http://dx.doi.org/10.1016/S0142-727X(00)00068-0

[R5] **Eastwood, D. Coren, D. D., Long, C. A. Atkins, N. R.,** Childs, P. R. N., Scanlon, T. J. and Guijarro-Valencia, A. (2012) Experimental Investigation of Turbine Stator Well Rim Seal, Reingestion and Interstage Seal Flows Using Gas Concentration Techniques and Displacement Measurements. ASME J. Eng. Gas Turbines Power, Vol 134, Issue 8. http://dx.doi.org/10.1115/1.4005967

[R6] Dixon, J. A., Valencia, A. G., **Coren, D. D., Eastwood, D.** and **Long, C. A**. (2013) Main Annulus Gas Path Interactions – Turbine Stator Well Heat Transfer. ASME Journal of Turbomachinery 136 (2). http://dx.doi.org/10.1115/1.4023622

4. Details of the impact

In 2019, there were approximately 25,900 commercial aircraft in the world and the majority (54%) were equipped with GE engines.

An extensive experimental project funded by GE Aviation used the Multiple Cavity Test Facility to acquire design information for use in modelling disc life and compressor blade clearances.

The quality of the data obtained from this test facility is superior to that from an engine test for two reasons. Firstly, there is far greater spatial density of instrumentation in the test rig. Secondly, in an engine test it is not possible to decouple some of the important variables (e.g.

rotational speed, bore flow, surface temperatures and shaft speed) whereas in the test rig, these can all be controlled independently. Consequently, there is also far greater confidence in the rig data than in previous engine test data [S1, S2 and S3].

To quote Julius Montgomery, Principal Engineer at GE Aviation:

> "To date, the multiple cavity test facility has provided extensive high-quality data. The immediate and direct impact is that it has done so without requiring an expensive engine test, which I estimate would cost around £4M. The work to date has also led to reduced uncertainty in our design process, improved modelling methods, confidence and maintenance scheduling. It has also informed a number of design changes in our engines, which may contribute to improvements in both fuel consumption and emissions. For a single engine over its typical life, the savings in fuel and CO_2 emissions that may be possible through this project I estimate to be in the region of 75 tonnes of fuel and 200 tonnes of CO_2." [S5]

The additional impacts of this work are:

1) The maintenance schedule for an individual engine is predicted using mathematical models tailored to its flight cycle history. Due to uncertainties in the flow physics, this can lead to a costly pre-emptive engine overhaul. For a GE engine, this typically costs around £2M and its timing is usually dictated by the disc replacement schedule. The data from the test rig [S1, S2, S3] was used to improve these models, reduce uncertainty and potentially reduce unnecessary engine overhaul.

2) The test rig provided design information to support flow and thermal modelling of the latest and subsequent generation of GE engines (the replacement for the CFM56, the LEAP with more than 2500 engines in service with an indicative value of £30B; and the replacement for the GE90, the GE9X with over 700 engines on order with an indicative value £30B). The test programme [S1, S2, S3] addressed the effects of geometric changes in the design of the disc bore and central drive shaft on the heat transfer in the disc cavities. This allowed for improved confidence in the modelling, by GE, of not only disc stress and life, but also in the transient behaviour of the radial clearance between the compressor rotor blades and outer casing, significantly affecting performance, fuel consumption and emissions.

3) Due to differential thermal expansion between rotating and stationary components and depending on mounting arrangements, the main rotor can sag during cool down when rotation ceases. If engine power is applied too soon, then undesired contact can occur between these components. This can place limitations on the turnaround time for short-distance shuttle flights, where the time between landing and take-off is relatively short to allow for maximum use of the aircraft. A solution is to rotate the engine, slowly, under the power of an electric motor during this cool down period. However, no data existed to take the concept through to detailed design. Data was acquired from rig testing at Sussex to supply engine designers at GE with this information, and used in the GE LEAP engine.

GE Aviation also funded an experimental test programme on the Turbine Rim Seal Test Facility to acquire data for the modelling of the behaviour of the flows in a high-pressure, turbine stage, representative of their latest designs. This work [S4] has led to additional impacts that benefit GE Aviation from improved disc life, reduced blade clearance and reduced aerodynamic sealing flow without use of an expensive engine test.

To quote Julius Montgomery, Principal Engineer at GE Aviation:

> "This [turbine rim seal] work has also saved having to carry out a further engine test, leading to a direct saving of £4M. The indirect impacts (reduced uncertainty, improved modelling confidence and maintenance scheduling) will be similar to that from the multiple cavity test facility. For a *single* engine over its typical life, the savings in fuel and CO_2 emissions that may be possible through this project I estimate to be in the region of 18 tonnes of fuel and 50 tonnes of CO_2." [S5]

There are also the benefits of supplying high-quality rig data to improve the design process through improved confidence and reduced uncertainty. It is difficult to quantify these benefits, but

Julius Montgomery has suggested that it would take an extra six person-months of effort (£150k) to overcome the problems associated with poor quality engine data [S5].

5. Sources to corroborate the impact

For reasons of confidentiality, the work leading to the impact described in Section 4 has limited exposure in the open literature (see the open source publications cited below [S1-4]), nor are there any written progress reports. The projects were managed through weekly conference calls between GE Aviation and Sussex and the data transferred directly to GE using the company's own bespoke data transfer system e-distrib. This current document has however been prepared in consultation with a senior member of staff at GE Aviation, whose responsibility has been to oversee these projects. He has provided a letter of support to corroborate the claims made in this document [S5] and his contact details have also been supplied via the submission system.

[S1] Puttock-Brown, M. (2018), Ph.D. Thesis, Experimental and Numerical Investigation of Flow Structure and Heat Transfer in Gas Turbine H.P. Compressor Secondary Air Systems, University of Sussex. http://sro.sussex.ac.uk/id/eprint/75214

[S2] Fazeli, S. M., Kanjirakkad, V. and Long, C. A. (2020) *Experimental and computational investigation of flow structure in buoyancy dominated rotating cavities.* ASME 2020 Turbo Expo, Virtual Conference, 21-25 September 2020. Published in: Proceedings of the ASME Turbo Expo 2020. https://doi.org/10.1115/GT2020-14683

[S3] Puttock-Brown, M. R. and Long, C. A. (2020) *Heat transfer analysis in a rotating cavity with axial through-flow.* ASME 2020 Turbo Expo, Virtual Conference, 21-25 September, 2020. Published in: Proceedings of ASME Turbo Expo 2020. https://doi.org/10.1115/GT2020-14994

[S4] Payne, D. and Kanjirakkad, V. (2020) *Experimental investigation on the effect of varying purge flow in a newly commissioned single stage turbine test facility.* ASME 2020 Turbo Expo, Virtual Conference, 21-25 September 2020. Published in: Proceedings of the ASME Turbo Expo 2020. https://doi.org/10.1115/GT2020-14975

[S5] Testimonial letter from Julius Montgomery. Principal Engineer – Thermal Dynamics, GE Aviation (26 January 2021).