Institution: Cardiff University		
Unit of Assessment: Engineering (12)		
Title of case study: New international standards for non-volatile Particulate Matter (nvPM) in the aviation industry		
Period when the underpinning research was undertaken: 12/12/2008 – 01/07/2020		
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:**
Andrew Crayford	Reader	14/02/2006 - present
Phil Bowen	Professor	16/05/1994 - present
Richard Marsh	Professor	01/05/2005 - present
Period when the claimed impact occurred: 1/11/2010 – 31/12/2020		
Is this case study continued from a case study submitted in 2014? No		

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

Non-volatile Particulate Matter (nvPM) aircraft emissions are responsible for approximately 14,000 premature deaths every year globally. Cardiff's research into nvPM quantification developed methods of sampling and measuring aviation nvPM, which were adopted as best practice worldwide. This resulted in the first engine nvPM certification requirement ratified into law by UN member states in 2017, and an international nvPM emissions standard for civil aviation engines from 2020. New standards and best practice further improved the testing cycle of aerospace companies including Rolls-Royce, where reductions in research and certification times resulted in annual savings of £5M (£15M to date).

2. Underpinning research (indicative maximum 500 words)

Aviation gas turbines emit ultra-fine non-volatile Particulate Matter (nvPM), which are typically half the size of automotive diesel engine emissions (between 15-80 nanometres in diameter). Ultra-fine particles are recognised by the World Health Organisation to cause and aggravate respiratory problems including lung cancer. They are, however, notoriously difficult to measure and regulate, and are underrepresented in mass-based local-air-quality metrics (e.g. PM10, PM2.5).

Since 1986, engine exhaust emissions have been certified using the smoke number methodology, developed to ensure the exhaust plume was not visible to the naked eye. This regulatory practice, which is biased towards larger particles, has not resulted in a clear reduction in harmful nvPM emissions; hence a more sophisticated method was required. To address this issue, Cardiff's researchers delivered projects to define, measure, and regulate nvPM by SAE International (the engineering standards association who advise the UN agency for civil aviation) and other regulatory bodies (European Aviation Safety Agency (EASA), the US Federal Aviation Administration (FAA), US Environmental Protection Agency (EPA), Transport Canada, and the Swiss Federal Office of Civil Aviation (FOCA)).

2.1 Development of best practice for nvPM measurement – SAMPLE I and II

Partnering with Rolls-Royce and the German Aerospace Centre (DLR), Cardiff led the EASA-funded (€2.5M) research project SAMPLE (Sampling and Measurement of Aircraft Particulate Emissions) to assess methods for measuring nvPM mass, and number concentrations and composition. SAMPLE comprised three large scale test programmes namely: SAMPLE I (2008-09), SAMPLE II (2009-10) **[G3.1]**, and the five subcontracts that made up SAMPLE III (2011-14).

Central to SAMPLE I was Cardiff University's Gas Turbine Research Centre, and their 'Hot End Simulator' test rig, co-designed by Marsh, that simulates aviation gas turbine soot generation. With partners (Rolls-Royce, QinetiQ, DLR, ONERA (France), and ARTIUM (USA)), SAMPLE I studies investigated nvPM sampling and measurement approaches, comparing gravimetric methods to real-time light absorption optical methods to determine black carbon mass. SAMPLE I demonstrated that select condensation-based particle counters were both accurate and reproducible if the exhaust sample was correctly conditioned, and showed, for the first time, that aviation nvPM could be traceably and reproducibly measured using real-time diagnostics **[3.1]**.

The SAMPLE II programme explored traceability of measurements and interaction between the sampling system and the PM sample: a necessary step towards international bodies agreeing nvPM certification procedures. Cardiff steered the development of a dilution-based sampling methodology to supress volatile matter nucleation **[3.2]**, resulting in the world's first prototype real-time aero nvPM sampling and measurement system. Demonstrated on a full-scale Rolls-Royce engine, this system was subsequently adopted by the SAE technical committee E31 (AIR6241) and now forms the basis of international regulatory best practices (ARP 6320) and standards (ICAO Annex 16. Volume II), each discussed in Section 4.

2.2 Development of international engine nvPM certification requirements and emissions standards – SAMPLE III, APRIDE and MANTRA

Following the success of SAMPLE I and II, EASA commissioned the Cardiff team to design, develop, and operate the European nvPM reference system required to measure nvPM emissions from aircraft engines in accordance with the SAE E31 AIR6241. As part of subsequent SAMPLE III (APRIDE) service contracts, Cardiff co-led two testing projects (SAMPLE III SC02 & 03), in conjunction with FOCA funding, to investigate variability of future certification-type data. Data from large-scale in-production engines tested at SR-Technics (Zurich) were generated by the European reference system in parallel with the independently developed Swiss and North American reference systems, which used slightly different components and specification ranges compliant with the AIR6241. This successful study demonstrated the operability of the proposed system and confirmed results were within expected uncertainties, but also highlighted a potential bias in reported nvPM mass concentration **[3.3]**.

To further assess observed discrepancies in mass concentrations, resulting from two different analyser technologies (permitted within the specifications of AIR6241), Cardiff worked alongside Rolls-Royce, NRC Canada and the US Air Force on the Transport Canada-funded MANTRA (Mass Assessment of nvPM Technology Readiness for Aviation) project at Rolls-Royce's Derby test facility, leading to the development of new mass calibration procedures.

SAMPLE III & MANTRA consolidated understanding of the transport and morphology of aircraft nvPM and specified variability in nvPM measurements whilst determining the associated measurement uncertainties **[3.4-3.6]**. The empirically derived uncertainties witnessed across the nvPM reference systems were deemed suitably low by the relevant international regulators, which facilitated the implementation of the inaugural ICAO nvPM certification requirement, as described in Appendix 7 of the *ICAO Annex 16, Environmental Protection, Volume II*.

2.3 Defining regulatory limits of nvPM emissions – DG-MOVE and Rolls-Royce

Through EU, government, and industry-funded programmes, including DG-MOVE, the Cardiff-developed European nvPM reference system, subsequently maintained and operated by the Cardiff team, generated certification-level emissions data, which was required for the development of an nvPM database for the ICAO. In conjunction with Rolls-Royce and leading French aerospace company Safran (previously SNECMA), Cardiff researchers measured and recorded nvPM emissions from five different aircraft engines. The combination of the emissions database of relevant aircraft engines, and knowledge and characterisation of measurement uncertainty, enabled the development of a new nvPM mass and number emissions regulatory standard (CAEP/11), approved in February 2019, for both in-production and new engines.

In summary:

- Research at the Cardiff Gas Turbine Research Centre demonstrated the first traceable and reproducible real-time measurement of aviation nvPM **[3.1]**.

- Cardiff led the development of a dilution-based sampling method, leading to the world's first prototype real-time nvPM sampling and measurement system **[3.2]**, which subsequently formed the now-established nvPM measurement procedure (AIR6421) and was adopted in best practices (ARP6320) and international standards (*ICAO Annex 16 Volume II*).
- Commissioned by EASA, Cardiff designed and developed the European nvPM reference system for measuring engine nvPM emissions **[3.3]**.
- Via SAMPLE III and MANTRA projects, Cardiff researchers determined that witnessed levels of uncertainty were acceptable for the regulatory measurement of aircraft nvPM using the developed sampling and measurement methodologies **[3.4-3.6]**.
- Using the European nvPM reference system, Cardiff led the measurement of certification-level emissions data necessary for the development of an ICAO nvPM database, used to set now adopted regulatory standards.

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

[3.1] A Petzold, **R Marsh**, M Johnson, M Miller, Y Sevcenco, D Delhaye, I Ibrahim, P Williams, H Bauer, **A Crayford**, W Bachalo, D Raper. Evaluation of Methods for Measuring Particulate Matter Emissions from Gas Turbines, *Environmental Science and Technology,* Vol 45(8), 2011, pp 3562-3568. DOI: 10.1021/es103969v

[3.2] R Marsh, A Crayford, A Petzold, M Johnson, P Williams, A Ibrahim, P Kay, S Morris, D Delhaye, D Lottin, X Vancassel, D Raper, S Christie, M Bennett M Miller, Y Sevcenco, C Rojo, H Coe, **P Bowen**. Studying, sampling and measurement of aircraft particulate emissions II (SAMPLE II). European Aviation Safety Agency, 2009, *EASA.2009/OP18.* PDF.

[3.3] A Crayford, M Johnson, A Llamedo, P Williams, P Madden, **R Marsh**, **P Bowen**. SAMPLE III: Contribution to aircraft engine PM certification requirement and standard, Third Specific Contract. Agency, 2013, EASA.2010.FC.10 Specific Contract No: SC03. PDF.

[3.4] D Walters, Y Sevcenco, **A Crayford**, **R Marsh**, **P Bowen**, M Johnson, & Williams, P. Differential mobility spectrometer particle emission analysis for multiple aviation gas turbine engine exhausts at high and low power conditions and a simulated gas turbine engine exhaust. *Proceedings of American Society of Mechanical Engineers (ASME) Turbo Expo 2014: Turbine Technical Conference and Exposition* GT2014 (GT2014-26902), June 16 – 20 2014, Düsseldorf, Germany. DOI: 10.1115/GT2014-26902

[3.5] TJ Johnson, JS Olfert, JP Symonds, MP Johnson, T Rindlisbacher, JJ Swanson, AM Boies, K Thomson, G Smallwood, DM Walters, Y Sevcenco, **AP Crayford**, R Dastanpour, SN Rogak, L Durdina, YK Bahk, B Brem, J Wang. Effective density and mass-mobility exponent of aircraft turbine particulate matter. *Journal of Propulsion and Power,* 51(6), 2015, pp1309-1319. DOI:10.2514/1.B35367

[3.6] P Lobo, L Durdina, BT Brem, **A Crayford**, MP.Johnson, GJ.Smallwood, F Siegerist, PI Williams, EA.Black, A Llamedo, KA.Thomson, MB Trueblood, Z Yu, DE Hagen, PD Whitefield, R C.Miake-Lye & T Rindlisbacher. Comparison of standardized sampling and measurement reference systems for aircraft engine non-volatile particulate matter emissions. *Journal of Aerosol Science*, 145, 2020. DOI: 10.1016/j.jaerosci.2020.105557

Selected grant:

[G3.1] R March, A Crayford, and **P Bowen**, SAMPLE II, EASA, start date: 11/12/2009, £600,000

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

Since 2008, Cardiff worked closely with leading international regulators, who wished to reduce the estimated 14,000 annual early deaths caused by aircraft non-volatile Particulate Matter (nvPM) emissions **[5.1]**. Cardiff's research informed the development of new regulatory practices, influencing decision making by regulatory bodies and guiding professional practice. This resulted in the following significant impact:

1) development of real-time nvPM measurement best practice, in the form of SAE Aerospace Recommended Practice (ARP 6320);
2) the first internationally adopted nvPM measurement and reporting standard, described in *ICAO Annex 16 Volume* II;
3) global regulation of aviation nvPM concentrations and compliance of all in-production and future aircraft engines;
4) immediate industrial impacts (£15M to date) for Rolls-Royce through more efficient combustion research and engine certification testing.

4.1 Development of nvPM Measurement Best Practice (2008-16)

A specialised UN agency, the International Civil Aviation Organization (ICAO), sets international standards and practices for its 193 member states ensuring that civil aviation operations conform to global norms. The ICAO's remit includes air quality, and the ICAO's Committee on Aviation Environmental Protection (CAEP) supports the creation of new policies relating to emissions, including nvPM.

CAEP tasked SAE International's technical committee E31, on which Crayford currently serves as Vice-Chair and Secretary, with developing new recommended best practice for the traceable measurement of nvPM. Utilising the research led by, and conducted at Cardiff, during SAMPLE I, II and III, SAE E31 produced three aerospace information reports (AIRs) between 2010-16, outlining best practice for nvPM measurement. These were integral to the development of Aerospace Recommended Practice (ARP6320), published in 2018.

ARP6320 now sets international best practice for the sampling and real-time measurement of nvPM from aircraft engine turbines **[5.2]**. Dr David Liscinsky, Chair of SAE E31, stated that the Cardiff team "*has been instrumental in the development and publishing of the aforementioned AIRs and ARPs*" that resulted in new global processes **[5.2]**. Illimar Bilas, Environment & Sustainability Section Manager at the European Aviation Safety Agency (EASA), stated that Cardiff's research facilitated "*concepts to de-risk experimental issues associated with the measurement of ultrafine nvPM during high cost full-scale aircraft engine testing*" **[5.3]**.

4.2 Development of the first global nvPM measurement and reporting Standard (2016-2019)

The ICAO required widespread testing to implement engine certification for nvPM emissions. CAEP requested international testing programmes organised through local regulators to provide nvPM measurements. In recognition of successful delivery and co-leadership of SAMPLE I, II & III (SC01&02), Cardiff was selected by EASA to design, build, operate and maintain the European nvPM sampling and measurement reference system in the SAMPLE III (SC03) project **[5.3]**. An international comparison programme (SAMPLE III/ APRIDE projects) compared Cardiff's European-EASA nvPM reference system against the independent Swiss and North American systems.

Dr S. Daniel Jacob, of the US Federal Aviation Administration (FAA), stated that the international comparison "*paved the way*" **[5.4]** for the accepted reporting standard and definition of emission standards for aircraft engines during certification tests. The FAA noted how Cardiff's "*tireless efforts led to the very successful completion [of SAMPLE] that was critical to the ICAO's standard setting process*" **[5.4]**.

Satisfied with the demonstrated levels of uncertainty in nvPM measurements across the three different reference systems, in 2016 CAEP voted to include a new nvPM sampling and measurement standard, described in Appendix 7 of the *ICAO Annex 16, Environmental Protection, Volume II* **[5.5]**. Known as the CAEP/10 nvPM standard, it has now been adopted into national legislation globally (e.g. (EU) 2018/1139).

Crayford was selected for the Measurement Experts Task Group responsible for drafting the new standard **[5.6]** after EASA recommended him as a Working Group 3 member to CAEP (2017) **[5.3]**. The FAA affirmed that Crayford "*directly contributed to the drafting of the* *inaugural CAEP/10 nvPM standard*" **[5.4]**. This new ICAO standard enabled nvPM concentrations from different engines and power settings to be compared and benchmarked. The CAEP/10 standard was adopted by the ICAO in 2016, additionally ratified by all UN member states into domestic law in 2017. This standard requires measurement and publishing of nvPM Mass and Number data from all civil aircraft engine certification tests **[5.3]**, with nvPM data added to the ICAO Emissions databank from December 2020.

4.3 Global regulation of aviation nvPM concentrations (2020)

The Cardiff team, using the European nvPM reference system that they developed and continued to operate, undertook parallel certification-type measurements in conjunction with Rolls-Royce and SAFRAN on their respective engines. This independent validation provided ICAO with the confidence that reported nvPM certification data was suitably robust for the setting of the new emission concentration limits, and ultimately demonstrated compliance of individual engines to the new nvPM standards **[5.3, 5.7]**.

Cardiff's certification-type measurements have, to date, provided nvPM number and mass data to ICAO's CAEP for five engine types **[5.3, 5.4, 5.7]**. Using these datasets, CAEP/10 (February 2016) agreed to the inaugural engine nvPM Certification Requirement and nvPM Emissions Standard, requiring compliance of all relevant in-production engines on or before 1 January 2020. These new certification standards are also applicable to new engine types produced after this date. The FAA confirmed that all aircraft engines produced after 1 January 2020 have already complied with this new standard **[5.4]**.

Building on the CAEP/10 standard and the CAEP datasets, each developed using Cardiff's research, at the CAEP/11 meeting (February 2019) it was agreed to establish new emissions standards for nvPM based upon both mass and number **[5.3]**, and at the 219th ICAO Council session, regulatory limits were agreed (March 2020). The ICAO stated: "The recent approval by (CAEP/11) of non-volatile Particulate Matter (nvPM) mass and number Standards is a ground-breaking achievement" **[5.8**, p97**]**. The CAEP/11 meeting also made the official recommendation to retire the longstanding smoke number method for certification, to be replaced by the more accurate real-time CAEP/10 nvPM standard **[5.8**, p98**]**.

4.4 Industrial impacts (from 2016)

The replacement of the time-intensive smoke number methodology with the new real-time CAEP/10 nvPM measurement standard, developed by Cardiff, led to immediate industrial benefits. Mike Spooner, Chief of Aerothermal Combustion at Rolls-Royce **[5.7]** stated that the reduction in measurement time achieved by implementing "*the new real-time nvPM measurement standard"* led to an economic benefit during certification testing. Rolls-Royce continued: "*Due to the faster data acquisition rate ca.£5Mpa savings in development testing is being achieved, resulting in £15M savings to date*", and *"will realise a ca.£0.25M per engine type saving in certification testing time"* **[5.7]**. Building upon the research into nvPM regulations, Rolls-Royce are continuing to work with Cardiff to develop new 'lean-burn' engine technologies to develop high-efficiency, low-emission gas turbine technology.

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

[5.1] 'Long-term exposure to aircraft emissions causes premature death', *EU Science for Environmental Policy*, July 2015, Issue 421
[5.2] Testimonial: Dr David Liscinsky, Serving SAE E31 Chair
[5.3] Testimonial: Illimar Bilas, Environment & Sustainability Section Manager, EASA
[5.4] Testimonial: Dr S. Daniel Jacob, FAA Research Programme Manager
[5.5] ICAO, *Annex 16 to the Convention on International Civil Aviation: Environmental Protection Vol II – Aircraft Emissions*. Fourth Edition, July 2017.
[5.6] ICAO invitation to Crayford to join the Measurement Experts Group tasked with drafting the international standard
[5.7] Testimonial: Mike Spooner, Chief of Aerothermal Combustion, Rolls-Royce
[5.8] ICAO Environmental Report 2019, *Destination Green: The Next Chapter*