Institution: The University of Leeds		
Unit of Assessment: UOA14		
Title of case study: Advances to jet engine operations developed from novel volcanic ash records		
Period when the underpinning research was undertaken: 2011-2017		
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:**
Dr Graeme Swindles	Associate Professor of Earth System Dynamics	2010-2019
Dr Elizabeth Watson	Researcher	2012-2016
Dr Ian Lawson	Lecturer	2005-2013
Period when the claimed impact occurred: 2015-2020		
Is this case study continued from a case study submitted in 2014? Y/<u>**N**</u>		

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

Ash from volcanic eruptions disperses over vast areas, causing a major threat to aviation safety and extensive financial losses (estimated GBP1,180,000,000 from the 2010 Eyafjalljökull eruption). NASA, in conjunction with engine manufacturers, evaluated aircraft jet engine performance with Vehicle Integrated Propulsion Research (VIPR) tests. Ash transport and deposition data, quantified from lake and peatland sediment cores across Europe, enabled NASA to verify ash particle size distributions for their VIPR-III experiment (2015). Rolls-Royce subsequently established ash cloud conditions that allow safe aircraft flight, allowing aircraft operators to change their risk assessments for low level ash clouds that would previously have been avoided entirely.

2. Underpinning research (indicative maximum 500 words)

Volcanic eruptions emitting ash clouds pose significant hazards to jet aircraft. Historically (e.g. during the 2010 Eyafjalljökull eruption in Iceland), poor understanding of the way in which ash particles of different sizes and densities interacted with jet engines meant that avoiding 'visible' or 'discernible' ash was the only way to operate. Swindles, Watson and Lawson, along with collaborators from Florida, Poznan, Polish Academy of Sciences, Stockholm and Belfast carried out pioneering work from 2010 onwards, analysing sedimentary volcanic ash layers preserved in lake sediments and peatlands in combination with historically-documented records of past volcanic ash fallout events **[1-4]**. These studies provided unique records of past volcanic ash clouds across Europe, which enhanced understanding of particle size distributions at different distances from eruptions **[e.g. 1, 4]**. Work was funded by a grant from the Climate and Geohazards Service (University of Leeds) and a NERC doctoral studentship (NE/K500847/1) with CASE support from Willis Insurance.

Rock fragments and particles ejected by volcanoes disperse through the atmosphere, and eventually accumulate in soils and lake sediments. The nature of the particles (shapes, size and geochemical composition) was studied further with colleagues from Edinburgh, the Met Office and Reykjavík to enhance understanding of the source, and thus mapping of the types of volcanic ash that can be transported far away from volcanoes **[5,6]**. Our research analysed particle size distributions, geochemistry, and glass shard morphology of 19 volcanic ash deposits distributed across northern Europe. The studies linked them to a specific volcanic eruption using geochemical methods; for example, ash from an Alaskan volcano was found as far away as Poland >7000 km from source **[2]**. For the first time, the replicability and reliability of glass shard size measurements was evaluated from peatland and lake archives. No consistent trend was found in the vertical sorting of glass shards by size within lake and peat sediments. The largest glass shards in the cryptotephra deposits were 250 µm (longest axis basis) and the median shard sizes of distal volcanic ash varied between 35 to 75 µm. Size distributions varied more between all sites than the within-site variation displayed in our investigations, allowing for an examination of regional trends **[5]**. This body of research documented the size range of ash particles that can be transported long distances through the atmosphere.

The new database of deposited ash records allowed estimation of an approximately 20% chance of an ash cloud over northern Europe in any 10-year period. The work also estimated the mean return interval of a volcanic ash cloud over the region to be 44 ± 7 years **[1]**. Tephra records from mainland northern Europe, Great Britain, Ireland and the Faroe Islands, compared with records of proximal Icelandic volcanism, suggested that an Icelandic eruption with a Volcanic Explosivity Index rating (VEI) ≥ 4 and a silicic magma composition presents the greatest risk of producing volcanic ash particles that can reach northern Europe **[1]**. None of the ash clouds in the European record which have a known source eruption are linked to a source eruption with VEI < 4. These results also suggested that ash clouds are more frequent over northern Europe than previously proposed from eruptions of both Icelandic and North American volcanoes. Together, these findings indicate the continued threat of ash transport through the atmosphere with particle size distributions likely to be similar to those we have already quantified **[2-5]**.

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

[1] **Watson, E.J**., **Swindles, G.T.**, Savov, I., **Lawson, I.T.**, Connor, C. and Wilson, J. 2017. Estimating the frequency of volcanic ash clouds over northern Europe. *Earth and Planetary Science Letters* 460: 41-49.

[2] **Watson, E.J.**, Kołaczek, P., Słowiński, M., **Swindles, G.T.**, Marcisz, K., Gałka, M. and Lamentowicz, M. 2017. First discovery of Holocene Alaskan and Icelandic tephra in Polish peatlands. *Journal of Quaternary Science* 32: 457-462.

[3] **Watson, E.J.**, **Swindles, G.T.**, **Lawson, I.T.**, Savov, I.P. and Wastegård, S. 2017. The presence of Holocene cryptotephra in Wales and southern England. *Journal of Quaternary Science* 32: 493-500.

[4] **Swindles, G.T.**, **Lawson, I.T.**, Savov, I.P., Connor, C.B. and Plunkett, G. 2011. A 7000-yr perspective on volcanic ash clouds affecting Northern Europe. *Geology* 39: 887-890.

[5] **Watson, E.J.**, **Swindles, G.T.**, Stevenson, J.A., Savov, I. and **Lawson, I.T.** 2016. The transport of Icelandic volcanic ash: insights from northern European cryptotephra records. *Journal of Geophysical Research - Solid Earth* 121: 7177-7192.

[6] Stevenson, J.A., Millington, S.C., Beckett, F.M., **Swindles, G.T.** and Thordarson, T. 2015. Big Grains Go Far: Reconciling tephrochronology with atmospheric measurements of volcanic ash. *Atmospheric Measurement Techniques* 8: 2069-2091.

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

The Icelandic volcano Eyjafjallajökull erupted on 20th March 2010. The relatively low volume eruption generated an extensive ash cloud, causing major air travel disruption over Europe. Iceland, UK, Ireland, and Finland experienced a 90% decrease in air traffic. The International Air Transport Association estimated the total loss for the airline industry was USD 1,700,000,000 (GBP 1,180,000,000). The Airport Operators Association estimated that European airports lost GBP 80,000,000 over six-and-a-half days, with 107,000 flights cancelled across Europe during an 8-day period accounting for 48% of total air traffic and roughly 10 million passengers.

Impact during the REF2021 period

Rapid decision-making during the 2010 disruption was hampered by a lack of reliable data on the dispersion of ash shards, with the lack of assurances for aircraft engine tolerance in these conditions leading to inefficient responses by governments, stakeholders and airlines. Leeds research findings contributed to policy changes after 2015 for aircraft jet engine operations and maintenance through validation of ash particle sizes used in engine performance experiments. Engine performance results were then incorporated into simulations which have enabled airlines to update their planning and risk assessments for future disruptive ash clouds.

Following Eyjafjallajökull, NASA initiated the Vehicle Integrated Propulsion Research (VIPR) Project (2011-2015), involving four NASA centres plus partners including Rolls-Royce. Part 3 (VIPR III, 2015) involved experiments where volcanic ash was injected into jet engines under controlled conditions, to gain increased understanding of the damage caused during different volcanic ash scenarios. NASA's Principal Investigator on the VIPR project approached Swindles for his database, to overcome one of the major problems when evaluating the experimental design: "*When preparing for the VIPR test we ran into a fairly good number of unknowns in regards to the composition of distal ash clouds. We were informed…that the average size of the particles would be smaller as the distance from the eruption increases, but we were also informed of several measurements of large particles at great distances. In general, there is a gap…in the knowledge of particle size distribution...more information on particle size would be very helpful"* **[A]**.

Our datasets enabled NASA and partners to determine that the ash used in experiments was representative of distal volcanic ash. The VIPR III tests subsequently led to a step-change in policy from the "AVOID AVOID AVOID" approach previously advocated by the International Civil Aviation Organization (ICAO), and executed following the eruption of Eyjafjallajökull in 2010, to a level of safe operation in volcanic ash. Rolls Royce's Capability Lead confirmed that **[B]** "*Without independent particle size data confirming that the VIPR-III experiments used realistic inputs, the confidence we had in the validity of testing would have been diminished. Similarly, the confidence we had in the conclusions we reached with regard to engine behaviour in volcanic ash would have been reduced, potentially leading us to declare a more conservative operating procedure*".

Rolls-Royce, which powers >35 types of commercial aircraft with over 13,000 engines in service around the world, including 13% of the jetliner fleet, has now established an ash dose test to define engine susceptibility to comply with the new EASA aircraft and engine certification regulations, for all Trent (40% commercial aircraft) and RB211 engines. New engine operational and maintenance policies within NASA and Rolls Royce were developed **[B]**: "*The information obtained from the VIPR-III test allowed our team here in Derby to complete work on defining safe operating limits for aircraft in dispersed volcanic ash environments, a position we released and made available for use in May 2017".* The guidance stated **[C]**: "*Engines exposed to a cumulative volcanic ash dose of 14.4 g s/m^3, between 0.2 to 4 mg/m^3 (e.g. operating for 1 hour in an actual ash concentration of 4 mg/m^3), or lower, should not lead to a significant reduction in engine related flight safety margins. If an exposure of 14.4 g s/m^3 is suspected to have been accumulated: Engine inspection required, followed by a decision to either: 1) Set 'clock' back to 14.4 g s/m^3 or a smaller number, 2) Commence a cleaning and monitoring regime, 3) Remove engine for repair"*. A key conclusion of the work is that doses equivalent to operating for 60 minutes in an actual ash concentration of 4mg/m^3 will not lead to significant reductions in flight safety.

The Rolls Royce work was considered to be "*ground-breaking and has been acknowledged, amongst others, by EASA, Boeing and Airbus, and is being adopted by other aircraft engine manufacturers e.g. GE and Pratt & Whitney in the USA"* **[B]**. The company's position changes to aircraft flight crew operating and maintenance manuals, were further noted by the Head of the Services for Aviation division at the World Meteorological Organisation (WMO): "…*such work has helped inform WMO's work on advancing the scientific and technological developments in support* *of the ICAO* **[D]**. The ICAO position then informed the work of individual airline operators allowing them to decide on their operational regimes. For example, the flight operations manager of Hibernian Airlines explained that the Rolls Royce developments, and the Leeds body of research on volcanic eruptions, were used in the development of their *"risk assessment concerning VA* [volcanic activity] */ mitigation process and an understanding of potential frequency of eruptions affecting Europe*" **[E]**.

Ultimately, the changes pioneered by Rolls Royce and the subsequent uptake of their new position statement by airline operators around the world means that "*another volcanic eruption like the Eyjafjallajokull eruption in 2010 will not lead to the same level of flight disruption. The* [Rolls Royce] *position will also minimise the flight disruption which regularly occurs in the more volcanically active regions of the world, such as SE Asia, Central America and the North Pacific. The work Dr Watson and Dr Swindles undertook has ultimately had a global impact*" **[B]**.

The Roll's Royce controlled ash dose work was integrated into a large-scale ash cloud simulation event (EUNADICS-AV) in March 2019 **[B]**. This work simulated operational centre displays for several large airlines in real time. Selected flights were played back via NAVSIM software connected to a flight simulator, to show both the operation in an air traffic control centre and in the cockpit. This work has informed airline planning for future ash clouds.

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

[A] Email from the Principal Investigator on the VIPR tests, NASA.
[B] Written corroboration from Capability Lead at Rolls Royce.
[C] Rolls Royce presentation on *Volcanic Ash Impacts on Jet Engines and Developments Since 2010*, at the 2019 European and North Atlantic (EUR/NAT) Atlantic Coordination Meeting of the International Civil Aviation Organization.
[D] Email from Head of the Services for Aviation division, World Meteorological Organization.
[E] Email from flight operations manager of Hibernian Airlines, Ireland.