Institution: University of East Anglia		
Unit of Assessment: 10 – Mathematical Sciences		
Title of case study: Making a splash: the effect of droplet impacts on aircraft icing and air safety		
Period when the underpinning research was undertaken: 2005-2019		
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 Richard Purvis	Senior Lecturer	2005 – present
Dr Peter Hicks	PDRA	2007-2009
Period when the claimed impact occurred: 2013-2020		
Is this case study continued from a case study submitted in 2014? Yes		

1. Summary of the impact

Safety is of paramount importance to the airline industry, a worldwide sector worth around USD838,000,000,000 in 2019 and carrying 4,540,000,000 passengers a year. Despite being thought to be fully understood and controlled, a series of accidents caused by ice accreting on wings of aircraft certified as safe to fly, has recently led to a reassessment of how icing is modelled and understood. An important aspect of this has been predicting how the splashing of large droplets can significantly alter both the amount and location of icing. UEA research into droplet impacts has increased understanding of these phenomena, fed into icing prediction codes used as part of aircraft design and compliance, and contributed to changes in international airline regulations that have had an estimated benefit of USD528,900,000. The UEA research has had a direct **economic impact** through the improved performance of AeroTex, the company that developed the icing codes, with consequent **impact on public safety** whilst flying.

2. Underpinning research

Fundamental research led by **Dr Richard Purvis** in the School of Mathematical Sciences at UEA has considered many aspects of droplet impacts and splashing, with a focus on how such events can influence ice formation on an aircraft. The underpinning research uses a combination of numerical and analytical techniques to gain an understanding of what happens when a supercooled large water droplet hits a moving object. The research was partly supported by an EPSRC grant to Purvis (2007-2009).

The research into large droplet impacts and ice formation started as part of an international effort to improve aircraft safety after a series of incidents led to a re-evaluation of the dangers of aircraft icing. The objective throughout was to better understand the splashing process, and thereby inform the empirical models of splashing that are now included in icing prediction software. The added complications of larger droplets, such as droplet distortion and, especially, of splashing meant the predictions of existing trusted models were wrong. They significantly over-predicted the rate of ice growth and did not predict ice formation as far back on the wing as seen in practice. Initial attempts to include simple empirical models failed to significantly improve the predictions. Since 2003, much research effort worldwide has been focussed towards understanding the fundamental problems in large droplet impacts and how they relate to icing. At UEA, this has included studies of droplet dynamics ahead of and during splashing, and of liquid impacts onto rigid, flexible and porous surfaces, to understand and predict splashing, as well as to investigate how splashing might be controlled. The work has also involved collaboration within the UK, including mathematical modelling at UCL, and experimental work at Cranfield.

The main underpinning research includes using a Volume-of-Fluid numerical technique to investigate which parameters influence a droplet splashing onto a thin water film (R1). This technique predicts how much water is splashed for a variety of droplet sizes, impact speeds and impact angles. Additionally, it demonstrates that much of the splashed water is displaced from the relatively warm water lying on the wing rather than the colder water originating in the droplet. This finding has implications for the speed of ice growth; previous tentative splash models had assumed that all the splashed water would be cold, a deficiency that has now been corrected.

Despite having many applications beyond just icing, little was understood about the mathematics of droplet impacts onto water films. A theoretical study (R2) considered an analytical asymptotic small-time approach, capturing the initial behaviour as a large droplet enters a thin water layer. This work validates the numerical approaches and offers an estimate of the initial impact pressure that may erode any surface coating of the wing that could prevent ice build-up.

Advances in high-speed photography have revealed the complex and important influence of air close to droplet impacts. Papers (R3, R4 and R5) develop models of air cushioning in droplet impacts, focusing on the entrapment of air bubbles as droplets approach both dry and wetted surfaces. Considering the local behaviour near touchdown, coupled viscous-inviscid models were developed by exploiting the large density and viscosity differences between air and water. The research identified the important parameter ranges for air cushioning, and these compare favourably to experimental measurements (R6).

Passive anti-icing systems are currently in development that use flexible or porous surfaces to prevent or control ice formation. Recent research (R7 and R8) has focussed on understanding and predicting impact onto such complex substrates, demonstrating how minor changes in the substrate can substantially change the splashing dynamics, and hence any subsequent icing.

3. References to the research

Research Outputs:

The underpinning research outputs have all been published in competitive, international, peer-reviewed journals and form part of a larger body of such published work. Citation numbers are from Google Scholar.

(UEA authors in **bold**)

R1 Analysis of super-cooled water droplet impact on a thin water layer and ice growth.
M. Quero, D.W. Hammond, **R. Purvis** and F.T. Smith
Paper AIAA-2006-466 *of 44th AIAA Aerospace Sciences Meeting and Exhibit 9-12 January 2006, Reno, Nevada, USA.* (**2006**) DOI: 10.2514/6.2006-466.
Cited by 32.

R2 Droplet impact on a thin fluid layer.
S.D. Howison, J.R. Ockendon, J.M. Oliver, **R. Purvis** and F.T. Smith
Journal of Fluid Mechanics, (**2005**) 542, 1-23 DOI:10.1017/S0022112005006282.
Cited by 86.

R3 Air cushioning and bubble entrapment in three-dimensional droplet impacts.
P.D. Hicks and **R. Purvis**
Journal of Fluid Mechanics, (**2010**) 649, 135-163 DOI:10.1017/S0022112009994009.
Cited by 115.

R4 Air cushioning in droplet impacts with liquid layers and other droplets.
P.D. Hicks and **R. Purvis**
Physics of Fluids, (**2011**) 23, 062104 DOI:10.1063/1.3602505.
Cited by 48.

R5 Liquid-solid impacts with compressible gas cushioning.
Hicks, PD. & **Purvis, R**.
Journal of Fluid Mechanics, (**2013**) 735, 120-149. DOI:10.1017/jfm.2013.487
Cited by 34.

R6 Air trapping at impact of a rigid sphere onto a liquid.
P.D. Hicks, E.V. Ermanyuk, N.V. Gavrilov and **R. Purvis**
*Journal of Fluid Mechanics, (**2012**)* 695, 310-320 DOI:10.1017/jfm.2012.20.
Cited by 44.

R7 Gas-cushioned droplet impacts with a thin layer of porous media.
Hicks, P.D. & **Purvis, R**.
Journal of Engineering Mathematics (**2017**)102: 65. DOI:10.1007/s10665-015-9821-y
Cited by 10.

R8 Droplet impact onto an elastic plate: A new mechanism for splashing.
Pegg, M., **Purvis, R**., & **Korobkin, A.**
Journal of Fluid Mechanics, (**2018**) *839*, 561-593. DOI:10.1017/jfm.2018.60
Cited by 16.

Research Funding:

Richard Purvis: Three-dimensional droplet impacts and aircraft icing
Funder: Engineering and Physical Sciences Research Council (EPSRC)
Dates: (31/7/07-30/07/09) Grant value: GBP156,762
Publications (**R3**), (**R4**) and (**R5**) came from this grant.

4. Details of the impact

This case study demonstrates that UEA research has had a direct **economic impact** through the improved performance of AeroTex, with consequent **impact on public safety** whilst flying.

Photograph courtesy of AeroTex UK LLP, www.aerotex.co.uk

In-flight aircraft icing occurs when super-cooled water droplets suspended in clouds impact upon wings, and other forward-facing components of an aircraft, and then turn into ice. Significant ice build-up must be prevented, as it can quickly lead to a loss of lift and subsequently control of an aircraft, with serious safety implications. Aircraft icing was thought to be fully understood until the total loss of an ATR72 American Eagle flight 4184 in 1994 at Roselawn which killed all 68 people on board. Icing was found to have caused the accident, despite the aircraft being certified as safe to fly in the weather conditions of the time, and the anti-icing systems being fully functional.

The aircraft accident report found that:

> *"following exposure to a complex and severe icing environment including droplets **much larger than those specified in certification criteria for the airplane**, and during a descending turn immediately after the flaps were raised, the ailerons abruptly deflected in the right-wing-down direction, the autopilot disconnected, and the airplane entered an abrupt roll to the right, which was not fully corrected before the airplane impacted the ground".*
>
> **[corroborating source A - page 252]**

It was ultimately revealed that, while the existing certification and icing models were effective in conditions with clouds of small droplets of around 20 microns, they were not valid for supercooled large droplets (SLD) which can be up to 1500 microns.

> *"Weather observed in the area of the accident appears to have included supercooled water droplets in the size range of about 40 to 400 microns."*
>
> **[corroborating source A - page 254]**

Although rare, this is not an isolated incident. A similar fate befell Aero Caribbean flight 883 in 2010 where icing caused by large droplets was again the primary cause of the accident, again with the loss of 68 lives. This discovered threat to air safety resulted in a large joint international effort, led by NASA, ONERA and QinetiQ, to improve models of ice formation, and to update the aircraft certification requirements. **[corroborating source B]**

A key part of that process was to understand the dynamics of large droplet impacts and splashing, in order to understand why existing models could not accurately predict the rate of ice growth, or the location of ice forming on a wing. Richard Purvis was involved in this response, with the research described above providing important insights and understanding of droplet impacts and their role in ice formation which has helped to improve design tools.

AeroTex is an SME offering consultancy to the aircraft industry in the field of aircraft icing, including ice prediction, icing protection and design. They develop icing prediction codes and help to design and certify ice protection systems. Whilst details of their customer base are confidential, they have confirmed that it includes:

> "*five aircraft manufacturers, five Tier 1 suppliers and two national research agencies"*
> **[corroborating source C]**

Subsequent to being at UEA, Peter Hicks spent a year working at AeroTex helping them develop their numerical models. Hicks' research and expertise in aircraft icing was developed during his postdoctoral position at UEA, making him ideally placed to carry out this work for AeroTex.

UEA research on large droplet impacts and splashing has improved overall understanding and offered crucial insight into an important, and previously little understood, aspect of aircraft icing. AeroTex have confirmed that the research:

> "*has enhanced AeroTex expertise by informing and improving our knowledge of splashing. As a result, we can offer ice prediction and icing protection design software, which enables us to compete effectively against our rivals, including ADSE in the Netherlands and Ansys (a global software company)."*
> **[corroborating source C]**

They also confirm that:

> "*the mathematical research into droplet impacts and splashing carried out at UEA has helped to inform our knowledge of large droplet dynamics and splashing and that, along with a range of other experimental and theoretical investigations, it has contributed to an improved understanding of the role of splashing in SLD icing. The knowledge of SLD is now routinely used as part of the design activities for our clients, helping them to meet the stringent certification requirements which are in place and therefore to maintain a high level of safety within the aerospace* industry.*"*
> **[corroborating source C]**

Airline safety is a vital aspect of a commercial airline sector that is worth USD838,000,000,000 globally. Alongside the stark human cost of air accidents, there are also enormous economic consequences, both for the companies involved and associated sectors such as insurance, following any aircraft accident. In response to the spate of SLD icing related accidents in aircraft certified as safe to fly, the international aviation safety agencies (Federal Aviation Authority – FAA and European Aviation Safety Agency – EASA) introduced additional specifications to include demonstrating that new aircraft can operate safely in freezing drizzle or rain (SLD conditions), known as Appendix O. Appendix O replaced Appendix C, which had no mention of SLD conditions.

> *"Appendix O consists of two parts. Part I defines Appendix O as a description of supercooled large drop (SLD) icing conditions … Part II defines ice accretions used to show compliance with CS-25 specification."*
> **[corroborating source D - page 298]**

The FAA note that:

> *"The estimated cost of the rule is USD61,300,000, and the benefits are an estimated USD528,900,000 .... Affected parties include airplane manufacturers, engine* manufacturers *and operation of affected equipment."*
> **[corroborating source E – page 2]**

AeroTex confirm that the UEA research findings:

> *"were part of a larger contribution which led to a revision of FAA and EASA certification criteria to account for icing* with *large droplets."*
>
> **[corroborating source C]**

The EASA guidelines state that:

> *"CS 25.1420 requires that the aeroplane be able to either safely exit following the detection of any or specifically Appendix O icing conditions, or to safely operate without restrictions in the icing* environment *represented in Appendix O."*
>
> **[corroborating source F – page 39]**

The financial value of the UEA research to AeroTex is confirmed in the supporting letter from their Aircraft Icing Consultant:

> "*I estimate that our expertise in large droplet behaviour and its influence on icing has a financial value of around an additional GBP40,000 of increased revenue a year to our company. AeroTex has developed a reputation as an accomplished business in relation to SLD and the UEA input to our research activities certainly played a part in this."*
>
> **[corroborating source C]**

This corresponds to around 10% of AeroTex's total revenue. **[corroborating source G]**

In summary, this case study demonstrates that by developing a mathematical understanding of droplet impacts, UEA research has helped AeroTex, and thereby the wider aircraft industry, to improve models of aircraft icing, and ultimately improve air safety.

5. Sources to corroborate the impact

[A] National Transportation Safety Board
Aircraft Accident Report for American Eagle Flight 4184
Dated 31st October 1994. Quotes are from pages 252 and 254 of Appendix C

[B] Update in SLD Engineering Tools Development (2004)

[C] Letter of support from Aircraft Icing Consultant of AeroTex UK (20th October 2020)

[D] European Aviation Safety Agency – Certification Specification and Acceptable Means of Compliance for Large Aeroplanes CS-25 (22nd June 2016) Appendix O page 298 ff

[E] Federal Aviation Authority Press Release – FAA Issues Final Rule Updating Aircraft Icing Standards (3rd November 2014)

[F] European Aviation Safety Agency Notice of Proposed Amendment 2015-07 (12th June 2015)

[G] AeroTex financial statements for year ending 31st March 2019
Downloaded from Companies House 29th October 2020