Institution: University College London		
Unit of Assessment: 10 – Mathematical Sciences		
Title of case study: Improving aircraft safety in icing conditions		
Period when the underpinning research was undertaken:		
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:**
Frank Smith	Goldsmid Professor of Applied Mathematics	1983 - present
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 (indicative maximum 100 words)

UCL research on supercooled water droplets and aircraft icing contributed to the design of improved ice protection systems for fixed wing or rotor aircraft by AeroTex. These new designs enabled AeroTex's customers (aircraft manufacturers and Tier 1 equipment suppliers) in Europe, Asia and North America to comply with the raising regulatory changes on aircraft certification standards, and to operate aircraft more safely in icing conditions with substantial financial savings [TEXT REDACTED FOR PUBLICATION] on wind tunnel testing. The application of methods developed by UCL increased AeroTex's capabilities that positioned them as experts in the airplane icing industry and trusted partners in international programmes.

2. Underpinning research (indicative maximum 500 words)

Mathematical research by Professor Smith and his team developed and applied quantitative models to resolve and understand various aspects of aircraft icing which are critical for aircraft safety. Impacts of supercooled water droplets onto a plane wing are crucial for plane's performance. When frozen, these droplets form icing that distorts the effective wing shape. This research conducted between 2001 and 2020 focused on key aspects of impacts of relevance to aircraft icing, taking a novel approach by including modelling and analysis of large droplets, providing scenarios that are more realistic. Specifically, work on asymptotic expansions and matching, involving complex multi-phase fluids, irregular geometry, air-water interactions, shallow-layer impacts and ice-skimming, produced reduced-equation computations and code supported by comparisons with real-world findings.

Early work (2001-2003) by Professor Smith pioneered the development of models that simulate how a layer of air between a droplet and a water layer affects the impact of the droplet (**R1**). The impact of splashing of supercool large droplets (SLD) on a layer of water under various parameters (such as air flow, water depth and droplet size) has been investigated by the UCL team since 2002 (**R2**). Findings include the first-ever prediction of the surface roughness effect after impact, and how much of the water layer is splashed away. Following this, research focused on modelling impact when a solid body approaches another solid body with one or two fluids (air and water) between them (**R3**-**R5**). This work represents an aircraft-icing scenario when an ice crystal impacts upon a solid aircraft surface that is covered with a layer of water.

A related research strand (2008-2020) involved skimming impacts and rebounds. A methodology for a solid body (such as an ice crystal) undergoing an oblique skimming impact with a shallow liquid layer and then rebounding from it, explained both entries into and exits from water (**R6**). Further development of this model includes fluid-body interactions with multiple bodies and multiple impacts of relevance to wind-blown ice particles travelling along an aircraft wing (**R2-R5**).

The body of research discussed in this section generated new and simpler computational methodologies for aircraft icing calculations. It provided flexible mathematical predictions of the precise extent of a splash, rebound duration, effects of surrounding air motion, and shapes resulting from ice accretion or melting, which take into account highly variable parameter values including droplet size, impact speed and angle of incidence.

Multiple site visits, collaborations and discussions with QinetiQ, GKN and AeroTex, together with complementary experimental input from Cranfield University, were important for much of the above modelling work (**R1-6**).

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

R1. **Smith FT**, Li L., Wu GX. (2003). Air cushioning with a lubricationinviscid balance. *Journal of Fluid Mechanics*, *482*. https://doi.org/10.1017/S0022112003004063
R2. Elliott JW, **Smith FT.** (2017). Ice formation on a smooth or rough cold surface due to the impact of a supercooled water droplet. *Journal of Engineering Mathematics*, *102*(1). https://doi.org/10.1007/s10665-015-9784-z
R3. **Smith FT**, Ellis AS. (2010). On interaction between falling bodies and the surrounding fluid. *Mathematika*, *56*(1). https://doi.org/10.1112/S0025579309000473
R4. **Smith FT.** (2017). Free motion of a body in a boundary layer or channel flow. *Journal of Fluid Mechanics*, *813*. https://doi.org/10.1017/jfm.2016.706
R5. **Smith FT**, Palmer R. (2019). A freely moving body in a boundary layer: Nonlinear separated-flow effects. *Applied Ocean Research*, *85*. https://doi.org/10.1016/j.apor.2019.02.002
R6. Palmer RA, **Smith FT.** (2020). Skimming impacts and rebounds of smoothly shaped bodies on shallow liquid layers. *Journal of Engineering Mathematics*, *124*(1). https://doi.org/10.1007/s10665-020-10063-6

References (R1), (R4) and (R6) best indicate the quality of the underpinning research.

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

Professor Smith investigated and modelled various aspects of aircraft icing impacts. Accurate information on the accumulation of ice on aircraft flying through cloud (at or below freezing temperature) is crucial for planes' performances and has been a significant factor in a number of accidents. AeroTex UK (AeroTex) used UCL's research findings to underpin its specialist icing work, ranging from ice accretion physics to the design and certification of ice protection systems for customers in Europe, Asia and North America, including Meggitt Aerospace, GKN Aerospace, Zodiac-Intertechnique (now part of SAFRAN) and Villinger R&D (trading as Laminar De-Ice). The realistic modelling has informed the design of aircrafts and ice protection systems, resulting in improved aircraft safety. The collaboration between UCL's team and AeroTex influenced the development of new methods to fulfil regulatory requirements. It also improved productivity and financial performance of the company.

Development of new methods and their influence on capabilities and industry standards

Investigations into several plane crashes in the 1990s and early 2000s found that accidents were caused by ice build-ups on the wings during conditions such as freezing rain. In 2010, FAA proposed new regulations that require airplanes most affected by SLD and ice crystals to meet certain safety standards during icing conditions. These proposals formed the basis for the final rule approved in 2014. The European Aviation Safety Agency (EASA) proposed similar updates to their certification specifications for large aeroplanes in 2011. It is now mandatory to certify new aircraft against the new requirements, for Large Aircraft (CS-25), and is strongly encouraged for smaller business jet and regional aircraft (CS-23).

AeroTex provides industrial solutions for clients (such as Boeing and Airbus) to comply with the FAA and EASA regulations. Professor Smith's research has enhanced the modelling capabilities of AeroTex since 2014 through the development and adaptation of computational codes for ice growth, ice crystal impact, splashing, disintegration and particle trajectories within the company's modelling framework for complex icing problems. Stated by the founder of AeroTex: "Over the course of our collaboration with Prof Smith's team at UCL, the developments related to our icing work have significantly increased our modelling capabilities. Early work with Prof Smith integrated the icing physics that is included in our 2D Lagrangian code into a 3D Eulerian code allowing the analysis of complex 3D geometries that were previously outside of our capabilities" (**S1**). These codes formed the basis of the Aircraft Icing Design (AID) analysis tool that AeroTex uses for analysing the on-plane ice protection systems for major industry clients.

AeroTex supports aircraft manufacturers, airframers and systems suppliers in gaining icing certification for their products by providing accurate simulation tools. In one of several recent projects, AeroTex implemented methods developed by Professor Smith and his team to efficiently and accurately calculate the heat transfer coefficient over a range of aircraft geometries and airflows. This enabled AeroTex to model a wider range of scenarios and physical dynamics as well as to increase the scope for the application to a diverse range of aircrafts (from helicopter rotors and inlets, through to business jets and large commercial aircrafts). As stated by AeroTex's owner: "With the valuable input provided by UCL to our code development, we have managed to maintain our position as one of the leading suppliers of aircraft icing design support services worldwide" (**S1**).

Furthermore, testing in a wind tunnel can take many days and cost approximately GBP50,000 per day (**S1**). [TEXT REDACTED FOR PUBLICATION].

<u>Increased commercial performance of AeroTex</u>

The application of methods developed by UCL helped AeroTex to become competitive in aerospace consultancy and to secure commercial and development bids. [TEXT REDACTED FOR PUBLICATION].

<u>Capacity building for aircraft safety assessment</u>

AeroTex benefited from the computational codes developed by Professor Smith's team as part of their industry placements. These codes allowed the company to apply expertise in modelling for the analysis of large droplets, and hence improve Aerotex's abilty to "assess more physical aspects of the large droplet phenomena. This allows [us] to predict the details of the impingement more accurately on various aircraft surfaces and therefore tailor heater positions, power and scheduling, to fully address these issues" (**S1**). AeroTex continued contributing to the sector's understanding on aircraft icing, modelling and prevention part of several large international programmes (FP7 STORM; Cleansky 2 – InSPIRE & GAINS; SENS4ICE) between 2014 and 2020 (**S1**).

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

S1. Supporting letters from Partner & Aerospace Engineering Consultant at AeroTex UK received on 11/05/2020 and 11/01/2021 corroborate how Aerotex benefited from codes and models developed by the UCL team.
S2. Commentary of Boeing Commercial Airplanes on Regulatory Impact Assessment (5.4.1.2 Certification costs for new projects for larger CS-25 aeroplanes) corroborates costs of wind tunnel testing.
S3. Fact sheets on STORM, SENS4ICE and INSPIRE projects corroborate funding received by AeroTex's.