Institution: **10007822**
Unit of Assessment: **12**
Title of case study: **Aircraft anti-icing: improved design and certification**

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

Cranfield's understanding and modelling of aircraft icing, a critical part of the safety, operation and design protocols for all types of aircraft, has changed the way in which aerospace companies approach the design of new aircraft. Cranfield's research has produced high quality predictive software and an extensive experimental validation database the impact of which is its use in the design, optimisation and certification of aircraft and their components.

The impact of Cranfield's icing research is in the design processes for:

- All major Airbus programmes, including A350, A400M, A320 (new engine option)
- All current Rolls-Royce large civil aircraft projects up to and including the Trent XWB
- Airframe & UAV (Unmanned Air Vehicle) applications for BAE Systems and its customers.

2. Underpinning research (indicative maximum 500 words)

Understanding aircraft icing is a critical part of the safety, operation and design protocols for all aircraft. At temperatures below -30°C there is no significant liquid water on an aircraft. At temperatures up to 5°C, ice and liquid water exist on an aircraft's surfaces. It is important to understand the flow patterns of impacting water, where the ice forms and how much ice forms. Knowing this, aircraft designers can then decide where to incorporate heating to prevent the formation or build-up of ice.

Until the mid-1990s, aircraft designers used an ad hoc model that did not correctly capture the momentum balance of the flowing water. Cranfield developed an improved mathematical system which accurately models the energy, momentum and conservation laws for water and ice.

The underlying model uses lubrication theory. Cranfield's researchers enhanced this to include the freezing and melting processes and the geometry of the airframe and its components [P1]. The boundary conditions associated with these systems are complex, the system of differential equations degenerates. Surface tension effects were modelled using a pre-cursor film approach.

The nature of the flow fields observed in this class of flows are characterised by very sharp gradients. Cranfield undertook significant work to devise Total Variation Diminishing (TVD) schemes which provided accurate and reliable predictions [P2-P4].

Other aspects of the research include:

- A formulation which supports rotating frames of reference (for helicopter rotors and turbine blades).
- Automatic error estimation and grid adaptivity for error control. These features improve the usability of the code.
- Support for structured grids (ICECREMO 1) and unstructured grids (ICECREMO 2), this meant that the code could be used more easily with complex geometries.
- ICECREMO 2 included Cranfield work on ice protection – the inclusion of heat sources used to protect critical areas. The computational model was extended to include heating and conduction in the airframe.

A key aspect of this work is that the code(s) developed at Cranfield have been integrated into the design and certification processes. This forced obvious requirements on software development standards. Moreover, the code had to be compatible with the design codes of various collaborating organisations. Cranfield developed number of data format translators to support integration with commercial and in-house codes for computational fluid dynamics; this was important to make the code accessible to industry engineers.

Following problems in service, the US Federal Aviation Authority (FAA) led an activity to expand icing requirements to force aircraft manufacturers to address icing due to larger droplets such as freezing drizzle. To support this activity, Cranfield undertook research projects to provide experimental data and analysis on large droplet icing. This work has shown how larger droplets impact different areas of the airframe and have different splash characteristics. This data has allowed ice prediction codes, such as ICECREMO, to be adapted to improve their accuracy for larger droplets. This capability is helping to underpin the industry's response to the FAA's new requirements [P5, P6].

Key Researchers	**Post details and dates**	**Research**
Dr D. Hammond	SL (2002→Present)	Experimental icing research
Dr O. Harireche	Research Fellow (RF) (2004→'06)	Modelling of ice protection
Dr T. Myers	Senior RF(1996→'02)	Mathematical modelling of freezing & thin film flows
Prof. C. Thompson	SL, (1994→'99) Prof.(1999→Present)	Mathematical & computational modelling of icing
Dr P. Verdin	RF (2008→'12) SRF (2012→Present)	Mathematical & computational modelling of icing

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

Evidence of quality – Peer reviewed publications

P1* Myers T G, Charpin J P F and Thompson C P, *Slowly accreting ice due to supercooled water impacting on a cold surface,* Phys. Fluids **14**, p. 240-256, 2002.
DOI: 10.1063/1.1416186

P2 Quero, M, Hammond, D W, Purvis[a], R, Smith[b], F T, *Analysis of supercooled water droplet impact on a thin water layer and ice growth*, AIAA 2006-466, 2006.
DOI: 10.2514/6.2006-466

P3* Harireche O, Verdin P, Thompson C P, and Hammond D W, *Explicit Finite Volume Modeling of Aircraft Anti-Icing and De-Icing*, Journal of Aircraft, **45**, pp. 1924-1936, 2008.
DOI: 10.2514/1.34855

P4 Verdin P, Charpin J P F, and Thompson C P, *Multistep Results in ICECREMO2*, Journal of Aircraft, **46**, pp. 1607-1613, 2009.
DOI: 10.2514/1.1451

P5 Lou D and Hammond D W, *Heat and Mass Transfer for Ice Particle Ingestion Inside Aero-Engine,* J. Turbomach., **133**, 031021 (5 pages), 2010.
DOI: 10.1115/1.4002419

P6* Alègre N, Hammond D W, *Experimental Setup for the Study of Runback Ice at Full Scale Journal of Aircraft*, **48**, pp. 1978-1983, 2011.
DOI: 10.2514/1.C031398

* 3 identified references that best indicate the quality of the research

Key to publications
a) University of East Anglia, Norwich; b) University College, London

Evidence of quality – underpinning research grants

G1 ICECREMO I, 1996-2000 (DERA, Rolls-Royce, GKN Westland Helicopters, BAE Systems, Cranfield University), Approx. Funding-Total £1M, Cranfield-150k, PI: C P Thompson.

G2 ICECREMO II, Jan 2003 – Dec 2005, (Rolls-Royce, GKN Westland Helicopters, BAE Systems, Cranfield, Dunlop Aerospace/Meggitt)(Approx. Funding-Total £1M, Cranfield-£160k), PI: C P Thompson.

G3 EU FP6 EXTICE, 2008-2012 **(**CIRA, ONERA, CEPR, Dassault, Airbus (ES), Alenia, Uni. Di Napoli, INTA, Piaggio, Cranfield Uni., Technical Uni of Darmstadt, Uni. Of Twente, Eurocopter) (Overall budget: €429k, Cranfield Budget: € 115k**)**, PI: D Hammond

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

The Cranfield icing research programme has comprised mathematical models, high quality computer code and experimental validation data which has become part of the design and certification processes for major parts of the UK/European aerospace industry. Specific details are company confidential, since they form part of the core business processes; three statements from the technical leads in major organisations explain how the work has had impact.

Airbus [C1]
Airbus uses the computational and experimental aircraft icing programmes, including developments of the ICECREMO programs, as part of all major development programmes. The annual expenditure of these programmes is several billion euros. The codes support design decisions relating to ice risks associated with regions where air flow is strongly three dimensional. The certifying authorities accept this type of analysis as part of the certification documentation [C2].

Since 2008, Airbus programmes where ICECREMO derivatives have been extensively employed include A350, A400M and the A320 (new engine option). In the case of the A400M, Airbus used the work by Hammond and Alègre [P6] to justify how ice formed by runback water (runback ice) is represented on a sub-scale wind tunnel model. In 2006, Airbus performed the final A400M Wind Tunnel test, which included runs to investigate the sensitivity to the aircraft handling qualities to runback ice. Those wind tunnel tests demonstrate the most critical ice shape and also justify that the wing performance is acceptable even when degraded by the icing degraded wing anti-icing performance is acceptable, in terms of the effect of any runback ice on an aircraft's handling qualities. Runback ice shapes were generated in the Cranfield Wind Tunnel and the experiments showed that using surface roughness alone resulted in a similar disturbance to the boundary layer as the moulding of runback ice taken from the wind tunnel validating the experimental approach. Airbus also used this work to show that for the A350 it was appropriate to apply roughness elements smaller than 3mm to runback ice shapes. The European Aviation Safety Agency (EASA) gave icing clearance certification by June 2013.

A further example of the use of ICECREMO is in a response to a challenge Airbus received from the airworthiness authorities. The US FAA asked Airbus to justify the use of 2D icing codes to predict ice on the A350 wing. The FAA suggested that Airbus could make comparisons against a 3D code. Airbus compared the droplet catch efficiencies with another code (from ONERA) and ice shapes with those from ICECREMO, demonstrating good agreement between both codes. This satisfied the FAA that in using 2D icing codes we were adequately capturing the 3D effects of ice accretion on a swept/tapered/twisted wing. The ICECREMO comparisons were presented to EASA and the FAA on 2nd March 2010. They were satisfied with the Airbus response. This was a key milestone in the certification process: type certification is expected in the middle of 2014.

BAE Systems [C3]
BAE Systems has made extensive use of technology and software developed within ICECREMO 2, to support internal programmes and to provide consultancy to outside organisations.

Internal programmes to BAE supported by this technology include:

- Herti UAV (sensor placement and airframe icing analysis), 2011
- Mantis UAV (sensor placement and airframe icing analysis), 2011
- Support to general research activities, including novel ice protection systems 2005-07/2013

Code use and support for external customers including icing analysis of 2008-07/2013:
- Fuel tank vents
- Intake ducts
- Deployed slats and flaps
- Fairings

These are examples of business which would not have been possible without the original ICECREMO technology development. Direct contract work undertaken by BAE Systems associated with these programmes is estimated to be approximately £600,000.

Although the business impact is difficult to quantify, the technology has provided a capability, through its 3D modelling ability, for assessment of aspects of airframe design and performance not otherwise readily achievable. ICECREMO codes have been used to provide design guidance, e.g. specification of ice protection systems and location of icing sensors. In addition to providing design guidance, this has a direct impact on risk and safety assessment.

Rolls-Royce [C4]
Rolls-Royce has found the modularity and clear methodology of the ICECREMO code especially useful in developing its own in-house analysis tools and methods. In one form or another, the main elements of code have been used in all current large civil aircraft projects up to and including the Trent XWB. The methods have proved to be very valuable in supporting a shift of emphasis of the certification process away from expensive, on-wing and simulated altitude testing, to analysis and numerical simulation backed up with ground testing.

It is difficult to put a figure on the economic benefit as this capability is one of many essential to how Rolls-Royce currently works. In essence, the level of fidelity of the company's current analysis methods is high enough that, whilst it spends more time on analysis, the dependence on experimental work is reduced, resulting in significant financial savings.

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

C1 Contact: Wing Integration & Icing Skill Group Leader, Airbus UK

C2 "ICECREMO is a great example where Airbus has turned University research into tools of applied practical value." Wing Integration & Icing Skill Group Leader, Airbus UK

C3 Contact: Group Leader, Fluid Dynamics, BAE SYSTEMS

C4 Contact: Icing and inclement weather specialist, Rolls Royce