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PROJECT FINAL REPORT

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Project acronym: STORM

Project title: Efficient ice protection **S**ystems and simulation **T**echniques **O**f ice **R**elease on propulsive syste**M**s

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Name of the scientific representative of the project's co-ordinator[1], Title and Organisation:

Morgan Balland, SAFRAN AIRCRAFT ENGINES

Tel: +33 160 59 81 68

Fax: +33 160 59 92 45

E-mail: morgan.balland@safrangroup.com

Project website address: www.fp7-storm.eu

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

1. Final publishable summary report

1.1. Executive Summary

Icing conditions are one of the most severe for aircraft and engines as experienced in the certification process and in-service events. With the development of next generations of engines and aircraft, there is a crucial need to better assess and predict icing aspects early in design phases and identify breakthrough technologies for ice protection systems compatible with future architectures.

The STORM project aims to improve and develop simulation methodologies in three specific fields: ice release, ice accretion with runback aspects and ice trajectory applied for aero propulsive systems. A second major objective of STORM is to evaluate existing low TRL Ice Protection Systems (IPS) at further TRL level : Technologies with active source (Active IPS), icephobic coatings (Passive IPS) and combination of both.

The main outcomes of this project, achieved with the involvement of the 14 partners are:

- A TRL3 for modelling of Ice shedding from heated surface
- Academic database on ice adhesion with 3 types of test measurements for metallic and non metallic material)
- A TRL3 and TRL4 for Ice debris trajectory high fidelity modelling
- Two aerodynamic & trajectory databases for 5 real ice shapes
- A TRL4 for simulation of runback water film and reemission droplets from a trailing edge
- An accretion database on a cascade rig geometry
- A academic database on droplet re-emission
- A status of existing icephobic coatings lower than TRL3 except for two coatings developed by Airbus Group Innovation quoted at TRL 3
- A TRL 3 identified for two electro-thermal technologies

1.2. Project context and objectives

1.2.1. Rationale

The European aeronautical industry must continue to provide **cost efficient products** in order to maintain a competitive advantage over their traditional and emerging competitors. This is achieved through the continued use of innovative solutions which **reduce development costs** for the manufacturers and provide **cheaper operational costs** while improving performances. Additionally, societal needs require products to be environmentally greener, typically through reduced fuel burn, lower gas and noise emissions, and making travels easier and cheaper.

In view of this, aircraft and engine manufacturers are continually investigating **new aircraft and engine architectures** (LEAP or GTF to equip the A320 NEO and Comac C919) or refinements to existing products. Looking ahead more radical solutions are also studied for products that will enter into service in + 2025 such as the Counter-rotating Open Rotor (CROR) for the future Airbus single aisle and even further into the future with Ultra High Bypass Ratio (UHBR) solutions. Common to all new development work, they must be optimised in terms of performance: weight, fuel burn, noise and gas emissions.

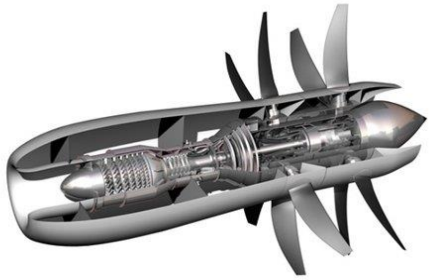

Figure 1: Model of the LEAP CFM International

Figure 2: CROR engine

To enable these developments to occur, technical solutions investigated today anticipate the progressive abandoning of hydraulic and pneumatic solutions in favour of **electrical systems** in line with future all-electric aircraft trends. Also the use of new hybrid materials, such as ceramic based composites, strongly influences developments.

One important **design constraint** on the propulsion system (that is to say the engine and nacelle), is its ability to **operate safely in icing conditions**. During the different phases of a flight, aircraft face severe icing conditions such as super-cooled droplets. When these droplets collide with both hot and cold surfaces, ice accretion occurs on engine air intake, spinner and inlet fan blades. Frozen fan blades cause overload and unbalanced mass that would, with a high likelihood, damage the engine immediately. When this ice then breaks away, and is ingested through the reminder of the engine and nacelle it creates multiple problems.

Figure 3: Rotor blades damaged by ice debris

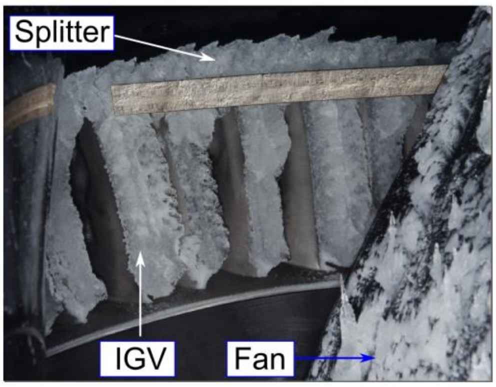

Figure 4: Examples of ice accretion on different parts of the propulsion system

These include mechanical damage as well as performance and operability issues (flame out, surge, excessive vibrations, partial gas inlet obstruction causing compressor stall or degradation, etc.). These damages have a serious **negative impact on the operations costs and may also generate some incident issues.**

To minimise ice accretion, propulsion systems are equipped with **Ice Protection Systems** (IPS) which are mostly based on air-heated technology through engine bled offs and carry associated design penalties (installation difficulties, failure mode, additional mass of around 10-100 kg) and have themselves performance issues (difficulty to regulate, not efficient at lower engine power).

Design methodologies used to characterise these icing conditions and the behaviour of ice within propulsion systems are based on **empirical methods and past experience** gained on in-service products. The work is time consuming and renders difficult the exploration of design alternatives. Because of the associated design uncertainties, cautious design margins are used leading to conservative non-optimised designs solutions.

More importantly, as new propulsive systems architectures such as CROR (Contra-Rotating Open Rotor) or UHBR (Ultra High Bypass Ratio) concepts present radical design changes (no fan, lower operating speeds, more inlet surface vulnerable to ice accretion, new materials) it will be more difficult to rely on comparative analysis, making future development extremely difficult to accomplish efficiently and within short development cycles.

These development difficulties will be increased by the **forthcoming changes in certification regulations**[2] which will require manufacturers to certify their products against more stringent requirements[3].

As a consequence, the understanding of icing phenomena and the development of adapted predictive modelling approaches has already been initiated within the European aeronautical industry through projects such as EXTICE, HAIC, AEROMUCO. Although this research work is partly applicable to propulsive systems, there is an **urgent need to examine specific issues related to the engine environment** such as the behaviour of ice on rotating surfaces, multi-stage systems with interacting parts and hot surfaces. In addition, engine manufacturers need to develop new IPS technologies adapted to future propulsive systems environments (based on electrical technologies).

In 2012, the FP7 WEZARD (WEather haZARDs for aeronautics) Coordination and Support Action, responsible for establishing a European R&D roadmap covering research gaps and priorities, identified the current European show-stoppers within the European industry:

- Poor predictive capability for glaze ice and runback accretion
- Low knowledge on Ice release, trajectory and runback accretion mechanisms. Similarly, low knowledge on Thermal effect on hot parts for water film. Need for low cost and energy efficient IPS technologies

It is hence in this context that STORM proposes to:

- **Characterise ice accretion and release** through partial tests to characterise adhesion and release mechanisms, including static and rotating tests
- **Model ice accretion, ice release and ice trajectories** to understand macro- & micro physics of phenomenon and their implementation in simulation tools

[2] The European Aviation Safety Agency (EASA) produced Certification Specifications such as CS-25 dedicated to Large Aero-planes, and CS-E for Engines. Manufacturers have also to certify their engine with the foreign authorities' requirements, which can vary slightly from one another (for example, Federal Aviation Authorities (FAA): 14 CFR part- -25, Icing requirements for engines are addressed in CS-E780 and 14 CFR part-33.68 and 14 CFR part-33.77

[3] Further to the recent work of Ice Protection Harmonization Working Group (IPHWG), additional specifications will be released. Originally, CS/FAR Appendix C only considered icing of droplets with a diameter lower than 50µm. A review of past aircraft incidents related to icing had been made, to assess the icing risks for weather conditions outside the range specified in CS/FAR Appendix C. The IPHWG has established a new icing conditions range, which will address the effects of the ice crystals (FAR Appendix D and CS Appendix P) and SLD (CS/FAR Appendix O).

- **Develop validated tools for runback**: study of fundamental film in engine environment (hot walls, centrifugation effects, droplet re-emission...) including partial tests, and validation of simulation tools
- **Characterise ice phobic coatings** by identifying the main characteristics and performances of existing coatings
- **Select and develop innovative low cost and low energy anti-icing and de-icing systems by** studying promising active systems to manage icing accretion. The most promising concept will be validated through academic tests on features representative of nacelle and engine components.

1.2.2. Objectives

The overall ambition of STORM is to:

a) **Develop and validate advanced simulation tools** which will provide a predictive capability on ice accretion and release mechanisms within a propulsive system environment
b) **Investigate and validate cost and energy efficient innovative IPS solutions** for future propulsive system architectures

This ambition can be broken down into the following technical objectives:

- Improve the capability of simulation tools for the prediction of ice accretion with runback phenomena due to glaze ice conditions or activation of the thermal IPS, with an accuracy of 20%. Indeed, the accuracy for the weight and shape of accreted ice in glaze ice conditions will be increased by a factor 2, from 50% today to 20% at the end of the STORM project. This will be possible through the development of more realistic models. That improvement will be assessed by experimental validation on representative components
- Develop a capability to predict droplet re-emission from trailing edges of blades and re-accretion in rear parts that currently does not exist at all. This will be achieved by building and testing components representative of re-emission phenomena in engines, such as water film centrifugated on rotating blades and fixed rows of blades placed in front of each other
- Improve ice block trajectory models in terms of positioning deviation compared to experimental findings with an increase from 25% to 50% in the accuracy of ice trajectory simulation tools thanks to:
    - A better characterisation of aerodynamics characteristics (lift, drag, moment) of considered ice shapes
    - The use of more realistic, full 3D deterministic numerical approaches that take into account all effects driving ice trajectory, whereas all these effects are not considered so far (such as ice block rotation)

  That accuracy will be assessed through experimental databases produced by two tests facilities

- Reduce the conservatism for fan blade mechanical design and the required energy for Nacelle Anti-Ice (NAI). This objective will be achieved through the development of more accurate predictive simulation tools for ice release on heated walls (TRL3), for runback aspects on ice accretion (TRL5) and for ice trajectory (TRL4). For instance, reducing the overestimation (from 30% to 50% compared to 100% today) of released ice blocks weight will decrease the energy required for IPS system per 25% and weight by 10% for an air-heated system through the reduction of ducts size
- Be able to factor in with confidence new materials on ice release properties in propulsion systems to greatly reduce screening. STORM will investigate a wide range of new materials (such as polymeric and titanium based coatings)
- Prove the feasibility of coating for IPS in engine environment, including erosive aspects. STORM will assess the selected ice phobic coatings on unheated walls and rotating spinner component. In addition, both icing and erosive tests will be preliminarily performed on coated samples.

Demonstration of such feasibility shall improve the behaviour of propulsive system in icing atmosphere, such as ground static freezing rain conditions by limiting ice block weight released from engine spinner

- Demonstrate that it is possible to replace, with the same performance, level bleed air IPS with an electrical de-icing system showing energy, weight and acquisition/operation costs saving (priority). This will be achieved by testing 3 representative components of a propulsive system
- Show that ice phobic coating in combination with active IPS can produce an energy reduction of 30%. This will be achieved by a combination of low-ice adhesion coating with mechanical active IPS or a combination of innovative thermal IPS with a coating that provides enhanced droplet roll-off behaviour

1.2.3. Structure of the project

The project activities are centred on three parallel activities:

- Understanding and predicting ice release mechanisms (WP2 & WP3)
- Improving predication capabilities of ice accretion within the engine environment (WP4)
- Investigating and validating innovative prospective ice protection systems (WP5 & WP6)

These three work-packages will be based on the industrial technical requirements and assessments (WP1). Furthermore, to ensure efficiency in the management of STORM work and the wide adoption by the industry of the STORM results, STORM will dedicate two work packages to management and dissemination/exploitation:

- WP7 for the project coordination and contractual management
- WP8 for the dissemination and exploitation of STORM results

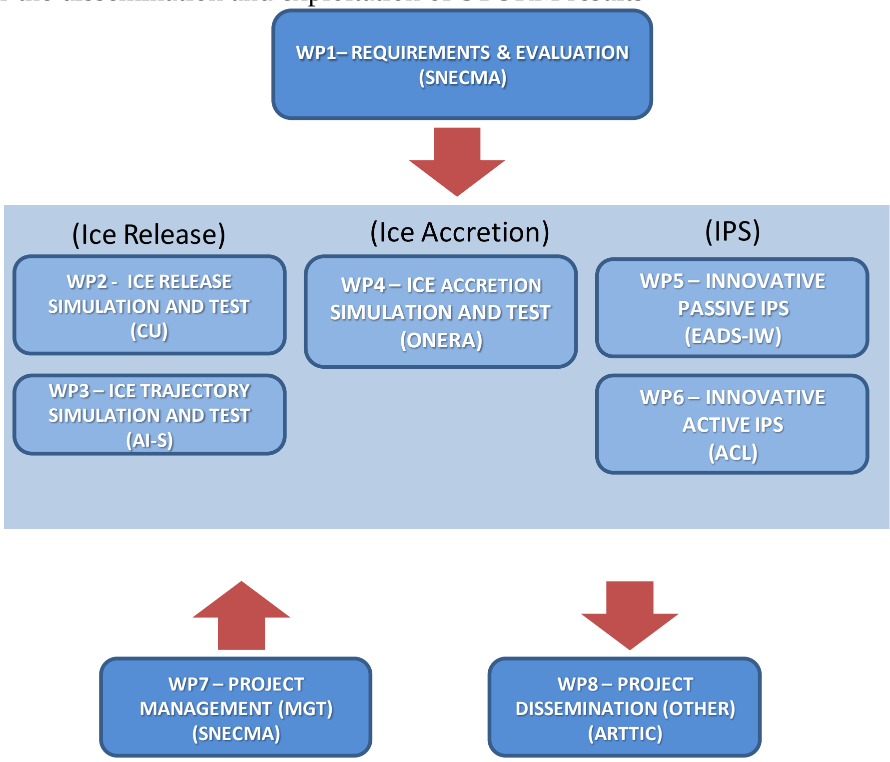

Figure 5: STORM WBS

1.3. Main results & foreground

A specific report has been delivered: D8.9 Technology Booklet Report. This is a public deliverable aiming at the dissemination of the STORM activity. Please refer to this document for further details. An overview of main results is presented hereafter.

1.3.1. Requirements

The industrial requirements for simulation tools, engine environment and Ice, Protection Systems have been synthesized in two reports (D1.2 and D1.3), and have been disseminated to all STORM partners. The methodology to evaluate the maturity of the STORM outputs has been defined. Finally, 11 TRL reviews were organized on 8 themes with dedicated panels of reviewers, most of them external to STORM project.

1.3.2. Ice release

For ice adhesion, available literature has been collected and analysed. Different ways of measuring the ice adhesion have been identified. Some conclusion has been drawn, related to dependence on surface roughness, wettability, ice accretion temperature and loading. An outcome of this work is the introduction of a standardized approach for the measurement of ice release based on a selection of reference materials and test conditions. Adhesion tests have been performed at Cranfield icing tunnel. Fracture energy has been established for various aerodynamic conditions for aluminium, titanium, platinium and alexit substrates in representative icing conditions. Mode 1 and shear stress results have been collected including repetitiveness aspect. Ice microstructure of ice has been studied at the interface and cross sections of samples, including size of grain and porosity properties. Finally, two heated rig has been set up (mode 1 and ice bridging rig) to identify effects of heat on shedding. Simulation of heated configuration has been established by ATX & CIRA, including implementation of a ice layer at interface with substrate and a new shed stress model. Comparison to Cranfield tests database has been performed and TRL 3 has been established

For ice block trajectory testing, five ice shapes have been identified based on industrial requirements and representative of typical shapes of accretion for engine and aircraft applications. Tests in ONERA rig have been performed to determine aerodynamic coefficients. Two of these shapes have been extensively tested in DLR tunnel to study trajectories of realistic ice blocks at different initial and environmental conditions. Concerning simulation of trajectory, an innovative high-fidelity approach has been developed by INRIA based on immersed boundaries method in conjunction with unstructured grid approach. Existing high fidelity approaches based on chimera technique have been compared with databases and qualified at TRL4.

1.3.3. Ice accretion

Concerning runback simulation, the literature review showed that inertial forces (such as centrifugation in rotating devices) are easily modelled in the framework of a two-equation integral film model (one equation for the mass transport – or, equivalently, the film thickness – and a second one for the momentum transport). ONERA, CIRA & ATX has implemented the 2 equations film model in 3 different codes: Cedre, Open Foam & Hetems. A specific model has been developed to reproduce the re-emission of the droplets at the trailing edge of blades in a turbofan engine. To support film model development, a rotating disk experiment has been established at ONERA lab. In this purpose, mono-dispersed and poly-dispersed injectors were used and visualizations of liquid evolution on the disk surface were made and correlation based on non-dimensional parameters was established. To extend this work to a more realistic configuration, scaled fan blade geometry has been run and droplet re-emission measurements were compared to model for validation. On CIRA side, a rivulet model has been developed and associated to two equations models to assess effect of unstabilities on runback. Finally, to validate the film model, ATX has performed comparisons to existing Papadakis database on heated profile in running back regime. Results show very good agreement on surface temperature and prediction of runback ice position. For non heated cases, a cascade rig experiment design representative of inlet geometry of an engine was build and tested in Cranfield icing wind tunnel. The tests performed were used to validate the liquid film behaviour on a row of heated blades and compared to results of models and tools. A final TRL level of 4 for simulation tools was established based on these works. In addition, a new type of test measurement rig was built by ONERA, a crack lap shear test. Prior to the ice deposit, a strap adherent was pre-stressed in order to avoid or to limit any initial deformation coming from the ice deposit. Once ice had accreted on the substrate, a force was exerted at each end of the latter with a tensile machine. The amplitude of the force was measured using a load cell. Bathes are used to control the temperature of air and water on the spray nozzle. Measurements of fracture energy at -15°C and -10°C were performed and consistent with Cranfield shear stress tests.

1.3.4. Ice protection systems

For coating technology, a score card has been established based on different applications requirements (Engine, Nacelle, Aircraft). In parallel, a list of most promising coatings has been compiled based on previous research projects or works and partners recommendations. Finally, 5 most promising existing coatings were evaluated in association with 6 baseline coatings and 4 references substrates. Multiple tests were performed based on aluminium samples to assess ice adhesion properties but also resistance to UV and erosive atmosphere, fluid resistance, Reach compatibility or thermal treatment. At the end, two coatings have been identified as the most promising and were quoted at TRL3.

For Active Ice Protection System technologies, 4 technologies have been selected among 15 initially identified: 1 mechanical technology (piezo) and 3 thermal technologies (heat paint, spraymat and PHL). The design and manufacturing of the three test components representative of engine and nacelle has been done: a nacelle lip, a cascade rig and a splitter mock up. These test components were tested in Cranfield and NRC icing wind tunnel to evaluate capability of these technologies to ensure anti-ice or de-ice function. Conclusive results were obtained for Spraymat & PHL technologies (TRL 3) whereas piezo and heat paint were not conclusive. Combination with passive coating was also assessed on heated engine blades of cascade rig mock up at different regimes (full evaporative and runback regimes). Results do not highlighted significant benefit of such combination.

1.3.5. Evaluation of results

Purpose of evaluation phase is to validate level of maturity of developed knowledge, tools & evaluation of selected passive and active IPS. Approach used in STORM project is based on TRL methodology. For the 8 themes defined with associated TRL targets, the first step was to defined detailed list of criteria. Two main categories have been built: Technology & simulation packages, with a common approach with methodology used in HAIC project. In a second step, maturity level was evaluated through TRL reviews. For each, a decision committee was composed with external reviewers from industry or experts relevant for the topic. Votes & recommendations have been collected from the decision committee to determine the final level of TRL for each themes. If the topic addressed partially the industrial requirements, a way forward was defined for full compliance. If the topic was not conclusive, the show stoppers that need to be addressed in future were identified.

The final TRL levels are summarized in the table hereafter:

	Topic	Initial TRL	Target TRL	Final TRL
Numerical tools	WP2: Ice shedding from heated surface	2	3	3
	WP3: Ice debris trajectory	2	4	3
	WP4: Ice accretion & runback	3	5	4
Ice Protection Systems	WP5: Passive IPS	2	4	3
	WP6: Active IPS for engine components (x2)	2	4	3

For each of the STORM WPs, an increase of the technology maturity was achieved.
Potential of the different technologies had been assessed, and way forward for future development identified.

1.4. Potential impacts, dissemination & exploitation of results

1.4.1. Ice release

The scientific knowledge gained from different tests performed during STORM project gives stronger position for Cranfield University in ice adhesion testing and make possible development of an international standard. Cranfield has also developed a capability of rotating rig in icing conditions. Manufacturing of the spinner rig will conduct to PhD projects. Enhanced capability for ice on spinner can be completed in 1-5 years with a potential financial impact estimated at ~500 K€ for aeronautical industry
The ice adhesion test bench in developed by Onera will be available to aeronautic Industry & research community. Potential further developments are new/alternative measurement methods to measure the level of ice adhesion. The size of the aeronautical industry or research projects susceptible to be interested in the bench is difficult to be estimated. However, further projects and funding can be attracted to Onera (~ 300 K€).
Development of mechanical modelling of ice failure on heated substrate will be further validated by ATX in 1-2 years and potentially used on programmes with a potential impact on market of 100 K€.
Ice trajectory databases will allow validating low & high fidelity methods for future aircraft development with rear engine fuselage installation and assess risk of mechanical damage. Expertise and knowledge developed will allow academic partners to valorise flight dynamic coupling for other applications (e.g. manoeuvring aircraft)

1.4.2. Ice accretion

Development of enhanced modelling of runback water film and reemission phenomenon make position of Onera stronger in icing community and make possible expertise for engine manufacturers. Improvement of icing suite tool will allow the dissemination to the industrial & academic partners at short term with a potential estimated at ~ 300 K€. For ATX, direct validation of the transient film code against test data under the programme lead to enhanced in house tools to deliver better solutions and IPS design to customers. In addition, increased number of people is aware of AeroTex and their capabilities. On Safran AE side, ice accretion and reemission databases will conduct to further validation and a PhD thesis to improve film model developed in the project. Accretion databases including reemission effects will also be exploited by CIRA for further validation and development of their icing code.

1.4.3. Passive IPS

This technology is still very far from an aircraft application. No direct exploitation of the results will be done such as technologies are not yet at the desired maturity level. New studies could be undertaken to develop new coatings that address lessons learnt established within STORM project. Airbus Group Innovation will participate to EU-Phobic2Ice project for developing new materials. AGI has also the possibility to further characterize TRL of metallic coatings for leading edges. On Safran AE side, potential use of these coatings for rotating parts might be investigated. Requirements on durability and performance will also be investigated to support future development. Certificability of such IPS have also to be assessed .

1.4.1. Active IPS

Further TRL assessment of identified electro-thermal technologies will be evaluated by Safran. Performance established will be used for global integration studies of an electrical Ice Protection system. Requirements and lessons learnt will be shared with heating paint & piezo manufacturers in order to improve these technologies. Benefit of hydrophilic coating on heated surface make possible further validation & verification of such IPS combination.

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