Final Report

4.1 Final publishable summary report

Executive Summary

The main goal of the SONEWIPS project was a significant contribution to Liebherr Aerospace in building up an A320 slat demonstrator equipped with an electro-thermal solution for wing ice protection system. The first part of the technical development was the definition of the eWIPS operational requirements, driven by Liebherr and Airbus system performance specifications. On the basis of those requirements, SONACA conducted technological developments to evaluate innovative solutions complying with the performance specifications, and integrating electrical components in an hybrid lay-up, using advanced composite and metallic materials. A first technological demonstrator representative of an A320 outboard slat provided with the eWIPS, was designed and manufactured, to support the validation of the ice protection performance by 'full scale' tests in the NASA IRT icing wind tunnel test (IWT), in collaboration with Liebherr and Airbus. The demonstrator manufacturing also supported the feasibility of the manufacturing process and the tooling concept.
The demonstration of the ice protection performance was fully successful, validating the heating configuration and the system control strategy, defined in collaboration with Liebherr and predicted by numerical simulations. Following the Icing Wind tunnel test demonstration, the technical maturity level 4 (TRL4) was approved by AIRBUS.

As the full scale eWIPS validation flight test campaign was disregarded by AIRBUS, the following development were devoted to the optimisation of the system configuration, mainly driven by the need for a significant simplification of the system architecture. The main goal of simplifying the system architecture is a large improvement of the system robustness and reliability, associated with a subsequent cost reduction. Following developments were therefore devoted to the design and the performance predictions of an optimized architecture provided with a significantly reduced number of system components. The investigations were carried out for 3 different functional modes: A/I only, combined A/I & D/I, and a mode based on power regulation only (External cooling rate survey). The 3 functional modes were then validated through a full scale IWT campaign, for which demonstrators were designed and manufactured. The IWT test demonstration was fully successful for the 3 functional modes, showing that the ice protection performance can be achieved with largely simplified system architecture.

Summary description of project context and objectives:

Ice protection systems for transport aircrafts are a significant contributor to the fuel consumption. Therefore, intensive investigations from aircraft manufacturers must be carried out with the aim of reducing their impact on general performances. This aim is totally consistent with the 'cleaner' element of ACARE and the objectives of Clean Sky JTI, in particular 'System for Green Operation' which focuses among other subjects on all-electrical aircraft equipment and system architectures.
The main objective of the SONEWIPS project is to use SONACA technical background to develop an electro-thermal wing ice protection system (eWIPS) strongly integrated in the leading edge structure, in order to optimise both structural and system functionalities.
The eWIPS concept was already developed by Sonaca, but these innovative developments need further full scale demonstrations in order to improve their Technological Readiness Level.

Technical context of the project

Icing occurs when an aircraft encounters a cloud of water droplets which are in a liquid state, despite the fact that the ambient static temperature is below 0° Celsius (super cooled droplets). Liquid water will then freeze almost instantaneously on parts of the aircraft impacting with it. This will lead to ice accretion and to possibly significant alteration of the external surface contour. Ice accretion on aircrafts leading edges is one of the most critical problems affecting flight performances, with possible severe impacts on the flight safety. It may largely disturb destroy the airflow, increasing drag while affecting the aerofoil lift. The airflow disturbance can possibly reduce the manoeuvrability of the aircraft and lead to stall at a much lower angle of attack and higher speed than normal, leading to catastrophic loss of flight control. Additionally, in-flight icing also leads to an increase of fuel consumption, impacting aircraft general performances and ecological footprint.

To protect aircrafts against icing, various protection systems have been developed for years. Different kinds of ice protection systems are in use on transport aircrafts, based on two main philosophies to prevent adverse effects of icing: anti-icing and de-icing. For large commercial jet aircrafts, hot air is easy to extract from low pressure stage of compressors and bleed air anti-icing system is the most commonly used solution to keep flight surfaces above the freezing temperature required for ice to accumulate (anti-icing). For 'full evaporative' anti-icing systems, the required amount of energy has to be able to evaporate all water impacting the surface.

The hot air extracted from the engine compressors is distributed through insulated pipes routing to wings, tail surfaces and engine inlets. Due to the degradation of the jet engine thermodynamic cycle, this leads to a reduction of the propulsive performance and aircraft manufacturers are therefore looking for alternative solutions. Electrical energy seems the right candidate as it is easy to produce and to be carried from generator to the final consuming devices and has less consequence on performances.

Several electric concepts were developed by the past in order to protect aircraft against ice accretion. Most of those concepts have major drawbacks in terms of protection performances and structural integration. Electro-thermal solution appears to be the only concept able to operate in both anti-icing and de-icing modes, leading to the achievement of the best compromise between compliance with ice protection requirements and reduction of the energy consumption.

Objective of the project:

An electro-thermal system can be operated in both anti-icing and de-icing modes, according to the fact that heating the protected external wing surface leads to melting or evaporating the impinging water. The electric heaters consist of flat electrical resistances encapsulated by dielectric isolative layers, which can be integrated within curved external surfaces.

The equipment required for electro-thermal systems consists of a source of electrical power, an electrical power distribution network and a control/monitoring system. The electrical energy is distributed to the areas requiring ice protection and flows through resistive heating elements designed to provide the necessary heat for ice protection of the surface.

A major objective of the project is the feasibility demonstration of the structural integration of heating elements and temperature sensors within a hybrid lay-up made of advanced composite and metallic materials. The purpose is to develop and validate a solution for resistance heating elements and the technologies to integrate them in a leading edge structure.

The other major objective is the definition of the heating strategy and the eWIPS architecture complying with performance expectations and general requirements applied to aircraft systems and structures. The system control laws have also to be investigated and optimised, in order to support LIEBHERR in the definition of the control-monitoring unit and the power supply components of the system.

In the first part of the project, the critical system and structural requirements were defined in collaboration with AIRBUS and LIEBHERR. These requirements are the basis for the electro thermal ice protection system concept development and give the criteria by which technology and concept down selection were made during the project.

The second part of the research activity had to explore how advanced materials and process technologies could be used to improve system integration in leading edge structural components. Both metallic and composite materials were combined in the heating element concept, with special care for the associated manufacturing process.

The third part of the project was devoted to the validation of the eWIPS efficiency in terms of wing ice protection. The expected achievement is the demonstration of the ice protection performance for the whole icing conditions envelope, on the basis of Icing Wind Tunnel tests.

The fourth part of the research activity was the optimisation of the eWIPS concept, with the aim of improving the system reliability. Three different options of simplified system architecture and associated functional mode were considered, based on configurations requiring significantly less system components.

The fifth part of the project was devoted to the validation of thermal performances for the three different operating modes of the simplified system architecture eWIPS, through a test campaign in an Icing Wind Tunnel.

Description of main Scientific & Technical results/foregrounds

Following paragraphs give an overview of the technical results and foreground achieved in the five Work Package of the Sonewips project:

- WP 1 - Top Level Requirements
- WP 2 - Technology Development and System Definition
- WP 3 - Validation through IWT Test Campaign
- WP 4 - Development of a optimized architecture System
- WP 5 - Validation of the optimized System through IWT Test

WP 1 - Top Level Requirements:

WP 1was devoted to the definition of general requirements driving the design of the electro thermal Wing Ice Protection System (eWIPS), and to the definition of specific configurations applicable to IWT test demonstrations.

Definition of system and structural requirements:

The **technical requirements for the electro-thermal wing ice protection system** (EWIPS) were identified, in collaboration with LIEBHERR/AIRBUS, on the basis of the SID (System Interface Document) and the SIRD (System Installation Requirement Document) issued by AI. The geometry of the A320 Slat 4 was selected as baseline configuration, allowing the specification of technical requirements in a realistic environment, representative of a large commercial airplane,.
Requirements were defined in terms of space envelope (Definition of the wing leading edge surface requiring ice protection), electrical power supply parameters and implementation of sensors needed for the system control. These requirements guided the system design, in terms of number of embedded heating mats inside a slat, in terms of structural integration, of electrical architecture and power control. In co-operation with LIEBHERR/AIRBUS, a trade-off was made in order to define the A320 wing ice protection system configuration, for both Anti-Icing (A/I) and De-Icing (D/I) modes, accounting for 2 different engines location configurations: BASELINE (Engines under wings) & OPTION (Rear fuselage engines) (See figure 1)

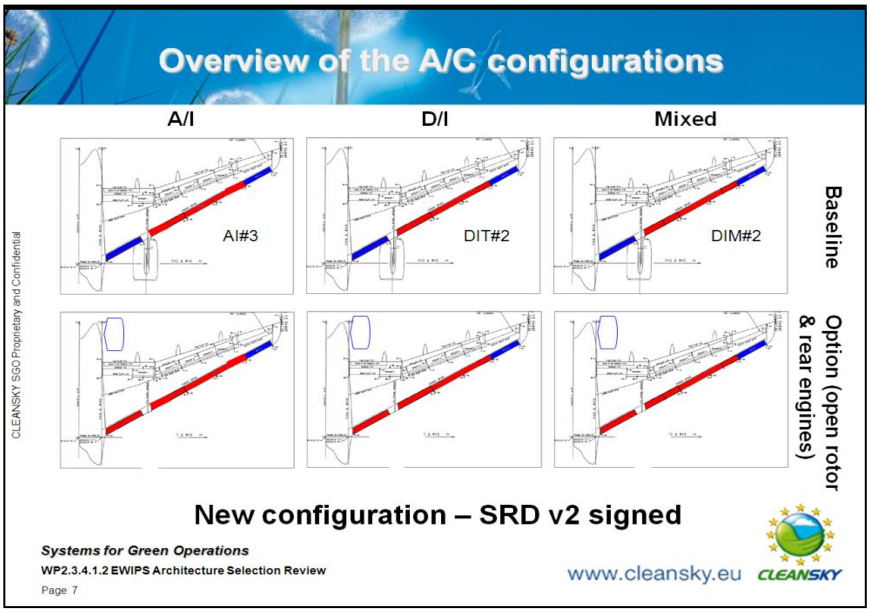


Figure 1: System architecture for both A/I and D/I modes & both engine locations

On another hand, investigations on the **heating skin architecture** considered different Electrical Heating Elements (EHE) configurations and a comparative analysis conducted the selection of a heating mats topology and its corresponding electrical power distribution network (See figure 2). The system configurations were presented during TRL3 maturity gate review. Compliance to all criteria was achieved.

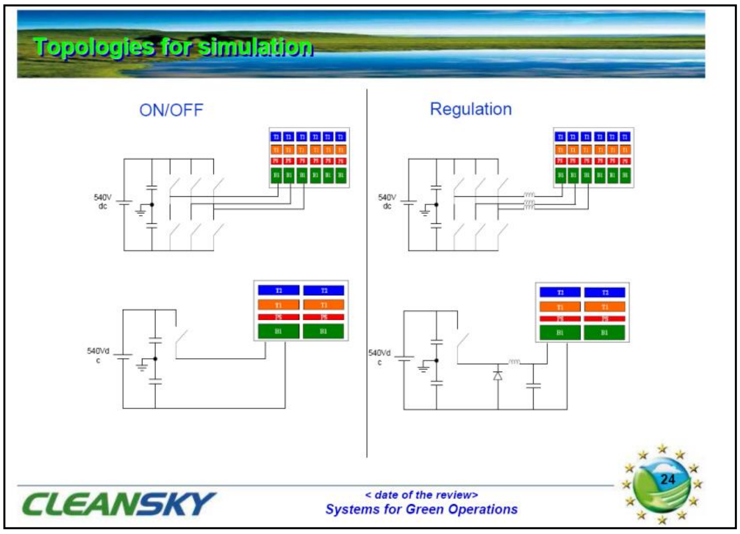


Figure 2: Heating mats topology and electrical power distribution network

<u>*Specific configurations applicable to IWT*</u>

During previous development projects, SONACA conducted several icing wind tunnel tests. Experience has shown that the IWT test specification and the definition of the test article closely depend on specific data related to the selected Icing Wind Tunnel facility. The geometry of the test section and the IWT performance possibilities must be known to design de test specimen, to issue the test specification and to select tools & processes needed to manufacture the test demonstrator.
In the framework of WP1, engineering test specification reports were issued for two test campaigns: the first one for the baseline eWIPS architecture validation tests in NASA IWT facilities, and the second one for the simplified system architecture tests in COX IWT facilities. Both reports describe the specific configuration of the 'eWIPS' wing leading edge specimens and the electrical bay to be tested, and present the goals of the tests and the performance predictions in both (A/I) & (D/I) modes. Numerical codes were used for performance predictions, to assess the electrical power control laws and the number of required temperature sensors for both anti-icing and de-icing modes.

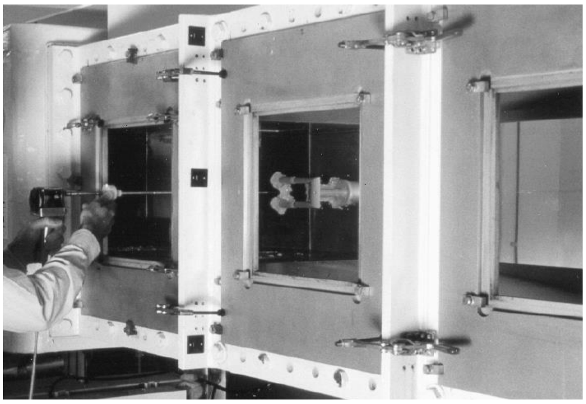


Figure 3: View of a typical Icing Wind Tunnel test section

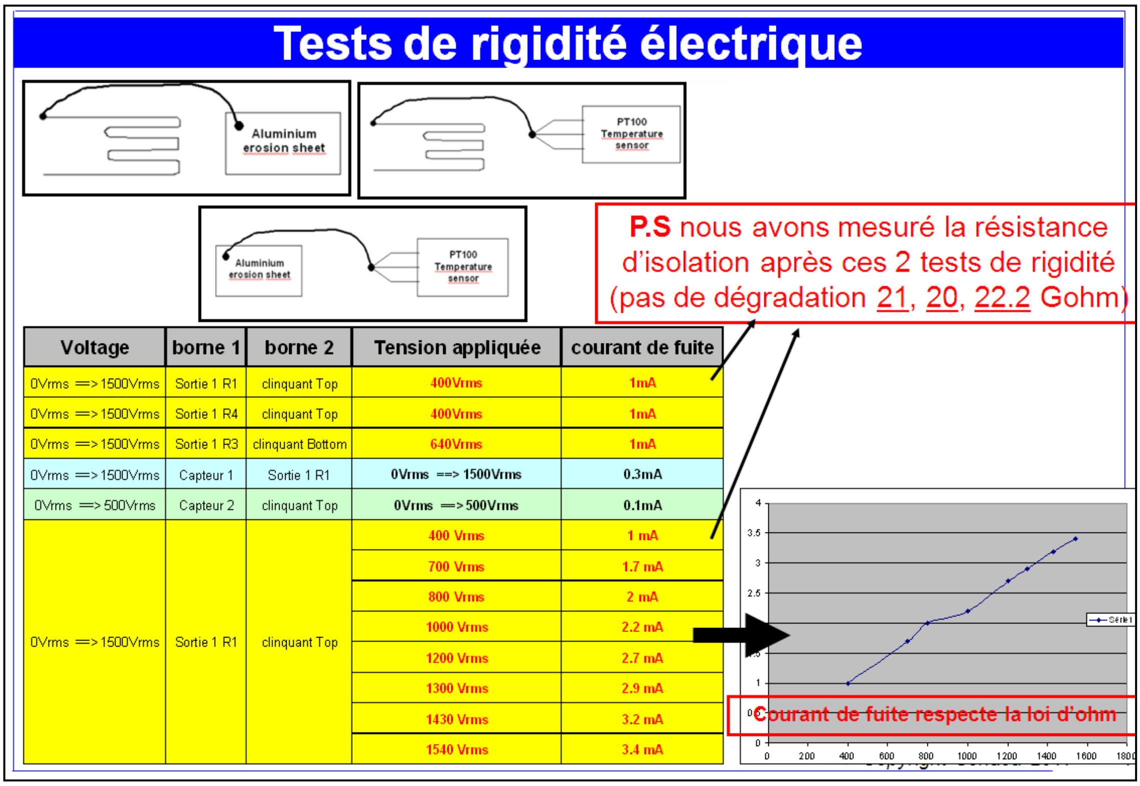
WP 2 - Technology Development and System Definition

Work Package 2 was devoted to:

- the assessment of material possibilities and system configuration;
- the eWIPS performances, electrical architecture and heating strategy;
- the design and integration of ice protection device;
- the definition, design and manufacturing of technological demonstrator.

2.1 Assessment on material possibilities and system configuration

Investigations were carried out to **select materials constitutive of the hybrid heating skin**. One of the most important technical aspects related to the heating laminate, is the electrical insulation of the heating resistances. Therefore, several studies were devoted to assessment of the performance of the dielectric insulation of the composite lay-up. The design of the insulation layer was optimised on the basis of numerous 'dielectric strength' measurements, conducted in order to validate the insulation material resistance and its dielectric robustness. The results of those tests have shown that the heating resistances electrical insulation complies with the electrical requirements from AIRBUS.



Voltage	borne 1	borne 2	Tension appliquée	courant de fuite
0Vrms ==> 1500Vrms	Sortie 1 R1	clinquant Top	400Vrms	1mA
0Vrms ==> 1500Vrms	Sortie 1 R4	clinquant Top	400Vrms	1mA
0Vrms ==> 1500Vrms	Sortie 1 R3	clinquant Bottom	640Vrms	1mA
0Vrms ==> 1500Vrms	Capteur 1	Sortie 1 R1	0Vrms ==> 1500Vrms	0.3mA
0Vrms ==> 500Vrms	Capteur 2	clinquant Top	0Vrms ==> 500Vrms	0.1mA
0Vrms ==> 1500Vrms	Sortie 1 R1	clinquant Top	400 Vrms	1 mA
			700 Vrms	1.7 mA
			800 Vrms	2 mA
			1000 Vrms	2.2 mA
			1200 Vrms	2.7 mA
			1300 Vrms	2.9 mA
			1430 Vrms	3.2 mA
			1540 Vrms	3.4 mA

Figure 4: Typical output from a di-electric rigidity test

On another hand, specific investigations were conducted on materials likely to comply with the requirements of 'Reach' legislation. The assessment was performed for each material family:

- Composites & Metallic materials: Selected materials are in Airbus Material and Process Selection List (MPSL).
- Heater element: The heaters elements are chromate free (Cr6+).
- Surface treatment: The Chromic Acid Anodizing (CAA) of aluminium alloy will be replaced by TSA or/and PSA in order to have a chromate free (Cr6+) surface treatment.
- Standard: The cadmium plated standards will be avoid and only used where no alternative technical solution exists in accordance with Airbus Standard Selection List (SSL).

2.2 Performances, electrical architecture and heating strategy

In order to predict the eWIPS performance, numerical simulations were performed. The predictive analysis allowed the assessment of electrical power consumption for the entire aircraft for both BASELINE (Engines under wings) & OPTION (Rear fuselage engines) configurations. For each of 4 wing profiles representative of mid-span section of the A320 slats 1, 2, 3 & 4, the critical icing parameters conditions were assessed in terms of droplet Mean Volumetric Diameter (MVD) leading to the maximum impingement.

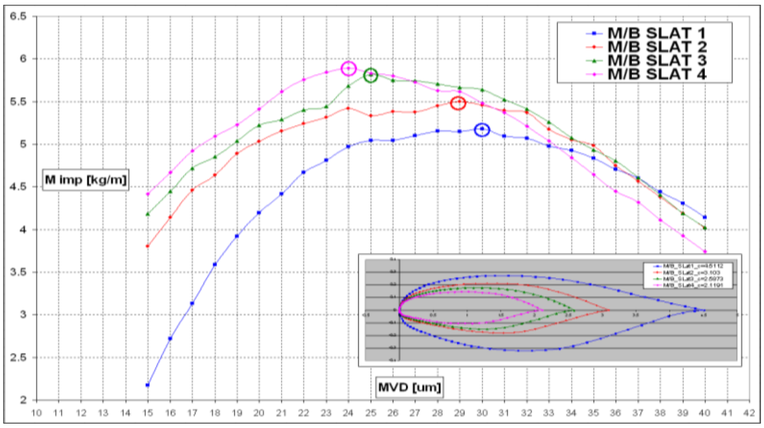


Figure 5: Critical icing parameters conditions for each airfoil

For each of 4 wing profiles, the chord-wise distribution of the heating mats was defined in order to ensure an optimized performance and the best reliability. Then, numerical simulations of the eWIPS performance were conducted to assess the power consumption needed for the ice protection of complete wingspan, in anti-ice and de-ice modes, for both aircraft configurations (BASELINE or OPTION). Studies were also performed to reduce the power consumption, by optimisation of electrical power distribution control. Numerical simulations output were compared with experimental results, leading to the validation of the numerical code.

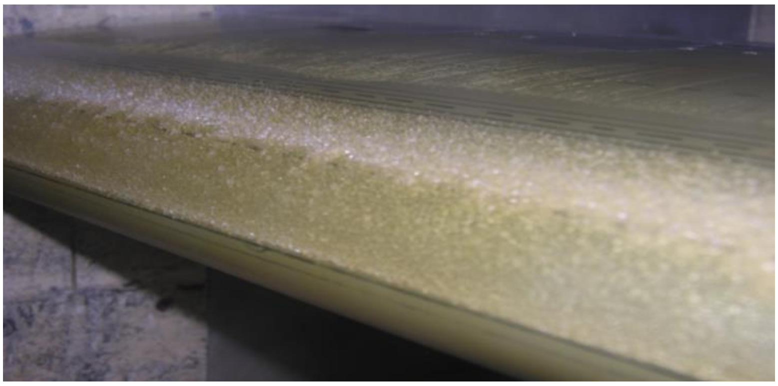


Figure 6: Typical ice accretion on ledge top skin behind heated nose zone

Based on the validated numerical code, predictive simulations were then performed to define the functional laws for electrical power control, in anti-icing and de-icing modes. For the de-icing mode, the analysis focussed on the optimisation of the heating cycle, in order to ensure full ice shedding all over the protected area, for a minimum electrical power consumption. For each of the heating zones, the local heat power density, the duration of heating activation and the activation sequence were defined, leading to an optimised 'de-icing cycle'. Based on identified electrical power densities for both A/I and D/I modes, the global power consumptions for the aircraft wing leading edges were assessed for the BASELINE configuration (Engines under wings) and for the OPTION configuration (Rear fuselage engines).

2.3 Design and integration of ice protection device

Integration of the eWIPS within the wing leading edges of a transport aircraft requires the demonstration of the compliance with several technical requirements. Environmental requirements, such as resistance to **lightning strikes** and **hail impacts**, appear to be quite important to comply with, as both types of impacts could possibly affect the structural integrity and/or the heating performance of the eWIPS hybrid laminated heating skin.

Wing leading edges are exposed to **lightning strikes** of various severities, especially in the vicinity of the outboard end of the wing and the engine pylons. Consequently, one of the most important demonstration related to the integration of the eWIPS, is the justification of the capability of the system to be subjected to lightning strikes, without catastrophic consequences.
Therefore, lightning strike tests were performed on samples of electrical heating elements integrated into the composite laminated skin, in order to identify the severity of the inflicted damage on the laminate.
On the basis of 'in service' experience, the wing leading edge of a transport aircraft is divided in several zones, according to the severity of possible lightning strikes. Figure 7 presents a typical scheme describing the lightning strike severity distribution for a large transport aircraft:

- Zone 1A (first return stroke zone): all areas of the aircraft surfaces where a first return stroke is likely during lightning channel attachment with low expectation of flash-on.
- Zone 2A (swept stroke zone): all the areas of the aircraft surfaces where subsequent return stroke is likely to be swept with a low expectation of flash hang on.
- Zone 3: regions which are unlikely to experience any lightning attachment but which are likely to have to carry lightning current by conduction.

For the wing span where the eWIPS system is installed, the most critical area for lightning strikes is located in the vicinity of the engine pylon (zone 2A).

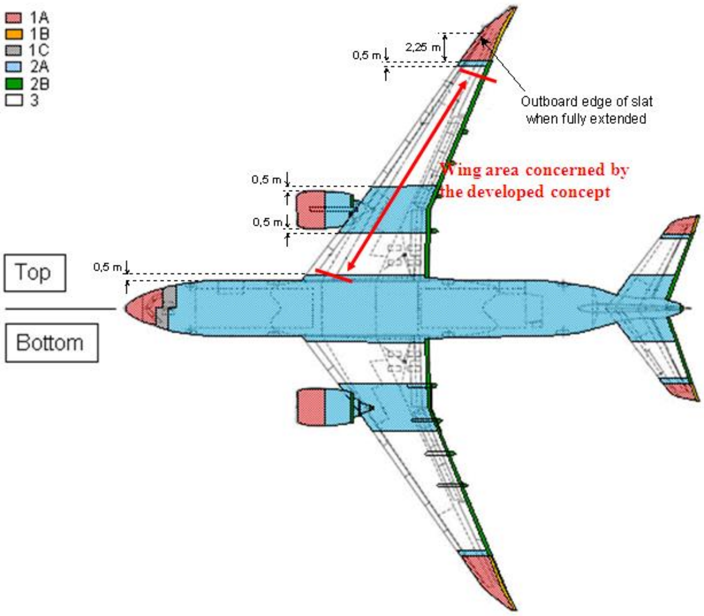


Figure 7: Typical lightning strike zone scheme

For lightning strikes tests, the specimen is a flat panel representative of the 'hybrid heating laminate' concept. It consists of a laminate made of composite materials, an integrated Electro-thermal Heating Element (EHE), dielectric insulation layers and two metallic facings. The dimensions of the demonstrator are approximately 1430 x 450 mm.

The tests were conducted in the facilities of a specialised company, 'Cobham Technical services' (UK). The Figure 9 presents some views of the specimen test set-up.
After lightning strikes, detailed controls of the damaged area were performed. As shown in the Figure 10, the visual inspection revealed local melting around the fasteners and at the lightning strike location. The aluminium facing was also marked by the high current at several locations. As seen on Figure 10, there are multiple points where the lightning arc has attached.

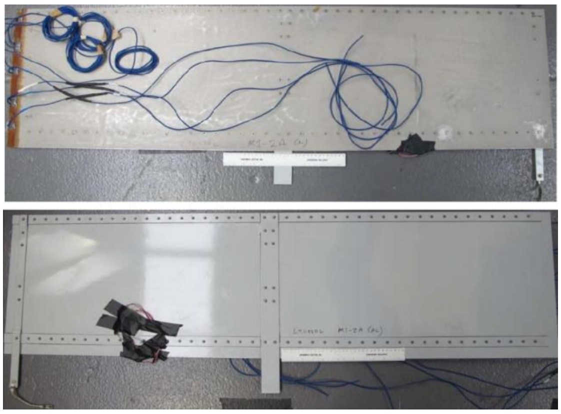


Figure 8: Views of the lightning strike test specimen

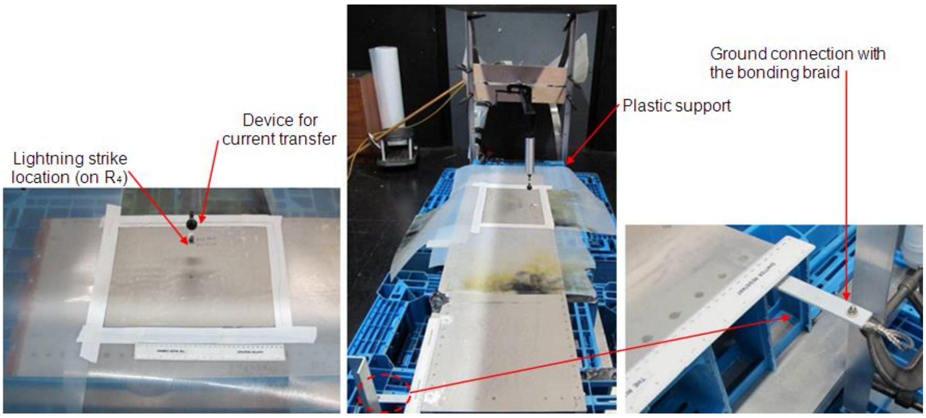


Figure 9: Views of the specimen test set-up

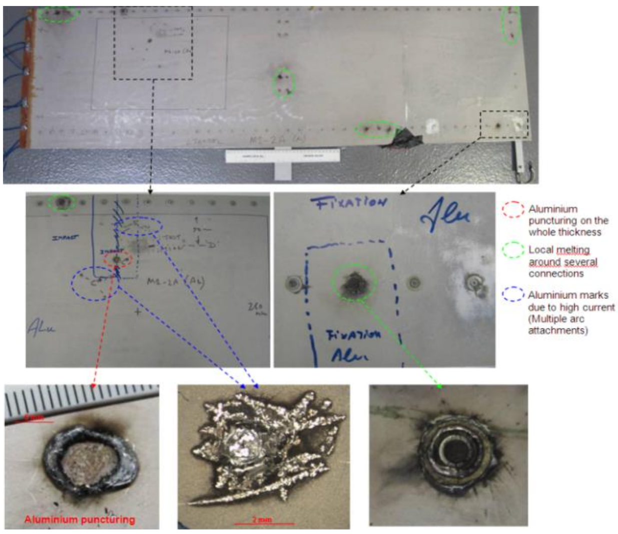


Figure 10: Visual inspection after lightning strike test

The conclusions resulting from the lightning strike test campaign on a eWIPS leading edge is that the laminated hybrid heating skin can support lightning strikes without detrimental damage on structural components and heating resistances. Nevertheless, some degradation of the dielectric insulation the heating resistance and the external metallic facing was detected, but the insulation remains acceptable. (See
Table ***1***).

Characteristic	Inspection	Conclusions	Status
BMI materials + Electro-thermal heating elements + Aluminium facings	Visual	- Local aluminium melting around the fasteners, - Local aluminium melting at the lightning strike location, due to the high current.	***Ok No catastrophic damages***
	Thickness	- Thickness within the tolerances.	***Ok***
	NDT	- No delamination or disbonding after lightning strike, - No disbonding of the aluminium facing around the fasteners.	***Ok***
	Micrographic cuts	- Local aluminium melting at the lightning strike location → diameter of ~ 5.4 mm, - Local aluminium melting around the fasteners → ~ 1 mm.	***Ok No catastrophic damage***
	Electrical	- No disruption and variation of the resistance after lightning strike test, - Degradation of the resistance insulation (under 250 VDC) between each resistance and the aluminium facing (from 40 to 75 %) after lightning strike test, but the insulation remains acceptable for the application (> 200 MΩ), - Evaluation of the indirect effect of the lightning strike with the measurement of the current going through the resistances. → with Rogowski coils (Max. 10 kA) : unusable results (too low currents) - No damage of the incorporated Pt100.	***Necessity to verify if the degradation of the insulation could be detrimental over the long term Necessity to have a better understanding of the indirect effect***

Table 1 : Summary of lightning strike test results

In addition to the assessment of lightning strike effects, the ‘design and integration’ developments also focussed on the assessment of **hail impact** effects on the ‘heating laminate’ and the evaluation of its fire resistance. During a specific test campaign, several hail impacts were inflicted on hybrid laminate specimens representative of the ‘integrated’ solution for serial production, and of the ‘added-on’ solution for a possible future flight test. The maximum impact energy was 25 J.

Visual inspection of the impacted specimens revealed significant dents in the external metallic skin. Nevertheless, detailed inspections of the Electro thermal Heating Element (EHE) and its dielectric insulation layers, did not reveal any damage. The variation of the EHE resistance before and after impact is lower than 0.1 %, which is negligible in terms of heating efficiency.

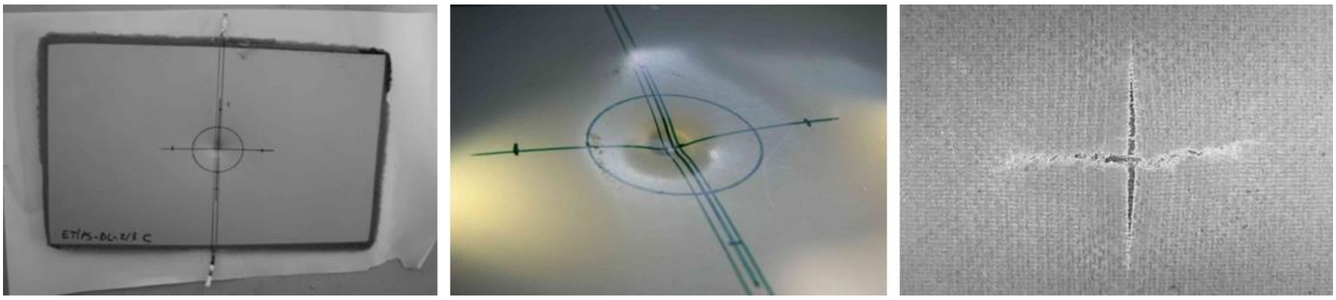


Figure 11: Surface dent damage resulting from hail impact tests

The ‘design and integration’ studies were also devoted to the assessment of **fire resistance** of laminated hybrid skin constitutive of the eWIPS heating element. The resins involved in the hybrid laminate have non-flammable properties and, as a consequence of the laminate configuration involving external and internal metallic facings, the fire resistance of the eWIPS heating element appears to be better than commonly used CFRP structures.

2.4 *Definition, design and manufacturing of technological demonstrator*

In order to evaluate the **manufacturing feasibility of eWIPS hybrid skins**, several full scale 'heating skin demonstrators' were manufactured for 2 configurations:

- 'Added-on' solution for a possible future flight test and
- 'Integrated' solution for serial production

'Added-on' solution for flight test

The 'Added-on' solution consists of a heating laminate designed to be installed on an existing slat. The goal is to modify an existing A320 slat 5 by simply covering the outer skin with a heating laminate. The Figure 12 presents an overview of the definition, the design and the results of the manufacturing demonstration of a technological demonstrator representative of the added-on solution. This solution should be installed with classical mechanical connections and interfay sealing between the heating laminate and the existing A320 structure.

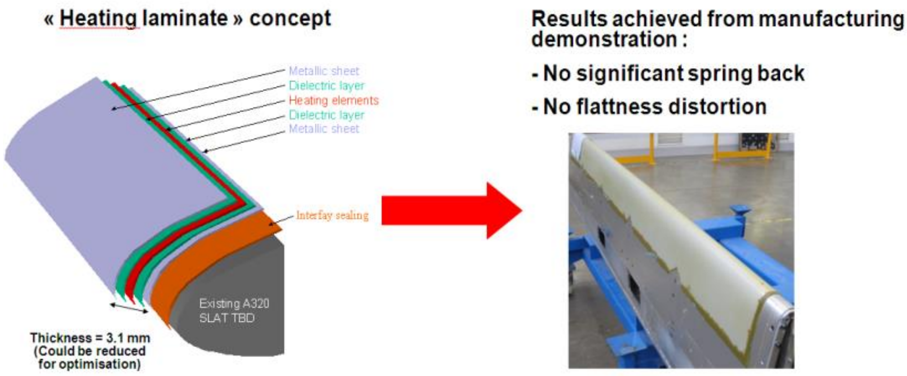


Figure 12: Manufacturing demonstration - Overview of the 'added-on' solution

Integrated solution for serial production

The 'Integrated' solution consists of a heating laminate designed to integrate the heating mats within a structural hybrid laminate skin. The Figure 13 presents an overview of the definition, the design and the manufacturing results of the technological demonstrator representative of the integrated solution.

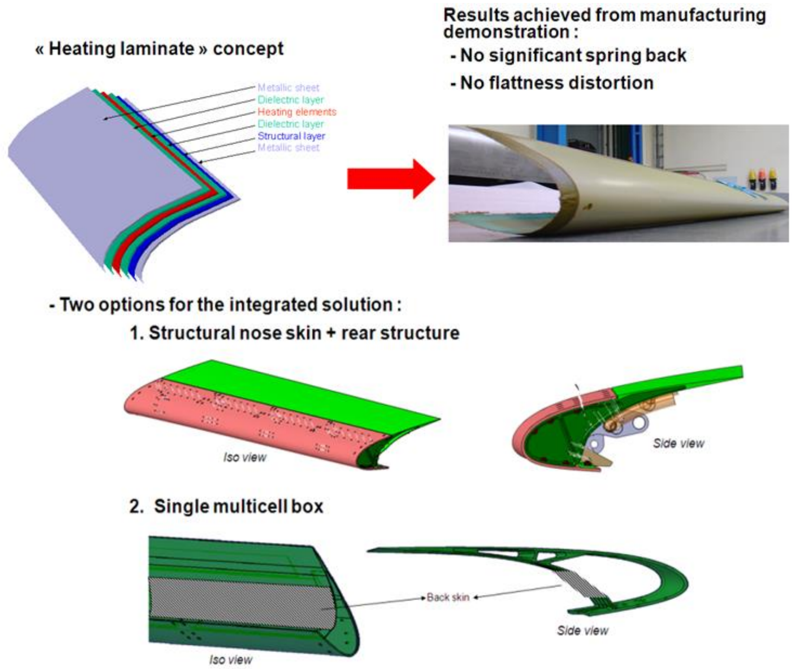


Figure 13: Manufacturing demonstration - Overview of the 'added-on' solution

In parallel to the ‘full scale’ demonstrators, the manufacturing feasibility demonstration also investigated specific aspects related to the integration of sensors needed for the system control/monitoring and to electrical terminals for electrical power supply to the heating resistances.

In order to control/monitor the skin temperature during system activation, temperature sensors have to be installed inside the lay-up. Several manufacturing trials were thus performed to evaluate the **deformation of the external skin due to the installation of temperature sensors and their wiring** within the laminate. Two hybrid laminate demonstrators were manufactured with local cut-outs of plies to provide space allocation for the temperature sensors and their wiring within the laminate: the first demonstrator has a local cut-out of 4 plies (Space allocation ~ 0.48 mm thickness), and the second demonstrator has a local cut-out of 7 plies (Space allocation ~ 0.84 mm thickness). The comparison between both demonstrators shows that the configuration with a local cut-out of 7 plies does not improve the dimensional quality of the heating skin, in terms of thickness and external faces deformation, but reduces the system robustness (dielectric insulation thickness alteration). The results of the ply cut-out trials were applied for the manufacturing of the icing wing tunnel (IWT) demonstrators.

Other demonstrators were also manufactured to evaluate the feasibility of different **resistance electrical terminals routing** through the hybrid laminate. Those manufacturing trials were conducted in order to evaluate different concept for electrical terminal concepts provided with welded connections.
On the basis of comparison between the manufacturing trials achievements, the configuration involving Mosite 1453 D materials in the process was selected for the IWT test demonstrators.
To ensure effective electrical insulation, flash breaker were inserted between the heating resistance (Nichrome strips) and the external aluminium facing, and each thermocouple was encapsulated within a film of Kapton.

WP 3 – Validation through IWT Test Campaign

WP 3 was devoted to the validation of the eWIPS efficiency in terms of wing ice protection. The expected achievement of the WP was the **demonstration of the ice protection performance** for the whole icing conditions envelope, on the basis of Icing Wind Tunnel tests.

3.1 IWT Test Campaign Definition and preparation

The selected test centre was the Icing Wind Tunnel of NASA IRT of Cleveland (USA). Sonaca issued an IWT test specification report (Ref: 0/1751/11-029-3). The test specification report highlights the objectives of the test campaign and presents the pre-analysis of anti-icing and de-icing system performances. The 'matrix' of the test cases is also presented and a 'test procedure sheet' regarding each run is prepared. Resulting from performance predictive analysis, some improvement in anti-icing and de-icing system operations is also suggested. The numerical codes were used for performance prediction. System performance analysis enabled the assessment of the de-icing power needed to ensure ice shedding from each heating zone and to define a heating sequence cycle for the aircraft operating in de-icing mode. Detailed analysis were also performed on the electrical power control and the number of control sensors for both anti-icing and de-icing modes.
The test specification report also describes the wing leading edge test specimen and the electrical bay to be tested. Figure 14 presents a view of the test specimen during assembly process.

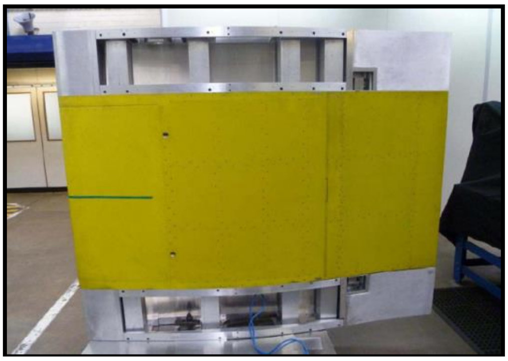


Figure 14: View of the test specimen during assembly process

3.2 IWT demonstrator definition, design and manufacturing

The IWT test specimen is representative of the mid span section profile of the A320 slat 4 geometry. The skin is made of a eWIPS hybrid laminate which incorporates the heating resistances. On the basis of the Wind Tunnel Specimen technical specification (aerodynamic surface profile, interface requirements), the definition of the basic lines and geometry of the leading edge model was completed. The eWIPS integration within the specimen was detailed in parallel, at the leading edge skin level. After an internal Preliminary Design Review, the detailed design was completed for each elementary component (Heating skin, ribs, stringers, interface dowels, connector supports, screws and standards). Figure 15 presents some views of the heating skin, which is a hybrid composite-metallic layup, and of the leading edge skeleton which is the assembly of 3 ribs, 2 stringers and a machined rear spar. The leading edge substructure was designed according to dimensional and structural requirements aimed to ensure aerodynamic flow quality and test safety.
A detailed structural analysis of the test model was performed to verify the structural integrity and the skin deflections under aerodynamic loads (Technical report Ref: 0/1751/11-031-3 SONEWIPS - Icing wind tunnel test model: Leading edge structural justification). ***Figure 16*** presents a view showing the distribution of the test model skin deflection under aero load, extracted from the structural analysis report. The frontier of the leading edge test model was designed and manufactured in order to ease the installation on the wing after-body structure. Two 'trial installations' were performed to prevent any problem during the test campaign. Figure 17 shows a view of the first trial installation of the model skeleton on the wing after-body structure.

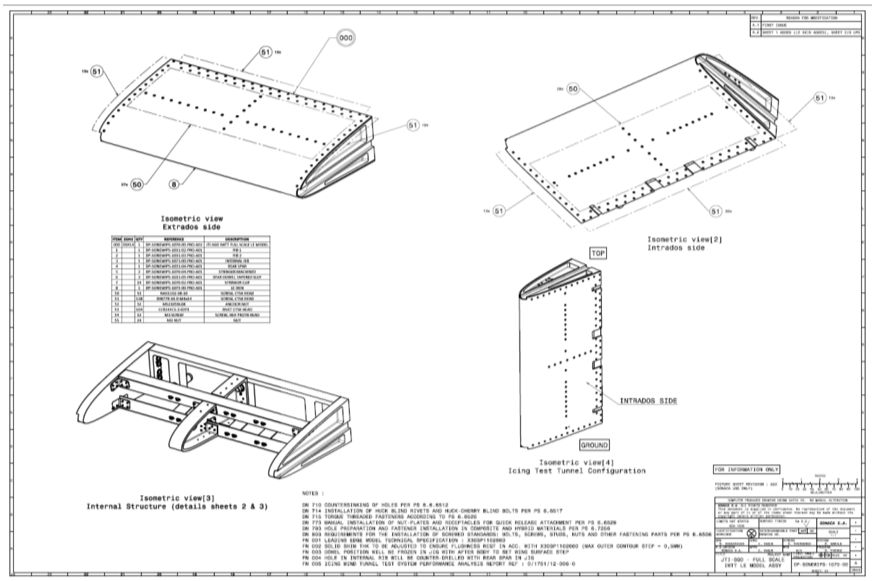


Figure 15: Views of the heating skin and the leading edge skeleton assembly

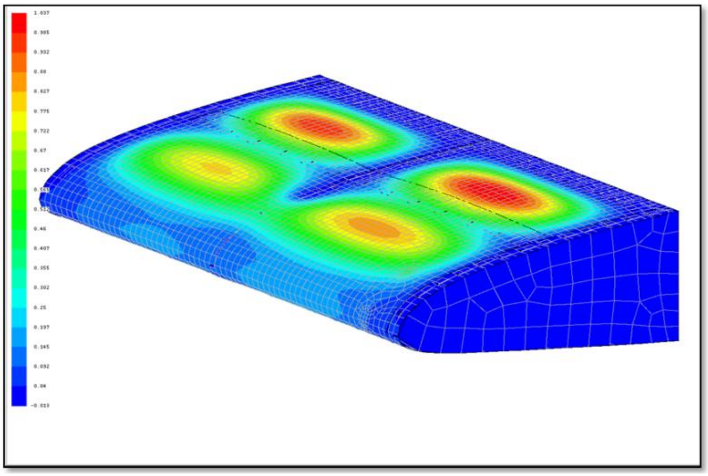


Figure 16: Distribution of test model skin deflection under aero loads

Figure 17: View of the first trial installation of the model skeleton on the wing after-body structure

To manufacture the leading edge test model heating skin, a dedicated moulding tool was developed and manufactured. It is made of aluminium and its contour is representative of the cross section of a full scale slat profile. Figure 18 presents several views of the 'layup tool' developed to manufacture the leading edge test model heating skin. The heating skin was designed and manufactured with the aim of being representative of an actual A320 Slat 4, provided with the eWIPS. Therefore, the laminate was provided with full scale heating resistances and temperature sensors. A second 'back-up' heating skin was manufactured, to anticipate any kind of failure of the 'baseline' heating skin during the tests.
After manufacturing, both heating skins were equipped with electrical cables and connectors. Finally, the equipped heating skin was installed on the model skeleton, by means of countersunk fasteners. Fast skin exchange exercises from the skeleton were performed before the test campaign. Figure 19 ***Figure 19*** shows the IWT leading edge model main structural components before and during the final assembly of the heating skin onto the skeleton. The test specimen was then submitted to dimensional control. Before shipment to the test centre, several functional tests were performed, in order to ensure reliable operation during the test campaign.

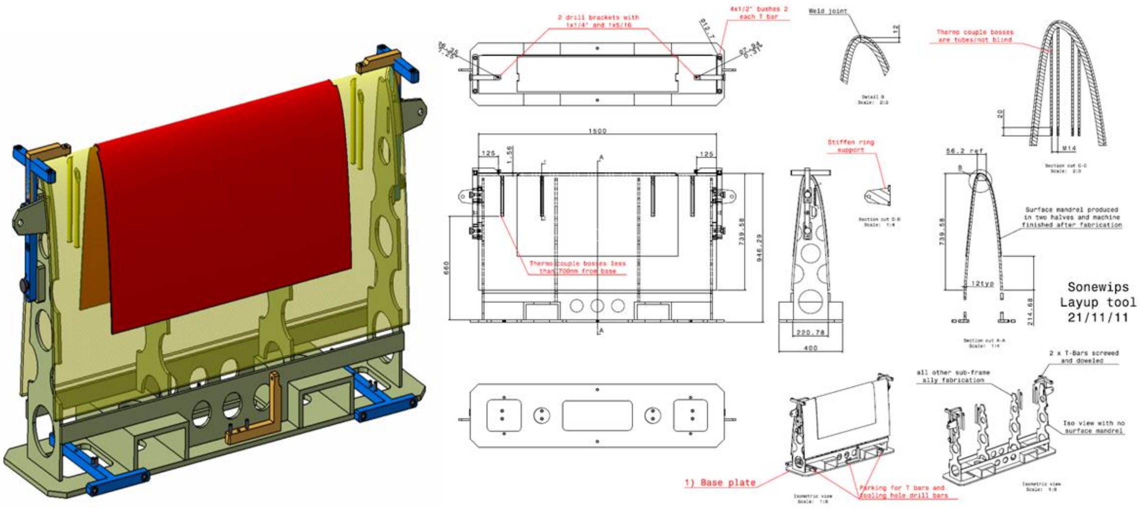


Figure 18: Views of the layup tool used to manufacture the leading edge test model heating skin

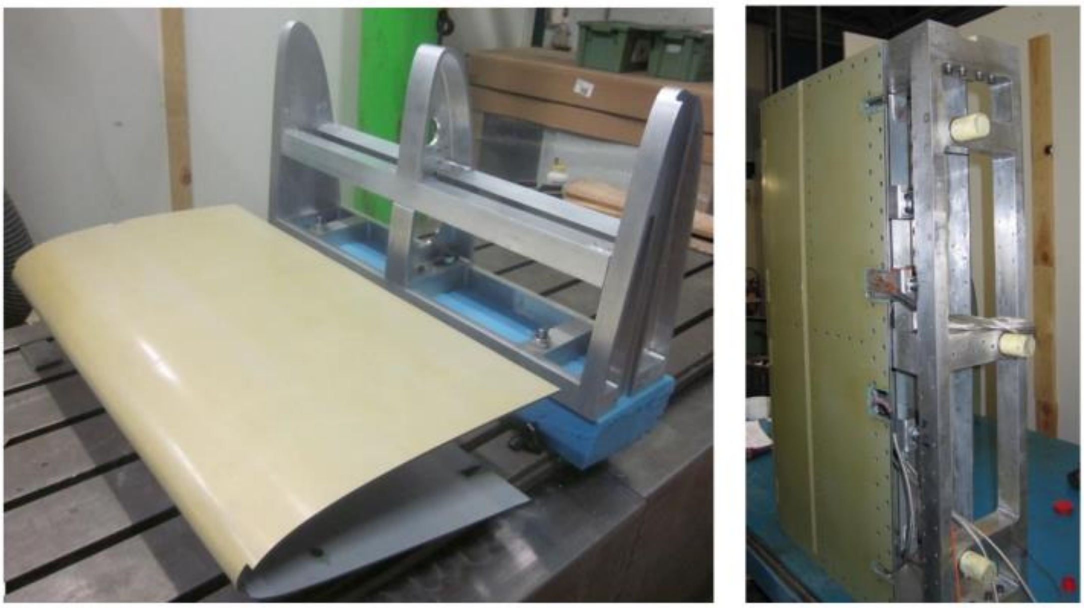


Figure 19: Leading edge model main structural components before and during final assembly

3.3 IWT Test Campaign:

The test campaign was carried out in the Icing Wind Tunnel of NASA IRT of Cleveland (USA), from the 7th to the 15th of November 2012. The installation of the eWIPS leading edge specimen on the wing box was made without major problem and the electrical bay was connected with the heating skin. During the test campaign, more than 20 different icing conditions were simulated, in order to validate the system performance in both anti-icing (Full evaporative criteria) and de-icing operation modes. For all selected cases, the performance requirements were fulfilled. All test parameters (aerodynamic, electrical and icing data) were recorded and analysed.

Figure 20: View of the test specimen in the tunnel showing ice accretion

3.4 Validation of ice protection system performances

The results achieved during the IWT test campaign were analysed and compared to numerical predictions, in order to verify the accuracy of the code. The IWT test results showed that the **eWIPS fully complies with the system performance requirement for both A/I & D/I modes** (See Figure 21). The eWIPS performance demonstration by test is presented in the IWT test report: ‘ITD SGO WIPS IWT TEST REPORT – Reference: SGO-D_4.2.3-1, Issue A01 – July 13st 2013). The system performance demonstration largely supported the achievement of the technical readiness level TRL4, as confirmed during the maturity gate closure review held on the 25th of September 2015.

Conditions	Result
ai_1	Pass
ai_4	Pass
di_1	Pass
di_2	Pass
di_3	Pass
di_4	Pass
di_8	Pass
di_9	Pass
di_10	Pass
di_11	Pass
di_12	Pass
di_13	Pass

Figure 21 : Summary of IWT test results for both anti-icing & de-icing modes

WP 4 - Development of an optimized architecture System

As a follow-up to the successful ice protection efficiency IWT test demonstration completed in WP 3 , the WP 4 was devoted to the optimisation of the eWIPS concept, with the aim of improving the system reliability. Three different options of simplified system architecture and associated functional mode were considered, based on configurations requiring significantly less system components (temperature sensors/heating mats). The architecture simplification developments were organised in two successive steps: a preliminary system configuration design analysis for each of the 3 technical options, followed by performance predictive studies.

4.1 Optimized architecture system: preliminary system configuration design:

Task 4.1 objectives were the **simplification and the optimization of the system architecture** for 3 different options of operating mode:

- 'Anti-Icing only' functional mode,
- 'Partial mixed' functional mode, with limited D/I envelope,
- 'Full mixed' functional mode, with 'cooling sensor'

Anti-Icing only functional mode: An optimized heating configuration was defined to comply with the 'full evaporative anti-icing' protection performances. This optimized heating configuration requires a reduced number of heating resistances and is provided with a substantially reduced number of temperature sensors. The sizing of heating areas and their associated power densities were assessed on the basis of numerical analysis, using prediction codes developed by SONACA. This optimized anti-icing mode configuration is the simplest system arrangement.

Partial mixed functional mode with limited D/I envelope: On the basis of the functional modes developed during previous analysis, an optimized heating configuration was defined to comply with A/I and limited envelope D/I performances. The partial mixed architectures is able to operate in A/I mode in the entire flight envelope, but the D/I mode is operated in a reduced part of the flight envelope. For warm cases (when -15°C<TAT<+10°C), the system works in A/I mode. For cold cases (when TAT<-15°C), the system works in D/I mode. The -15°C boundary temperature was chosen on the basis of experimental values. The control of the optimized heating sequence needs a substantially reduced number of temperature sensors. The sizing of heated areas, the heating activation times and the power density distribution were optimised to ensure ice protection performance with a minimum power need. Compared to the 'Anti-Icing only architecture' mode, the 'Partial mixed architecture with limited D/I envelope' needs less electrical power.

Full mixed functional mode with 'cooling sensor': The aim of this architecture is to provide a system with the same performances than the baseline "Full mixed mode architecture" for the entire flight envelope, while reducing the number of required sensors. The system operating mode uses a 'cooling rate' parameter which is based on a reduced number of sensors data, but representative of the external flow conditions. The 'cooling rate' parameter is based on the ratio between 'provided Heating Power to the heating mat (PS) and the temperature of the heating mat (PS)'. Based on this parameter and the analysis of test results, the control law for each heating mat was defined. The system is able to achieve performances and structural temperatures requirements, without temperature control and monitoring for heating zones B1, T1 and T2. The optimized heating cycle accounts for the various icing conditions on the basis of the external flow 'cooling rate' survey. The sizing of heated areas, associated power densities and heating activation times were defined accordingly. The achieved system design is the simplest electro thermal de-icing system arrangement, in terms of required sensors for control, leading to a substantial improvement of the system reliability.

4.2 Optimized architecture system: preliminary performance predictions:

For each of the 3 optimized operating mode options, a preliminary performance analysis was carried out, using numerical transient codes developed by SONACA. The numerical predictions supported the validation of the ice protection performance for icing conditions representative of the flight envelope, to be verified during the icing wind tunnel test campaign planned in WP 5.

The deliverable issued from Task 4 is the report describing the configuration, the operating modes and the performances predictions for optimized architectures of electro thermal anti-icing / de-icing systems (Report REF 0/1751/15-001-0)

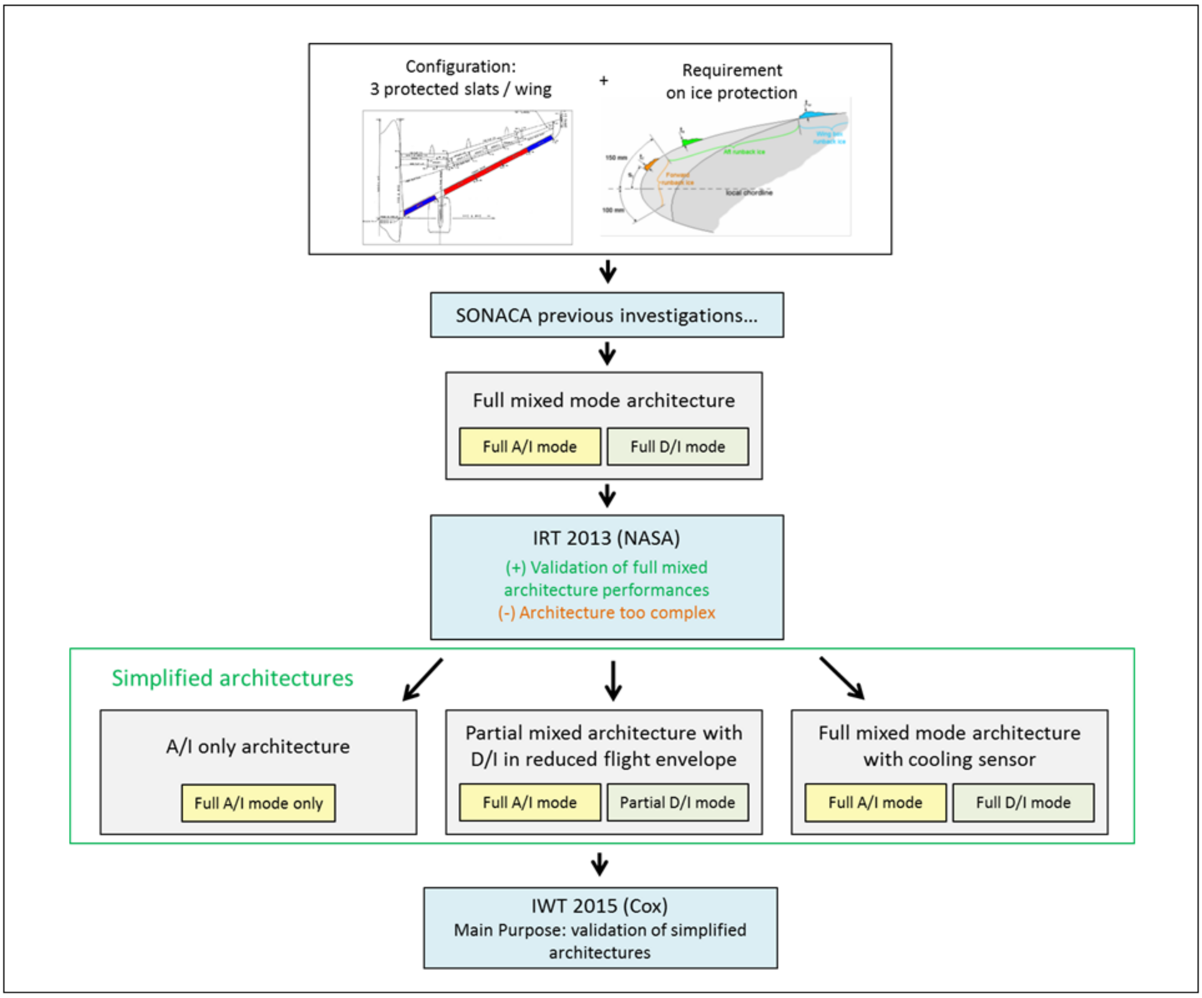


Figure 22 : Schematic view of the system architecture 'optimisation/simplification' process

WP 5 - Validation through IWT Test Campaign

The purpose of WP 5 is the validation of thermal performances for the three different operating modes developed in WP 4, through a test campaign in an Icing Wind Tunnel (IWT). The task was organised in four successive steps:

1. Definition and preparation of the IWT test campaign
2. Design, manufacturing and instrumentation of the IWT test models
3. Follow-up of the test campaign
4. Validation of system performances on the basis of test results.

The test matrix was defined to take into account respective ice protection performance expectations and test installation capabilities. The test specification (ETS Ref: 0/1751/15-010-3) describes the experiment plan, the test model configurations, the system control laws and the ice protection performance predictions. The document also specifies electrical and mechanical interfaces.

The test model configurations were defined to allow system operating modes representative of the three optimised/simplified architecture options developed in WP 4. The IWT test model was also designed in order to accommodate the interface with the icing wind tunnel test section of the LeClerc Icing Research Laboratory of COX & CO. Inc, in New York, USA.
Four heating skin test models were manufactured, representing 2 heating zone architecture configurations, with a 'back-up' specimen for each, in order to anticipate any kind of technical failure before or during test operations.

5.1 IWT Test Campaign Definition and preparation

Task 5.1 was devoted to the definition and the preparation of the Icing Wind Tunnel validation test campaign. All IWT test technical data were defined in order to support the validation of thermal performances for the optimised/simplified architecture system. The deliverable from task 5.1 is the Engineering Test Specification document (Reference: 0/1751/15-010-3). The purpose of the test specification document is to gather all data needed to carry out the IWT test campaign:

- The list of test conditions representative of the icing conditions flight envelope. The test campaign matrix was defined accounting for icing wind tunnel capabilities, documented by technical discussions with IWT technicians on feasible icing conditions.
- The required instrumentation and associated visual display/recording terminals to ensure that test results were accurately observed recorded and exploited.
- The detailed description of electrical interfaces with the heating power supply and the data acquisition system.
- A general model description including mechanical interfaces with the turntables of the test section, used to adjust the model angle of attack.
- The System electrical schematic including connection interfaces with the power supply and with control components ;
- Numerical simulations results in terms of predicted ice protection performances and anticipated potential modifications of test parameters during the campaign.

5.2 IWT demonstrator definition, design and manufacturing

The activity of Task 5.2 was the design, manufacturing and instrumentation of the Icing Wind Tunnel test models. Following steps were completed:

- The detailed design of the leading edge test models (primary parts, assembly drawings).
- The structural analysis of the test model and its supports in the test section.
- The detailed instrumentation drawings: temperature sensors location & wires routing.
- The definition of the pressure belt.
- Procurement of materials needed to manufacture the model.
- Manufacturing of model primary parts.
- Adaptation of the model ‘wing box’ to interface the test section.
- Instrumentation of the heating skins.
- Installation of the heating mats on the extension side ribs.
- Assembly of the electrical wiring bundles and connectors.
- Final assembly of the whole specimen and provisions for heating skins interchange.
- Handling provisions and transportation of the model from SONACA to Liebherr (Toulouse).

The four heating skin test models, the wing box with its side plates and the electrical wire bundles were delivered to Liebherr (Toulouse) on the 10th of august 2015. After several electrical pre-test controls of the test specimens and the electrical bay completed by Liebherr, the test equipment’s were shipped to the LeClerc Icing Research Laboratory of COX & CO. Inc, in New York, USA.

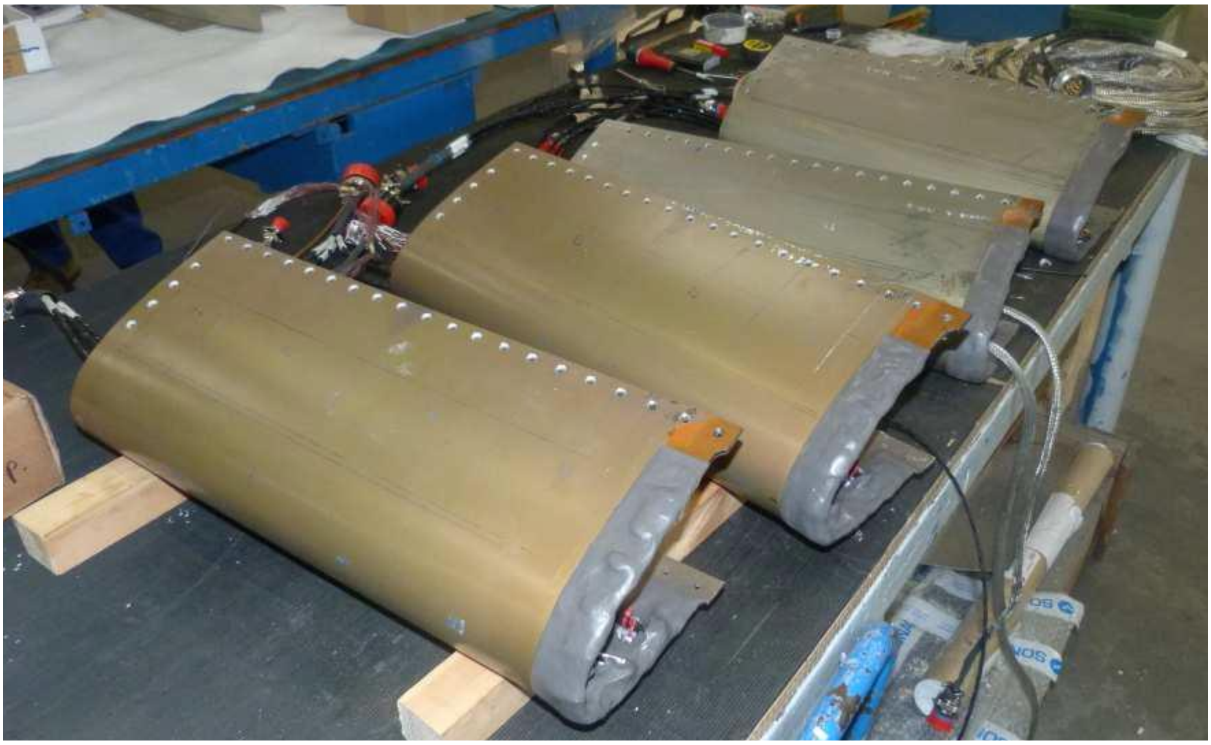


Figure 23: View of the 4 heating skins (2 configurations & their ‘back-up’ specimens)

Task 5.3 - IWT Test campaign

The validation test was carried out in the Icing Wind Tunnel of the LeClerc Icing Research Laboratory of Cox & Company Inc. in New York, from the 2d to the 13th of November 2015. The test campaign started with the model installation in the test section, connection of instrumentation and system devices, preliminary checks and aerodynamic adjustments.

Figure 24: LIEBHERR electrical bay and SONACA Leading Edge prototype during installation phase

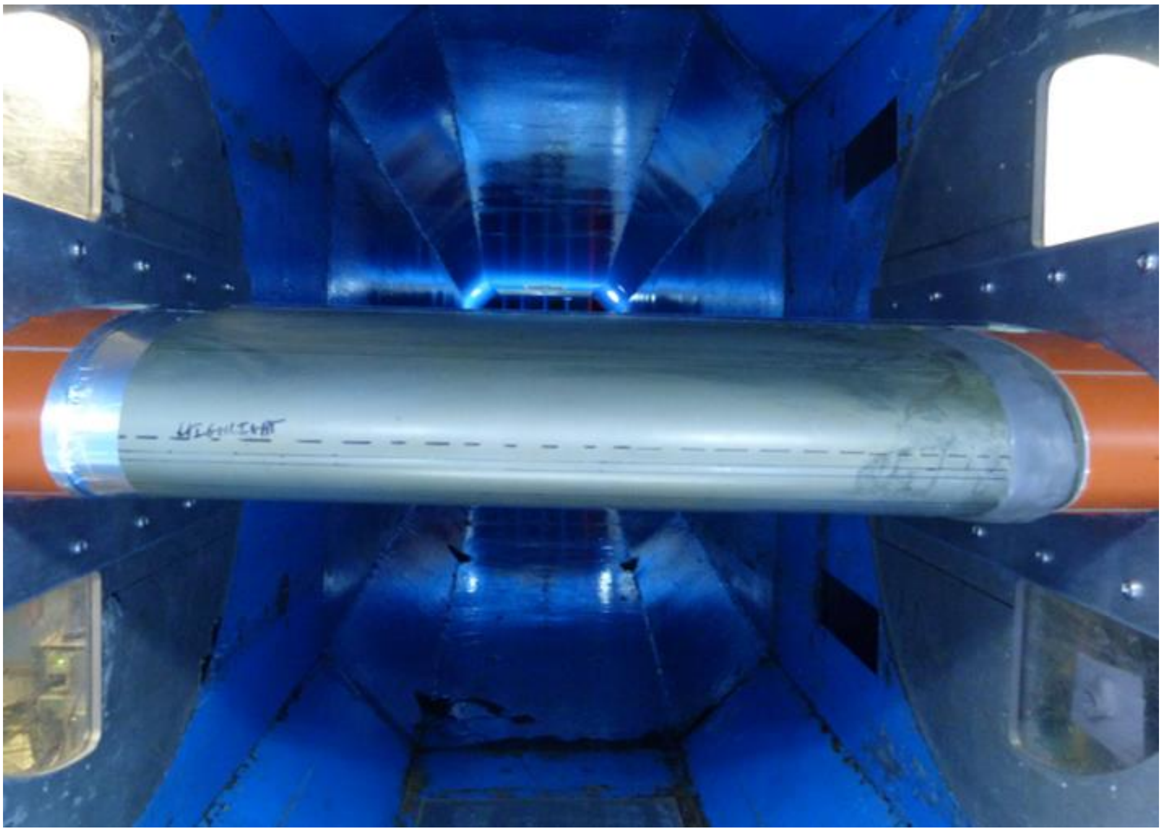


Figure 25: L/E prototype installed in the test section and electrically connected

During ten days of tunnel run, the tests covered several aspects: measurement of ice shape sizes on the unprotected leading edge, performance of the system in Anti-Icing (A/I) & De-icing (D/I) modes. Three different system architectures were simulated in terms of system operation: A/I only, A/I + limited envelope D/I, and D/I only, based on power regulation (Cooling sensor).

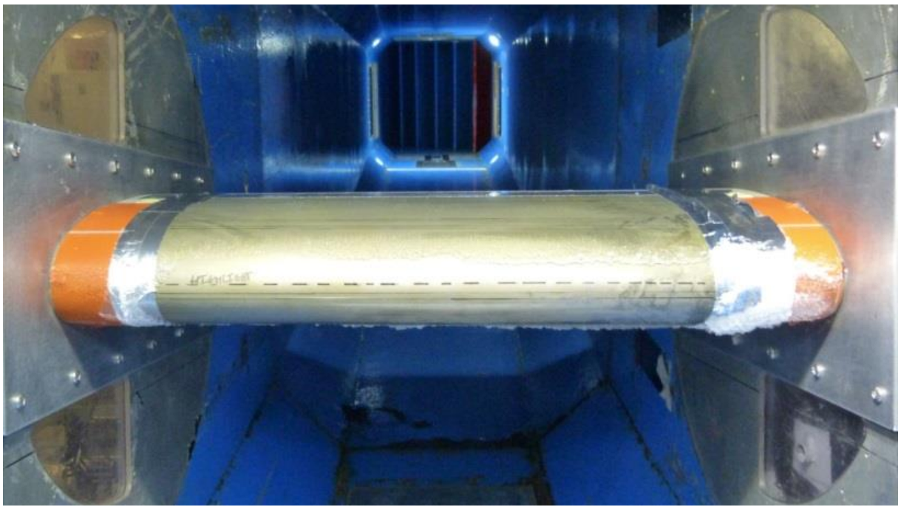


Figure 26: L/E prototype at the end of a de-icing run during the measuring phase

The tests allowed the 'fine tuning' of the system control laws, to ensure 'full envelope' ice protection efficiency, with a minimum electrical power consumption.
All test demonstrations appeared to be in good agreement with the numerical predictions, leading to following conclusions:

- For the 'A/I only' mode the system was substantially simplified (for control and monitoring sensors number and heating mats number) without performance penalty: compliancy to the top full evaporative performance requirement was demonstrated.
- For the 'partial mixed architecture with limited D/I envelope' mode, the system showed good performances in both A/I and D/I modes, with a more optimized architecture.
- For the 'Full mixed architecture with cooling sensor' mode, the system operation based only on power regulation mode showed good performances. For this mode, the number of temperature sensors needed for control and monitoring was substantially reduced, which is very positive in order to simplify the architecture of the device and increase the reliability of the system.

These tests results and observations are presented in an Engineering Test Report (ETR Ref: 0/1751/15-014-3).

<u>5.4 Validation of ice protection system performances.</u>

WP 5.4 was devoted to the post-processing of IWT test results. The test results were compared to the numerical predictions for each of the three optimized architecture options. The final performance analysis was completed.

Potential impact and main dissemination activities and exploitation results

The main impact of the SONEWIPS project is a significant progress in the development of a high-performance electro thermal ice protection system, fully integrated in a wing leading edge structure. The prime exploitation will obviously be through the implementation of the achieved technical foreground into future leading edge system and structure development programs for transport aircraft.

SONEWIPS technical achievements support the demonstration of the manufacturing feasibility of leading edge structural components made from different materials and process technologies, resulting in a ‘hybrid’ heating element. The achieved technical foreground will also advance the integration of the eWIPS technology on fixed or movable leading edges for large transport aircrafts. The exploitation of the technical knowledge issued from the project will promote performance and weight optimization, since system and structural functionalities are substantially more integrated.
On another hand, the successful demonstration of the ice protection actual performance is also a major achievement issued from the SONEWIPS project which substantially raises the Technical Readiness Level of the eWIPS technology.

The need for a mature electro thermal ice protection system should appear in short term new transport aircraft developments, as the use of electrical energy is increasing in several system areas. On future developments, the ratio between electricity and conventional power sources will clearly depend on the level of maturity of concepts based on electrical technologies.

As key leading edge supplier involved on several aeronautical programs, SONACA should be involved in new generation transport aircraft development programs, leading to the opportunity of exploiting the results issued from the SONEWIPS project. Nevertheless, such exploitation opportunity is very likely to arise a few years after the end of the project. This period should be used to complete developments and demonstrations in order to improve the maturity level of the concept.

Regarding the dissemination activity associated to the SONEWIPS project, some external communication was provided, without damaging the competitive position of SONACA: Presentation during the ‘SAE 2015 international conference on icing of aircraft, engines, and structures’, on the 22-25 june 2015 in Prague, Czech Republic, on the subject of ‘*Unsteady Thermal Simulations of Wing Ice Protection Systems Integrated in Metallic or Composite Structures*’ (SAE publication Ref 2015-01-2093 published on the 15th june 2015).