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Development and Validation Testing of the Collins Ice Differentiator System in App C and App O Icing Conditions

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Abstract

Protecting against atmospheric icing conditions is critical for the safety of aircraft during flight. Sensors and probes are often used to indicate the presence of icing conditions, enabling the aircraft to exit the icing cloud and engage their ice protection systems. Supercooled large drop (SLD) icing conditions, which are defined in Appendix O of 14 CFR Part 25, pose additional risk to aircraft safety as compared to conventional icing conditions, which are defined in Appendix C of 14 CFR Part 25. For this reason, developing sensors that can not only indicate the presence of ice, but can also differentiate between Appendix O (App O) and Appendix C (App C) icing conditions, is of particular interest to the aviation industry and to federal agencies. Developing a detector capable of meeting this challenge is the focus of SENS4ICE, a European Union sponsored project. This paper summarizes the work that was done to develop the Collins Ice Differentiator System, an ice detection and differentiation sensor developed by Collins Aerospace while participating in the SENS4ICE Project. A series of five icing wind tunnel campaigns were completed with the goal of developing the system and refining the underlying detection algorithm. A sixth integration wind tunnel test was then carried out to test all the Collins Ice Differentiator System's constituent parts together as a complete system. This integration icing wind tunnel test was followed by additional integration testing to ensure that the system would function correctly on-aircraft. Finally, a flight test was completed with the goal of seeking out natural icing conditions to evaluate the performance of the Collins Ice Differentiator System, and that of the other SENS4ICE sensors.

Introduction

The SENS4ICE project is an EU-funded consortium made up of 17 international partners focused on developing sensors capable of detecting and differentiating between App C and App O icing conditions [1–3]. Although developing sensors capable of differentiating within App O (i.e., freezing drizzle and freezing rain) is also of interest, this falls outside the SENS4ICE project's scope [4]. In addition, no freezing rain conditions were tested during the project, so discrimination performance within App O cannot be properly evaluated at this time. To facilitate the development and validation of these new sensor technologies, three icing wind tunnels (IWT) and two flight test platforms have been made available to the consortium. In the early stages of the SENS4ICE project, each sensor developer had the opportunity to test their technology in one or more of the IWTs. The project ended in March 2023, culminating in a series of flight test campaigns in which sensor developers had the opportunity to participate [1–3].

Collins Aerospace is a global provider of aerospace systems, including ice protection systems (IPS), and is participating in the SENS4ICE project in two capacities: As a sensor developer and an IWT provider. The novel ice detector that Collins designed to meet this challenge is known as the Collins Ice Differentiator System (Collins-IDS).

Collins Ice Differentiator System

The Collins-IDS technology is based on measuring heat flux variations in different icing conditions using a metallic or Advanced Carbon Nanotube (ACNT) heater. The system builds upon a patent pending ice detection technology based on thermal response to a heat impulse that changes from dry to icing conditions. The Collins-IDS is shown schematically in Figure 1.

The Collins-IDS is made of three components (see Figure 2 for an image of each): (1) Sensing Element (SE) that uses a proven and certified construction made of high temperature composite, temperature sensors and metallic heater that

FIGURE 1 Collins-IDS System Schematic

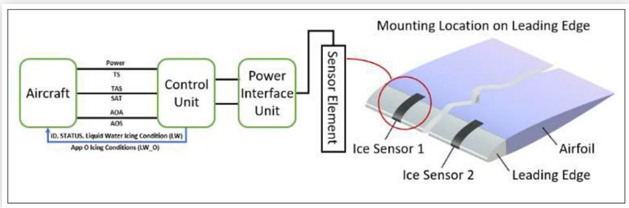

FIGURE 2 Collins-IDS System Components, (2a.) Sensing Element, (2b.) Power Interface Unit, (2c.) Control Unit

measure heat flux distribution and communicates this to the rest of the system. (2) A Power Interface Unit (PIU) that provides the necessary power to the sensing element. (3) Control Unit (CU) that analyses the measurements and makes recommendations on icing conditions (i.e., Dry air or App C or App O). Detection and differentiation is done with a built-in detection algorithm within the CU. The system is scalable to include one or multiple sensing elements positioned on sensitive areas of the airplane, powered individually, and controlled together by a master controller.

Installation of Collins-IDS on the aircraft is flexible. It can be integrated on the leading edge by being installed inside of the leading edge and/or areas of the leading edge where no ice protection is installed, for example the wing and/or tail tips or vertical fin. Further improvements can be achieved by installing the sensor in other more sensitive areas than the wing leading edge to ensure ice detection before wing or other aerodynamic surfaces. For easy maintenance and replacement, the sensor can be installed in a dedicated strip over the leading edge, under the leading edge, or integrated in a recessed composite leading edge. This way the Collins-IDS is replaceable without replacing the whole leading edge.

For the SENS4ICE project, the Collins-IDS SE was designed to contour to the vertical stabilizer of an Embraer Phenom 300 (P300). This aircraft is one of the flight test platforms that has been made available to the SENS4ICE consortium by its manufacturer, Embraer. Collins has selected this platform to fly on during the flight test portion of the project.

Initially, the Collins-IDS SE was designed to mount to the plane's horizontal stabilizer. The leading-edge surface of the horizontal stabilizer is ordinarily protected by a bleed air IPS and, to accommodate the Collins-IDS SE, that system would have needed modification. Unlike the horizontal stabilizer, the vertical stabilizer is an unprotected surface, and the SE can be mounted to it without making any significant modifications to the aircraft. For that reason, the leading-edge surface of the vertical stabilizer was selected instead as the mounting position for the SE during the flight test. A second-generation of the SE was designed to mount to the vertical stabilizer because the geometry of the horizontal and vertical stabilizer leading edges are significantly different.

Development Icing Wind Tunnel Testing

The Collins-IDS completed over 180 hours of development testing during five IWT test campaigns. One round of testing was performed at National Research Council Canada's Altitude Icing Wind Tunnel located in Ottawa, Ontario Canada [5]. The remaining four rounds of development testing took place at the Collins' Goodrich Icing Wind Tunnel located in Uniontown, Ohio USA [6]. A summary of each IWT test can be found in Table 1.

TABLE 1 Development IWT Test Summary

IWT Test	Test Facility	Duration	Description
Round 1, May 2020	Collins, Ohio	40 Hours	Feasibility tests to validate CFD models over Dry, App C and App O conditions and to verify App C/O discrimination.
Round 2, Oct. 2020	Collins, Ohio	40 Hours	Tested operation of integrated system over a wide range of icing conditions. Data used to validate the detection algorithm and its ability to detect and discriminate App C/O conditions.
Round 3, Jan. 2021	Collins, Ohio	40 Hours	Demonstrate (1) reduction in power requirements and improved sensor performance (2) the ice detection and differentiation between App C and App O icing conditions taking the sensor to the next level towards flight test.
Round 4, Mar. 2021	NRC, Canada	20 Hours	NRC facility provided more capabilities within the App O icing envelope. The data was used to expand the detection envelope beyond the capabilities in the Collins facility and to demonstrate the efficacy of the sensor in differentiating between App C and App O as well as to extend the number of points available for simulation verification & validation.
Round 5, Apr. 2022	Collins, Ohio	40 Hours	Evaluated the performance of the second-generation sensor, which was redesigned to be mounted on the vertical stabilizer. Data used to revalidate the detection algorithm and its ability to detect and discriminate App C/O conditions given the design changes to the detector.

The airfoil shaped test models were designed to replicate the shape of an Embraer P300's horizontal and vertical stabilizers. However, because the chord length of both airfoils is too large for the Collins and NRC Canada IWTs to accommodate, truncated test models were developed. These truncated models were designed to maintain the same leading-edge geometries and pressure coefficient distributions of the real horizontal and vertical stabilizers.

The first-generation SE, which was designed to mount to the horizontal stabilizer leading edge, was tested in the IWT using a truncated model designed to replicate the Embraer P300's horizontal stabilizer and was used throughout the first four IWT test campaigns listed in Table 1. The second-generation SE, which was design to mount to the vertical stabilizer leading edge, was tested in the IWT using a truncated model designed to replicate the Embraer P300's vertical stabilizer and was used in the final IWT test campaign listed in Table 1. For each IWT test, the model was mounted horizontally with the SE positioned at the centerline of the test section.

The primary focus of these wind tunnel tests was to develop and refine the SE and gather data to be used for tuning the detection algorithm. For that reason, the SE was not powered and controlled using the other components that constitute the Collins-IDS (i.e., the PIU and CU). Instead, a benchtop power supply and LabVIEW program were used to power and sense the SE respectively. The PIU and CU were incorporated in future testing that is described later in this document.

The Collins-IDS was subjected to a total of 87 icing conditions during the five IWT tests, covering much of the App. C and App. O envelopes [4]. Of these conditions, 54 were App. C conditions, 17 were App. O conditions (Icing conditions having LWC and MVD values within the range defined in 14 CFR Part 25 Appendix O), and 16 were SLD conditions (Icing condition having MVD values within the range defined in 14 CFR Part 25 Appendix O but LWC values higher than the acceptable range and a unimodal droplet distribution) [4]. The complete array of test conditions are shown as black markers in Figure 3. In Figure 3a., the App C CMI curves (upper shaded region) and App C IMI curves (lower shaded region) are superimposed over the test points for comparison [4]. Similarly, in Figure 3b., the App O MVD greater than 40μm curves (red shaded region) and MVD less than 40μm curves (orange shaded region) for App O freezing drizzle are also superimposed [4].

FIGURE 3 IWT Test – Icing Conditions, (3a.) Appendix C Test Conditions, (3b.) Appendix O/SLD Test Conditions

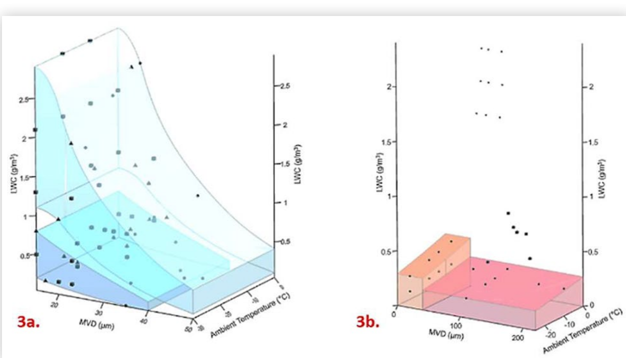

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FIGURE 4 Appendix C Icing Conditions, Test Procedure

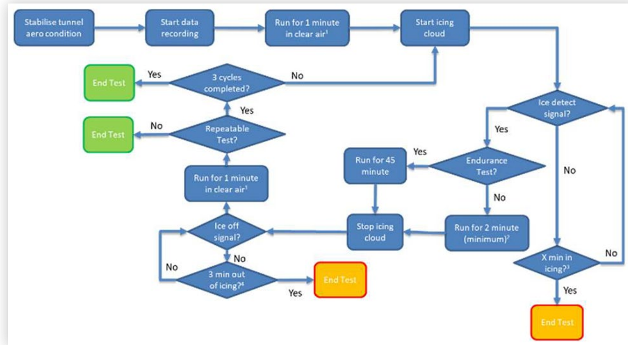

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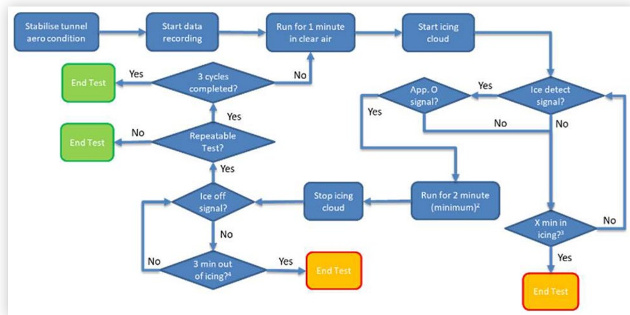
FIGURE 5 Appendix O Icing Conditions, Test Procedure



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The procedure for performing each test run was standardized across the SENS4ICE consortium to ensure that each sensor was tested using the same methodology and could be compared directly. Typically, each test run lasted for only a single cycle of icing, a cycle being defined as follows:

1. Start data recording
2. Record data for 1 min in clear air
3. Start the icing cloud
4. Once an icing signal is detected, run for 2 min
5. Stop the icing cloud

For a select subset of the test conditions, an endurance run was completed where the icing condition is held for 45 minutes instead of 2 minutes. For another select subset of test conditions, three cycles of icing were completed. The test procedures for the App. C and the SLD/App. O icing conditions are shown in flowchart form in Figure 4 and Figure 5, respectively [7].

Development Icing Wind Tunnel Test Results

The results from the third, fourth, and fifth IWT test campaigns at the Collins and NRC, Canada facilities are discussed in this section (the first and second IWT tests were used to develop the detection algorithm, and therefore results are not presented). As with the test procedure, the SENS4ICE consortium has established two main criteria for evaluating and comparing the performance of each sensor. Those two criteria are as follows:

1. Does the sensor correctly detect whether an icing condition is dry, App. C or App. O?
2. Does the sensor detect the icing condition within the required amount of time as calculated using methods defined by EUROCAE ED-103B [8].

These criteria were used to evaluate the performance of Collins-IDS over the course of the IWT campaigns. Several example graphs demonstrating the ability of the Collins-IDS to detect and discriminate icing conditions are shown in Figure 6–Figure 9.

Figure 6 shows the test results for the Collins-IDS measured at the Collins IWT for an App. C condition with the following parameters: An airspeed of 40m/s, a static air temperature (SAT) of -3.11°C, an MVD of 20 μm, and an LWC of 2.5 g/m³. The test starts with 60 seconds of dry conditions followed by 3 minutes in icing cloud and finishes with dry conditions. Green indicates dry condition detected and purple indicates App C condition detected. For this condition, the system was able to detect entry and exit from icing within the required response time. Once icing spray was initiated, the Collins-IDS was able to detect App C icing conditions in 2.0±0.25 s. After the icing spray was turned off, the Collins-IDS was able to detect dry air conditions in 23.0±0.25 s. The required response time for this condition was 24.5 s.

FIGURE 6 Appendix C Example Test Results

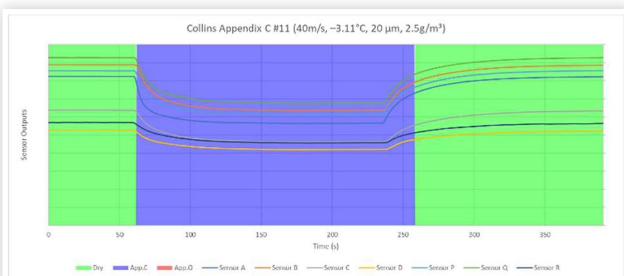

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FIGURE 7 Appendix O Example Test Results

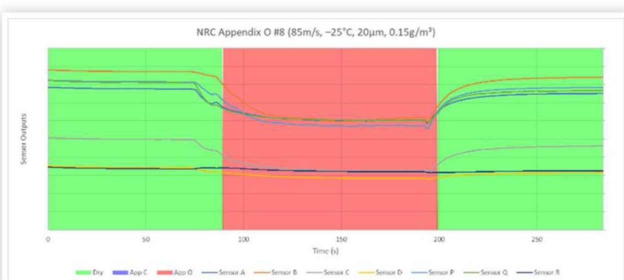

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FIGURE 8 Appendix C Example Test Results, Three Repeated Cycles

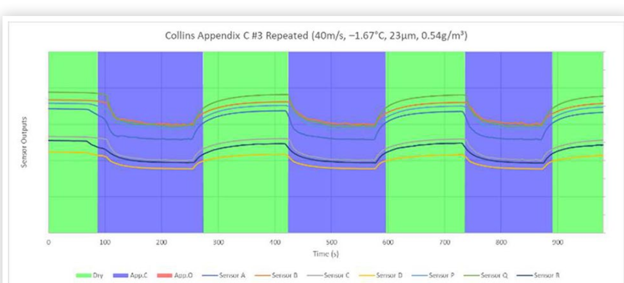

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FIGURE 9 Appendix C Example Test Results, Endurance Run

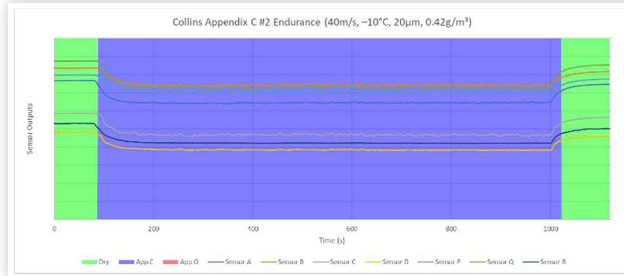

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Figure 7 shows the test results for the Collins-IDS measured at the NRC IWT for an App. O condition with the following parameters: An airspeed of 85 m/s, a SAT of -25°C, an MVD of 20 μm, and an LWC of 0.15 g/m³. The test starts with 60 seconds of dry conditions followed by 2 minutes in icing cloud and finishes with dry conditions. Green indicates dry condition detected and red indicates App O icing was detected. For this condition, the system was able to detect entry and exit from icing within the required response time. Once icing spray was initiated, the Collins-IDS was able to detect and discriminate App O icing conditions in 16.5±0.25 s. After the icing spray was turned off, the Collins-IDS was able to detect dry air conditions in 7.0±0.25 s. The required response time for this condition was 42.9 s.

Figure 8 shows the test results for the Collins-IDS measured at the Collins IWT for an App. C condition with the following parameters: Airspeed of 40m/s, a SAT of -1.67°C, a MVD of 23 μm, and an LWC of 0.54 g/m³. This is a repeated test with three cycles that start with 60 seconds of dry conditions followed by 3 minutes in icing cloud and finishes with 3 minutes in dry conditions. Green indicates dry condition detected and purple indicates App C condition detected. For this condition, the system was able to detect entry and exit from icing within the required response time before and after each of the three icing cycles. Once icing spray was initiated, the Collins-IDS was able to detect App C icing conditions in 19.5±0.25 s, 4.5±0.25 s, and 7.0±0.25 s for the first, second, and third icing cycles respectively. After the icing spray was turned off, the Collins-IDS was able to detect dry air conditions in 20.5±0.25 s, 18.0±0.25 s, and 16.0±0.25 s for the first, second, and third icing cycles respectively. The required response time for this condition was 63.8 s.

Figure 9 shows the test results for the Collins-IDS measured at the Collins IWT for an App. C condition with the following parameters: Airspeed of 40m/s, SAT of -10°C, MVD of 20 μm, and LWC of 0.42 g/m³. The test starts with 60 seconds of dry conditions followed by 15 minutes in icing cloud and finishes with dry conditions. Green indicates dry condition detected and purple indicates App. C condition detected. For this condition, the system was able to detect entry and exit from icing and maintain the icing signal throughout the duration of the test. The required response time for this condition was 24.1 s. Once icing spray was initiated, the Collins-IDS was able to detect App C icing conditions in 1.5±0.25 s which is well within the required response time. After the icing spray was turned off, the Collins-IDS was able to detect dry air conditions in 26.0±0.25 s, which is 1.9 seconds longer than the required response time.

Following the completion of the endurance run it was noted that the sensor signals did not return to their pre-icing value. This discrepancy was most likely due to ice that built up on the test model throughout the 15 minute test run. This is also the most likely reason that it took 26.0±0.25 s to detect dry conditions once the icing spray was turned off, rather than the required 24.0 s.

The graphs in Figure 6 through Figure 9 were selected to demonstrate the ability of the Collins-IDS to detect and discriminate between icing conditions, within the required time, for the different types of test runs discussed in the Icing Wind Tunnel Testing section of this report (i.e. single-cycle App. C condition test run, single-cycle App. O condition test run, three-cycle test run, and an endurance test run).

Figure 6 through Figure 9 show the plotted outputs from multiple sensors within the Collins-IDS. These sensor outputs are analyzed in combination with external data to make a recommendation on whether dry air, App C, or App O conditions have been encountered. Due to the nature of the system's detection algorithm, no one sensor is uniquely or even largely responsible for detection or differentiation.

Data from all 87 of the test conditions from these tests was analyzed and graphs like these were generated for each. The results from the third, fourth and fifth rounds of IWT testing have been summarized in Table 2. In addition, the detection times for the App C icing conditions and the differentiation times for App O icing conditions are represented graphically in Figure 10 and Figure 11 respectively. In these figures, the measured time for each condition is plotted with respect to the required time for that test condition. From Table 2, it can be seen that the Collins-IDS always detected the correct icing condition. This was true across both the Collins and NRC test facilities and for both App. C and SLD/App. O test conditions.

From Table 2 and Figure 10, it can be seen that the sensor has detection times almost always lower than the required values for App. C. While the lower detection times are significantly lower, the ones that are higher than the required

FIGURE 10 Detection Time, Appendix C Conditions

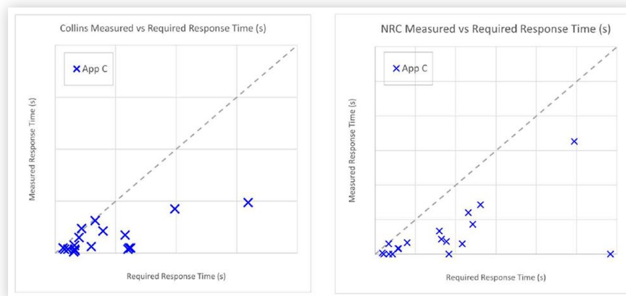


FIGURE 11 Discrimination Time, Appendix O Conditions

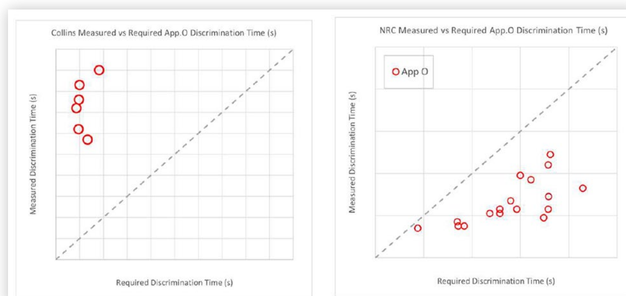


TABLE 2 IWT Results Summary

IWT	Test	Percentage of Test Points Detected	Percentage of Test Points Within Required Response Time	Percentage of Test Points Within 1.5x Required Response Time
COLLINS	Appendix C Test Points	100.00%	94.44%	100.00%
	Appendix C Repeat Points	100.00%	100.00%	100.00%
	Appendix O Test Points	100.00%	0.00%	0.00%
	Appendix O Repeat Points	100.00%	0.00%	0.00%
NRC	Appendix C Test Points	100.00%	100.00%	100.00%
	Appendix C Repeat Points	100.00%	100.00%	100.00%
	Appendix O Test Points	100.00%	88.24%	94.12%
	Appendix O Repeat Points	100.00%	100.00%	100.00%

values are higher by a small amount, which could be put down to experimental error.

From Table 2 and Figure 11, it can be observed that the SLD/App O. differentiation times are higher than the required values for the tests performed in the Collins IWT. However, knowing that the SLD/App. O conditions capable of being simulated in the Collins IWT are not within the envelope defined by ED103B, we conjectured that this discrepancy was attributable to two reasons [8]:

1. There is a significant difference/gap between the two groups of test conditions corresponding to App. C and App. O at Collins. As a result, the detector took longer to respond to changing conditions. This could have been corrected manually, had this been the only cause.
2. A bigger issue, which the team believes is the main cause of this discrepancy, relates to the method of calculating required differentiation times for the App O envelope as defined in ED103B. The LWC range of the Collins SLD conditions are well outside the defined App O LWC range and therefore ED103B would not directly apply to the Collins SLD conditions [4, 8]. This problem could not be corrected without significant effort of deconstructing and redoing the physics of ED103B, without using the simplifying assumptions [8].

From Table 2 and Figure 11 it can be observed that App O. differentiation times are almost always lower than the required values for the tests performed in the NRC IWT. The results from the App. O conditions tested at NRC gives us confidence in our assessment of why the response times for the SLD/App O. conditions tested in the Collins IWT were so high. The LWC values for the App O. conditions in the NRC IWT were within the envelope defined by ED103B and the Collins-IDS was able to meet the discrimination time requirement 88.24% of the time [8].

Of the 17 App O test points that were run in the NRC IWT, 16 could be discriminated within 1.5 times the required response time. The measured response time for the singular App O test point to exceed this 1.5 times threshold was 7±0.25 s, and the required response time for that condition was 4.5 s [8]. Therefore, the system only exceeded the 1.5 times threshold by 0.25 s, since 1.5 times the required response time equates to 6.75 s. This difference is within the uncertainty range for the response time measurement and can be put down to experimental error.

Systems Integration Testing

As previously stated, only one of the Collins-IDS's constituent components, the sensor element, participated in the development IWT testing. Instead, a custom LabVIEW program and benchtop power supply were used to control and power the SE. This setup was acceptable for the development testing, since developing a detection algorithm for the SE was the primary focus of those tests but was not sufficient to evaluate the performance of the other components. For that reason, an additional IWT test was planned for the remaining Collins-IDS components, the power interface unit and control unit, and would represent the on-aircraft setup as closely as possible. The purpose of this test was to evaluate the performance of the entire Collins-IDS, refine the CU's control software, and ensure that all three key components integrated seamlessly.

The System Integration IWT Test spanned one week and took place at the end of September 2022. In order to evaluate and retrain the SE, this time with the control and data interpretation being performed by the PIU and CU, the test plan called for the rerun of many of the icing conditions from the Development IWT Test Round 5. However, before any icing conditions could be performed, the control functions of the complete Collins-IDS needed to be evaluated.

First, the ability for the Collins-IDS to stabilize its internal temperature at the desirable level was evaluated. This was done by setting the IWT to the dry air conditions in Table 3 while the SE was installed in the tunnel. These conditions were selected so that the Collins-IDS's performance could be evaluated in a variety of environmental conditions, similar to what might be encountered on aircraft during the flight test campaign. These tests were ultimately successful and, with only minor adjustments to the control software, the Collins-IDS was able to stabilize the SE at its desired internal temperature.

Next, the functionality of two system safety protocols needed to be verified. The first of which was the control protocol that inhibits the PIU from distributing power to the SE when the WoW signal is indicating that the airplane is grounded. The WoW safety function ensures that the heater element in the SE will not overheat from a lack of cooling load, while the aircraft is on the ground. This functionality was evaluated as follows:

1. Simulating a true value for the WoW signal (indicating that the aircraft is grounded) and then attempt to supply power to the SE. This test was considered a success only if the PIU does not supply any power to the SE.
2. Simulating a false value for the WoW signal (indicating that the aircraft is flying), supplying power to the SE, and then simulating a WoW of true (indicating that the aircraft has landed). This test was considered a success only if, once the WoW signal changed from false to true, the power being supplied to the SE reduced to 0W.

TABLE 3 Dry Air Stabilization Test Conditions

Test No.	IWT SAT, °C	IWT Airspeed, m/s	Result
1	0	54	Stabilized
2	0	72	Stabilized
3	-15	54	Stabilized
4	-15	72	Stabilized
5	-30	54	Stabilized
6	-30	72	Stabilized

In both situations from the list above, the system performed correctly, meeting the success criteria for each. The other safety protocol was like the first, but inhibits the PIU from distributing power to the SE when the OAT is greater than +5°C. The OAT safety functionality ensures that the heater element in the SE will not overheat in the presence of an insufficient cooling load due to relatively warm environmental conditions. This functionality was evaluated as follows:

1. With the IWT operating above +5°C, try to turn on the system. This test was considered a success only if the PIU does not supply any power to the SE.
2. With the IWT operating at a SAT above +5°C and the Collins-IDS initially turned-off, turn on the system and attempt to supply power to the SE, then reduce the IWT SAT until it is below +5°C. The test was considered a success if the PIU began to supply power to the SE, only once the IWT SAT dropped below +5°C.
3. With the IWT operating at a SAT below +5°C and with power being supplied to the SE, increase the IWT SAT until it is above +5°C. The test was considered a success only if, once the IWT SAT increased above +5°C, the power being supplied to the SE reduced to 0W.

In each situation from the list above, the system performed correctly, meeting the success criteria for each.

The next step was to evaluate the Collins-IDS's ability to discriminate between dry, App C, and App O icing conditions in the IWT. Like in the Development IWT Tests, the system was subjected to a series of icing conditions. For the Integration IWT Test, 22 App C icing conditions and 6 SLD conditions were tested. The results of the icing tests are summarized in Table 4.

During the integration IWT testing, the Collins-IDS was able to detect icing from dry air conditions 100% of the time, demonstrating that the complete system functions well as an ice detector. The Collins-IDS was able to correctly categorize 73% of the App C conditions and 83% of the SLD conditions that it encountered in the wind tunnel. This equates to 75% of the overall icing conditions encountered throughout the integration testing.

The relative reduction in discrimination performance during the Integration IWT Testing is due to a difference in control scheme. During the development testing, the SE power was set manually before each run, resulting in less variability in the sensor outputs and a clearer discrimination signal. However, for the Integration IWT Testing, the goal was to replicate the on-aircraft setup, meaning that setting SE power manually before each run was not a possibility. Instead, a control logic was developed for the Collins-IDS which enabled it to automatically modulate SE power based on changing atmospheric and icing conditions. As a result, the sensor response times differed from the development testing and there was not enough data collected during the integration test to retune the detector.

TABLE 4 Integration IWT Icing Condition Results Summary

Condition	Percentage
Icing Conditions Detected From Dry Air Conditions	100%
Appendix C Conditions Categorized Correctly	73%
SLD Conditions Categorized Correctly	83%

The Integration IWT setup did not replicate the on-aircraft setup exactly, some examples of the discrepancies are listed here:

- Although the power input to the SE was being controlled by the CU and PIU, it used a different power supply than the one that will be used on the aircraft.
- Environmental information, such as air temperature and aircraft speed were not fed to the CU using a flight test computer. Instead IWT temperature was measured using an RTD and IWT airspeed was entered manually for each test condition.

The final stage of the integration testing process was to integrate the system onto the aircraft prior to the start of the flight test campaign. As previously stated, Collins elected to partner with Embraer for the natural icing flight test in North America. For that reason, all three components of the Collins-IDS were sent to Embraer's GPX Facility in Gavião Peixoto, Sao Paulo, Brazil. Embraer's flight test and integration team installed the components onto their Phenom 300 aircraft and connected the system to the aircraft's power supply and flight test computer. In January 2022, engineers from the Collins-IDS design team traveled to GPX for on-ground, on-aircraft integration testing. The Collins and Embraer teams jointly completed the following tests:

- WoW and OAT safety protocol testing, this time with the flight test computer sending signals to the CU.
- Tested the Collins-IDS ability to stabilize the SE's internal temperature at the desired value.
- Tested the communications between the Collins-IDS CU and the Phenom 300's flight test computer.

Following only minor changes to the control software, the on-ground, on-aircraft integration tests were completed successfully. After the Collins team's departure, Embraer completed an EMI test and a shakedown flight test. The completion of these tests brought an end to the preparatory integration testing and enabled Collins and Embraer to begin the flight test campaign with confidence in the performance and safety of the Collins-IDS.

Natural Icing Flight Test Campaign

The SENS4ICE project culminated in a natural icing flight test campaign which the Collins-IDS and several other sensor developers participated in. The base of operations for the flight test campaign was the St. Louis Regional Airport in East Alton, IL, a city near St. Louis, MO. The first flight test began on February 22, 2023, and the final flight test finished on March 10, 2023. The campaign was 25.7FH long which was spread out over 15 individual flights, most of which were

TABLE 5 Natural Icing Flight Test Summary

Flight No.	Date DD/MM/YY	Departure Airport	Arrival Airport	Flight Duration
1	22/02/23	St Louis Regional	St Louis Regional	0:39
2	23/02/23	St Louis Regional	Chicago O'Hare International	2:45
3	23/02/23	Chicago O'Hare International	St Louis Regional	1:12
4	25/02/23	St Louis Regional	Eugene F Kranz Toledo Express	2:03
5	25/02/23	Eugene F Kranz Toledo Express	St Louis Regional	1:37
6	01/03/23	St Louis Regional	Des Moines International	2:45
7	01/03/23	Des Moines International	St Louis Regional	2:12
8	06/03/23	St Louis Regional	South Bend International	1:07
9	08/03/23	St Louis Regional	Quad Cities International	2:21
10	08/03/23	Quad Cities International	St Louis Regional	0:40
11	09/03/23	St Louis Regional	St Louis Regional	1:23
12	10/03/23	St Louis Regional	Terre Haute International	2:15
13	10/03/23	Terre Haute International	St Louis Regional	1:08

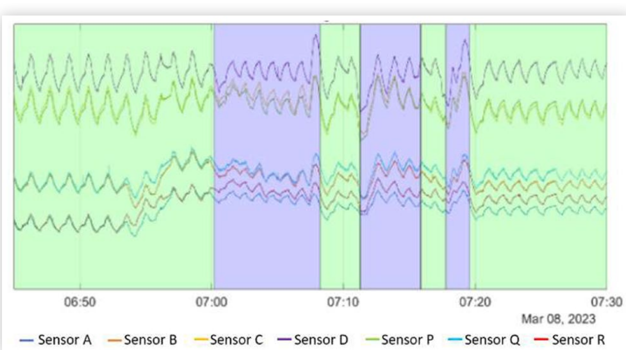
concentrated in the Great Lakes region of the United States. The Collins-IDS operated during the thirteen flights that were conducive for App O icing. These thirteen flights are summarized in Table 5.

The Collins IDS had 40 icing encounters during operation, but it is currently unknown whether the encounters were in App C or App O icing conditions. The raw flight test data did not include any information about when an icing encounter started or what type of condition was encountered. For this reason, there is no way to evaluate the Collins-IDS's ability to discriminate between App C and App O icing conditions currently. Similarly, at this time there is no official indication as to when the icing encounter began. Therefore, the time to detect either variety of icing from dry air also cannot be evaluated. This is addressed in more detail in the Conclusions and Future Work section.

While the ability to discriminate between App C and App O icing conditions cannot currently be evaluated, its ability to detect icing conditions from dry has been clearly demonstrated from the initial results. A visualization of the Collins-IDS's detection capability can be found in Figure 12.

In Figure 12, the purple shaded area indicates that the Collins-IDS has detected an icing condition and the green shaded area indicates that the sensor is operating in a dry air condition. Since it is not yet known when ice was officially encountered or when an ice encounter began, statistics regarding the Collin-IDS's ability to detect icing conditions from dry air cannot be calculated at this time. This is addressed in more detail in the Conclusions and Future Work section.

FIGURE 12 Collins-IDS Natural Icing Flight Test Example Ice Detection



Conclusions and Future Work

The Collins Ice Differentiator System has completed 180 hours of development IWT testing, 40 hours of system integration IWT testing, and 28.8 hours of flight testing in the system's various iterations. During that time the Collins-IDS has proven to be robust, never experiencing a significant system or component failure. In addition to its robustness, the Collins-IDS has demonstrated its ability as a capable ice detector. During the development and integration IWT tests, the system detected ice 100% of the time. More importantly the initial results of the natural icing flight test data indicate that the system was able to detect ice successfully during icing encounters on-aircraft. In the IWT the Collins-IDS has proven to be a capable ice differentiator as well. The system was able to correctly categorize App C, App O, and SLD icing conditions 100% of the time in both the Collins and NRC tunnels during the development IWT tests. In the Integration IWT Test, the Collins-IDS was able to correctly categorize 73% of the App C conditions encountered and 83% of the SLD conditions encountered during the test.

Although the initial results look promising, it is currently not possible to fully evaluate the Collins-IDS's performance during the natural icing flight test. This is because the raw flight test data is missing some critical information, specifically when ice was encounter, when that icing encounter began and what type of ice was encountered (i.e., App C or App O). Fortunately, the raw flight test data is being analyzed and refined by members of the German Aerospace Center (DLR) who are also participating in the SENS4ICE project. This refined data will contain flags to indicate when an ice encounter has started and whether that ice encounter is App C or App O. This will allow the evaluation of the Collins-IDS's performance during the flight test to be completed. It will also ensure that all the SENS4ICE partners are evaluating their own sensors using a common definition of which icing encounters were App C and which were App O.

The refined flight test data is expected to be available to the SENS4ICE partners by the middle of May 2023. With this timeline, the analysis of the refined flight test data will be completed and ready to present at the SAE International Conference on Icing of Aircraft, Engines, and Structures in June 2023.

References

1. SENS4ICE, "SENS4ICE: Context and Challenge," accessed March 27, 2023, https://www.sens4ice-project.eu/context-and-challenge.
2. SENS4ICE, "SENS4ICE: Objectives," accessed March 27, 2023, https://www.sens4ice-project.eu/objectives.
3. SENS4ICE, "SENS4ICE: Partners," accessed March 27, 2023, https://www.sens4ice-project.eu/partners.
4. Federal Aviation Administration, "14 CFR Part 25 - Airworthiness Standards: Transport Category Airplanes," Rev. January 2023.
5. Government of Canada, "Altitude Icing Wind Tunnel Research Facility," last modified January 12, 2022, https://nrc.canada.ca/en/research-development/nrc-facilities/altitude-icing-wind-tunnel-research-facility.
6. Collins Aerospace, "Icing Wind Tunnel," accessed April 30, 2023, https://www.goodrichdeicing.com/services/icing-wind-tunnel/.
7. Ridouane, E.H., "SENS4ICE Icing Wind Tunnel Capabilities and Test Procedures," in *PowerPoint presented at SENS4ICE 1st Project Symposium*, Virtual, October 22, 2020, https://www.sens4ice-project.eu/sites/sens4ice/files/media/2020-10/SENS4ICE_SAE_Symposium_Icing%20Wind%20Tunnel%20Capabilities%20and%20Test%20Procedures_20201022.pdf.
8. EUROCAE - European Organization for Civil Aviation Equipment, "EUROCAE ED-103B - Minimum Operational Performance Specifications for Inflight Icing Detection Systems," Rev. April 2022.

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Definitions/Abbreviations

ACNT - Advanced Carbon Nanotube
App. C - Appendix C to 14 CFR Part 25
AOA - angle of attack
AOS - angle of sideslip
App. O - Appendix O to 14 CFR Part 25
CFD - computational fluid dynamics
CMI - continuous maximum icing conditions
Collins-IDS - Collins Ice Differentiator System
CU - Collins Ice Differentiator System Control Unit
DLR - German Aerospace Center
EMI - electromagnetic interference
FH - flight hours
IMI - intermittent maximum icing conditions
IPS - ice protection system
IWT - icing wind tunnel
LWC - liquid water content
MVD - median volume diameter
NRC - National Research Council Canada
OAT - outside air temperature
PIU - Collins Ice Differentiator System Power Interface Unit
RTD - resistance temperature detector
SE - Collins Ice Differentiator System Sensor Element
SAT - static air temperature
SLD - supercooled large drop icing conditions
TAS - true airspeed
TS - time stamp
WoW - weight on wheels

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