# AIAA 2003–0023

# ICING SCENARIOS WITH THE ICING ENCOUNTER FLIGHT SIMULATOR

Glen A. Dimock, Robert W. Deters, and Michael S. Selig
*Department of Aeronautical and Astronautical Engineering*
*University of Illinois at Urbana–Champaign*
*Urbana, Illinois 61801*

## 41st AIAA Aerospace Sciences Meeting and Exhibit
## January 6–9, 2003/Reno, NV

# Icing Scenarios with the Icing Encounter Flight Simulator

Glen A. Dimock,* Robert W. Deters,† and Michael S. Selig‡
*Department of Aeronautical and Astronautical Engineering*
*University of Illinois at Urbana–Champaign*
*Urbana, Illinois 61801*

**As part of the Smart Icing System (SIS) project at the University of Illinois at Urbana–Champaign, the Icing Encounter Flight Simulator (IEFS) integrates various SIS components in a simulated aircraft icing environment. The IEFS combines a customized version of FlightGear, an open-source flight simulator, with a suite of SIS support software using multiple desktop PCs connected through a local area network. The resulting simulation integrates most SIS concepts for testing and demonstration purposes. To this end, two fictional but historically-motivated icing scenarios are used to illustrate the various SIS interventions capable of preventing icing events. Specifically, a tailplane stall event during a steep descent and a roll upset event during an emergency approach are considered. During each scenario, multiple SIS intervention points are examined.**

## Introduction

Ice formation on an aircraft in flight is a safety hazard in that it greatly affects the performance and controllability of the aircraft. In order to investigate this hazard, the Smart Icing System (SIS)[1,2] project was started and funded principally by NASA Glenn Research Center. The goal of the project is to develop new technology that will sense ice accretion, inform the pilot, and if necessary perform the required measures to ensure the safety of the aircraft. An Icing Encounter Flight Simulator (IEFS) was developed in order to integrate and test the new technologies developed by the aerodynamics, controls, and human factors groups of the SIS project. To demonstrate these components of the SIS project, two fictional but historically-motivated icing scenarios were created. The first scenario is a tailplane stall of an aircraft in a steep descent, and the second is a roll upset of an aircraft on an emergency approach. The scenarios consider a 40-passenger aircraft. Flight dynamics are modeled after the twin turboprop DHC-6 Twin Otter, but it should be noted that this approach applies to a wide array of aircraft. The Twin Otter flight model was used due to the extensive body of icing data available for this aircraft and because NASA typically uses it in icing research.

The SIS components developed during this project include an icing model,[3] a neural-network-based icing characterization algorithm,[4] an envelope protection system,[5] an ice protection system, and a glass cockpit incorporating new icing-specific instrument concepts aimed at increasing flight safety.[6] These components along with a reconfigurable aircraft model[7,8] and an autopilot[9] were implemented in software and integrated into an existing flight simulator to create the IEFS. Additional literature specific to each of these models and components can be found in the aforementioned references.

The simulator chosen to be modified is the FlightGear flight simulator (FGFS),[10] an open-source multiplatform simulator written in C/C++ that adheres to the GNU General Public License (GPL). For a realistic out-the-window display, the Microsoft Flight Simulator was used. Computationally intensive processes, such as the IEFS flight dynamics, glass cockpit, and out-the-window display, were distributed over several computers to reduce the workload on a single computer and to ensure realtime simulation.

In this paper, a brief discussion on the components of the Icing Encounter Flight Simulator is first presented. Two fictional but historically-motivated icing encounter scenarios are then presented. Each proceeds as it would for a conventional, non-SIS aircraft, but possible SIS intervention points are listed along the way.

## Icing Encounter Flight Simulator

The Icing Encounter Flight Simulator was developed by integrating a reconfigurable aircraft model, autopilot, and SIS components into an existing flight simulator. SIS components that were created by the SIS research groups include an icing model, the Icing Management System (IMS), and an IMS-enhanced glass cockpit. For a better understanding of the icing scenarios, a brief discussion of the IEFS features is pre-

---

*Graduate Research Assistant, Student Member AIAA. dimock@uiuc.edu

†Graduate Research Assistant, Student Member AIAA. rdeters@uiuc.edu

‡Associate Professor, Senior Member AIAA. m-selig@uiuc.edu.

sented. For detailed information on these features and on the code organization of the flight simulator, refer to Sehgal et al.[7] and Deters et al.[8]

### Reconfigurable Aircraft Model

In order to simulate a multitude of aircraft models, a reconfigurable aircraft model was added to the LaRCsim[11] flight dynamics model (FDM) already contained in FlightGear. Using a keyword-based input file, the reconfigurable aircraft model defines an aircraft by just specifying the geometric, mass, engine, gear, aerodynamic, and icing parameters. From these parameters, the forces and moments acting on the aircraft are calculated and sent to the LaRCsim FDM to determine the next aircraft state. The aerodynamics of the Twin Otter used in the scenarios is based on a series of three-dimensional lookup tables defined in the body-axis system.[12]

### Icing Model

In order to create an icing scenario, an icing model had to be added. The effect of icing on the Twin Otter longitudinal aerodynamics was modeled by modifying the aerodynamic coefficients with an icing severity factor $\eta_{\text{ice}}$ and an icing scaling factor $k'_{C_{(A)}}$. The resulting iced coefficient is determined by

$$C_{(A)_{\text{iced}}} = (1 + \eta_{\text{ice}} k'_{C_{(A)}}) C_{(A)}$$

where $C_{(A)}$ is any longitudinal aerodynamic coefficient.[3] In the current model, $k'_{C_{(D)}}$ and $k'_{C_{(L)}}$ are functions of the angle of attack, and $k'_{C_{(m)}}$ is a function of the angle of attack and the elevator deflection. Instead of using the above icing equation for lateral-directional aerodynamics, the iced rolling moment coefficient $C_{(l)_{\text{iced}}}$ and the iced yawing moment coefficient $C_{(n)_{\text{iced}}}$ are a function of the asymmetric lift and drag, respectively, produced by different icing on the left and right sides of the wing. In conjunction with the icing model, a weather model was created to provide the liquid water content $LWC$, the median volumetric diameter $MVD$, and the air temperature. The weather model then passes these atmospheric values to an ice accretion function that, with the airspeed and angle of attack, calculates $\eta_{\text{ice}}$.

### Icing Management System

One of the main purposes of the historically-motivated icing scenarios is to demonstrate the effectiveness of the Icing Management System (IMS). This system is designed to sense ice accretion, characterize the effect of the ice accretion on the aircraft, notify the pilot of the icing conditions, and if necessary protect the aircraft either through the ice protection system or through recommended pilot procedures. There are three main components of the IMS: a neural-network-based icing characterization routine, an envelope protection system (EPS), and an ice protection system (IPS). The icing characterization routine estimates $\eta_{\text{ice}}$ by comparing current flight dynamic parameters with expected values.[4] It was integrated into the simulator,[7] but the algorithm proved too computationally intensive to estimate $\eta_{\text{ice}}$ in realtime, so it is currently not being used in the simulator. For the IMS routines that require $\eta_{\text{ice}}$, the value calculated from the weather model is used.

The envelope protection system is designed to keep the aircraft in a safe flight regime by limiting the angle of attack, pitch angle, roll angle, airspeed, throttle setting, and flap deflection. Icing effects on the performance of the aircraft vary with the icing severity, so limits must be calculated in realtime.[5] The current version of the EPS calculates the maximum angle of attack by estimating the stall angle of attack based on the current $\eta_{\text{ice}}$, and it calculates the maximum roll angle from the current lift and drag. From the maximum angle of attack, the maximum pitch angle, minimum throttle setting, and minimum airspeed are determined. If any of these limits are violated, the EPS provides recommended pilot procedures, such as pitch down and throttle up, to correct it. Alerts are given both visually, through the IMS-enhanced glass cockpit, and aurally.

The current ice protection system is modeled by de-ice boots for the left wing, right wing, and horizontal tail. This system allows the pilot to manually control the de-ice boots or have the system controlled by the IMS. When the IPS is in automatic mode, the IMS determines when the de-ice boots should be activated from the sensed ice accretion. Based on the ice accretion rate, the IMS also determines the cycle time of the de-ice boots.

### IMS-enhanced Glass Cockpit

Information about the icing conditions and the status of the EPS and IPS is displayed on the IMS-enhanced glass cockpit shown in Fig. 1. The goal is that this information should be presented in a manner that will aid in the pilot's decision making process.[2,6] Typical information that is displayed by the glass cockpit is the location and severity of the icing, the status of the IPS, the envelope limits from the EPS, and the recommended pilot procedures from the EPS. The design of the IMS features is based on research done by the human factors group on pilots' information requirements during icing conditions.[13] Examples of the how the IMS features in the glass cockpit display information are presented in the scenarios section, but for a more complete discussion refer to Sarter et al.[6]

### Autopilot

Autopilot functions left on during icing conditions can mask the effects of icing on the aircraft flight characteristics. To simulate such an event, an autopilot was created for the Twin Otter flight model.[9] The current autopilots implemented in the simulator are a

**Fig. 1 Glass cockpit display and IMS interface.**

pitch attitude hold and an altitude hold. For both autopilots, elevator deflections are the means by which the desire pitch angle or altitude is achieved.

### Distributed Simulation

As discussed in Deters et al.,[8] the IEFS contains several computationally intensive modules: the flight dynamics model, a set of SIS support functions, an out-the-window display, the IMS-enhanced glass cockpit display, and the neural-network-based icing characterization. As it is not yet possible to run all of these modules on a single PC in realtime, a distributed simulation environment was developed. Each module may be run on a dedicated or shared desktop PC, communicating with other modules over a local area network at 120 Hz using a specialized IEFS host application. It should be noted that the icing characterization module still cannot be run in realtime at its minimum speed of 20 Hz using the fastest hardware available—a dedicated 2 GHz Pentium processor. For this reason, the characterization module[4] is not included in the current IEFS implementation. Instead, the computed value of $\eta_{\text{ice}}$ from the weather model is fed directly to the SIS components.

### Simulator Batch Mode

To effectively demonstrate the simulator, a simulator batch mode was added. To use this mode, the user only needs to provide the initial conditions of the aircraft in the keyword-based input file and also time histories of the control inputs. During batch mode, the simulator uses these time histories instead of the inputs provided by the pilot.

## Icing Encounter Scenarios

The Icing Encounter Flight Simulator is designed to integrate all SIS component functions and demonstrate their effectiveness in a simulated icing environment. For this purpose, two scenarios have been developed to simulate potentially dangerous icing encounters in commuter aircraft. The majority of serious in-flight icing encounters may be categorized as either roll-upset or tailplane stall events,[14–16] each of which is represented by one of the scenarios. Although fictional, these icing encounter scenarios include elements of real-world incidents and accidents, showcasing the potential of the SIS to prevent icing-related accidents through various interventions. Real-world accidents typically result from a chain of unlikely and unfortunate events, each a necessary component in the final result.[17] The fictional scenarios are built on this premise, allowing the SIS to eliminate the icing threat by intervening at one of many possible points in the event chain.

### Historical Factors

A review of U.S. in-flight icing events over the past 20 years has revealed an extensive list of contributing factors. Specific events and individual factors are not listed here, but a list of common factors includes, but is not limited to:

- excessive loitering in large-droplet icing conditions
- ice accumulation behind de-ice boots
- aircraft inadequately equipped for large-droplet conditions
- pilots unaware of icing severity due to inadequate sensors and/or lack of pertinent weather information
- wing and/or tail at high angle of attack
- autopilot engaged during known icing conditions
- inoperative de-ice or anti-ice equipment
- atmospheric temperature inversion during approach phase
- use of flaps

As mentioned above, any one of these factors is normally insufficient to cause an icing event. Instead, three or more factors typically combine to produce a series of failures in the three lines of conventional icing defense: avoidance, IPS, and the pilot.[1,17] The tailplane stall and roll upset scenarios presented in this paper cast the SIS as an extra layer of protection in icing defense, reducing the risk of multiple factors combining to produce an event. Figure 2 conceptually illustrates this extra line of defense. As an event chain passes through weaknesses in the three conventional layers of defense, it is stopped by the new SIS layer. Each scenario refers to a conventional aircraft without SIS, but possible SIS intervention points are given throughout. Each hypothetical intervention is understood to be capable of breaking the icing event chain.

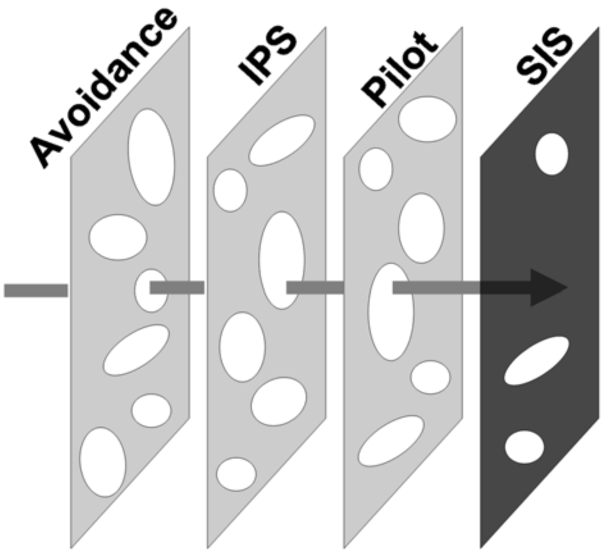

**Fig. 2 An icing event chain passing through the conventional layers of defense and being stopped by the SIS layer (adapted from Maurino et al.[17]).**

### Tailplane Stall

The first scenario represents a typical tailplane stall event, wherein ice accumulation on the horizontal tail causes a rapid, uncommanded down-elevator deflection and corresponding pitch-down moment. The onset of tailplane stall often occurs immediately following a flap deflection, which causes increased downwash on the horizontal tail and increases the likelihood of stall. In the fictional tailplane stall scenario, we consider a 40-passenger commuter turboprop approaching a mountainous airport in icing conditions. The aircraft is operating near the edge of its certified flight envelope with a full passenger load and forward CG. To add to the pilot workload, the scenario involves a runway change during the approach phase, as well as an unidentified hydraulic problem. Furthermore, the weather reports over the destination provide an incomplete picture of the quality and location of icing conditions.

The tailplane stall event scenario sequence is illustrated in Fig. 3. The initial descent (1) and approach (2) proceed normally until a runway change is issued because of changing wind conditions (3). At this point, the crew begin maneuvering for a new approach and become preoccupied with the tasks associated with this change. Around the same time, the aircraft enters icing conditions and begins accreting glaze ice (4). Distracted by the new approach, the crew are not immediately aware of the developing icing situation.

- **SIS intervention: Pilot notification.** As ice accretion begins to affect the aircraft dynamics, the icing characterization system would detect the change and alert the pilots to possible airframe icing through visual and auditory cues. Visually, an ambient strip would flash and surround the trouble area on the glass cockpit display, drawing the pilots' attention there. In this case, a small icon of an airplane with ice would be displayed. An auditory alert ("Tail icing likely") would also be played to provide additional emphasis. Figure 4 illustrates the resulting glass cockpit notification.

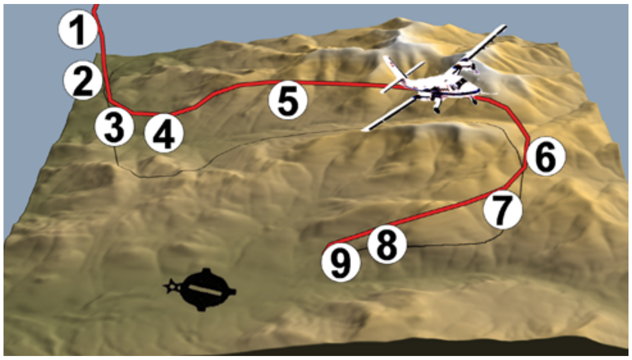

**Fig. 3 Tailplane stall event sequence.**

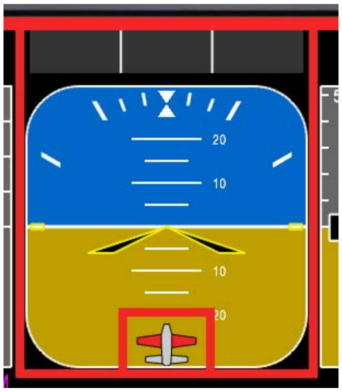

**Fig. 4 Ice accretion notification (wing ice shown). The red ambient strip flashes and surrounds the problem area (in this case a small airplane icon showing ice), while an auditory alert provides additional pilot cues.**

- **SIS intervention: IPS activation.** Upon detecting airframe icing, the SIS would automatically activate conventional Icing Protection System (IPS) devices such as de-ice boots and pitot heat.

The crew, following standard procedure, notice ice buildup on the windshield wipers after several minutes in icing conditions. They immediately activate Level-I IPS, turning on anti-ice devices and cycling de-ice boots on three-minute intervals (5). Shortly thereafter, the cockpit workload is further increased by the illumination of a master hydraulic warning light. No handling problems are observed, and the crew continue to fly the new approach while working the hydraulic problem. Shortly before turning final, the tail de-ice boot fails to deploy (6). A small warning light is displayed on the panel, but the crew's attention is dominated by the hydraulic situation and the approach.

- **SIS intervention: Pilot notification.** The SIS glass cockpit employs an attention-grabbing ambient strip to alert pilots to failures and critical warnings. Such a feature would be used to alert the scenario crew to the de-ice boot failure, prompting a more conservative approach angle. Figure 5 illustrates an ambient strip notification for a failed de-ice boot.

Unaware of the boot failure, the crew intercept the localizer (7) and begin the unusually-steep final approach for this mountain runway. Several minutes later, full flaps are deployed (8), followed shortly thereafter by a loss of longitudinal control due to tailplane stall (9).

- **SIS intervention: Envelope protection.** An SIS envelope protection system would alert the pilots to the initial unsafe descent attitude, as well as the maximum safe flap extension dictated by the tailplane icing. Either intervention would prevent the high tail force that leads to the tailplane stall. Figures 6 and 7 show envelope-protection warning displays corresponding to unsafe pitch and flap extensions, respectively.

### Roll Upset

The second icing encounter scenario involves roll upset, where ice accumulation on the main wings causes asymmetrical stall during high angle-of-attack flight. This scenario occurs at night in icing conditions when a 40-passenger commuter aircraft returns to the departure field following an engine failure. As in the first scenario, the crew are provided with an inadequate icing report prior to departure, and a high degree of ATC vectoring adds to the cockpit workload. In addition, the aircraft's ultrasonic icing probe is inoperative, unbeknownst to the crew.

The roll upset scenario event sequence is illustrated in Fig. 8. As the scenario unfolds, the aircraft departs 30 minutes late (1) and is quickly bombarded with ATC requests during an especially busy night in a major class-B airspace (2). During climbout, the crew observes abnormal temperature and oil pressure readings on the right engine (3) and immediately focuses attention on this issue. Anti-ice measures are activated as they climb through known icing conditions, but the inoperative icing probe fails to detect significant rime ice buildup on the main wings (4). The crew, distracted by the engine issue and ATC requests, does not place high priority on monitoring the icing status, instead relying upon the failed probe.

- **SIS intervention: Pilot notification.** As ice accretion begins to affect the aircraft dynamics, the icing characterization system would detect the change and alert the pilots to possible airframe icing through visual and auditory cues. Visually, an ambient strip would flash and surround the trouble area on the glass cockpit display, drawing the pilots' attention there. In this case, a small icon of an airplane with ice would be displayed. An auditory alert would also be played to provide additional emphasis. Figure 4 illustrates the resulting glass cockpit notification.

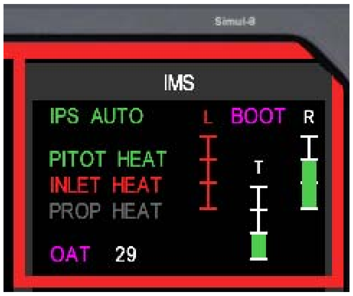

**Fig. 5** **Ambient strip warning for failed de-ice boot.**

**Fig. 6** **Envelope protection warning (pitch down).**

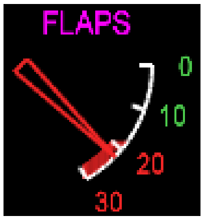

**Fig. 7** **Envelope protection warning (raise flaps).**

- **SIS intervention: IPS activation.** Upon detecting airframe icing, the SIS would automatically activate de-ice boots and set the IPS level.

As the engine problem worsens, the crew experience handling difficulties and elect to return to the point of origin (5). Still unaware of the growing ice accretion on the main wings, they attribute the handling problems to a loss of hydraulic pressure related to the engine problem. The right engine soon fails altogether, prompting the crew to declare an emergency and request priority vectoring to the airfield (6). As

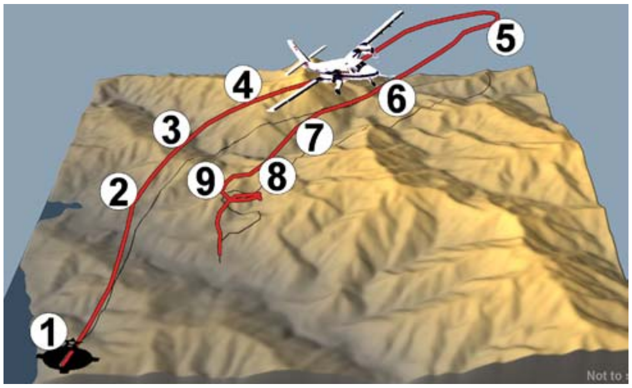

**Fig. 8 Roll upset event sequence.**

the aircraft approaches the final approach, flaps are deployed, and the airspeed is reduced (7). Soon after, the crew notice clear ice buildup on a nose-mounted probe, prompting them to activate the de-ice boots (8). Unfortunately, some aft wing ice remains following the late deployment of leading-edge boots, leading to severe flow problems on the main wings. Loss of lateral control occurs almost immediately, causing two roll excursion events (9).

- **SIS intervention: Envelope protection.** Sensing the diminished handling qualities caused by partial wing ice following the late activation of de-ice boots, the envelope protection system would issue angle of attack and pitch attitude alerts, discouraging the crew from placing the aircraft in an unsafe attitude during approach. Figure 9 shows an angle of attack gauge indicating an angle near the imposed limit.

## Summary

The Icing Encounter Flight Simulator integrates a customized version of FlightGear with several SIS functions. The new components include an icing aerodynamics model, an icing weather model, the Ice Management System, an IMS-enhanced glass cockpit display, and a separate out-the-window display. Components of the IMS include the icing characterization neural network to detect ice accretion, the envelope protection system to keep the aircraft in a safe flight envelope, the ice protection system to activate de-ice boots and other equipment, and a glass cockpit to display icing information to the pilot. The effectiveness of the IMS is evaluated using two fictional but historically-motivated icing scenarios: tailplane stall and roll upset. In both of the scenarios, distractions and undetected ice accretion lead to the eventual loss of control of a conventional, SIS-less aircraft. During each scenario, numerous SIS intervention points are suggested. Any intervention is understood to break the chain of events leading to a catastrophic icing event.

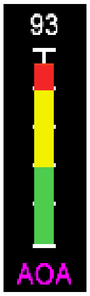

**Fig. 9 Envelope protection gauge (angle of attack).**

## Acknowledgments

This research has been sponsored by NASA Glenn Research Center, and its support is gratefully acknowledged. The authors wish to acknowledge Bipin Sehgal and Jeff Scott (both former UIUC AAE graduate students) for their valuable contributions to the IEFS code. Appreciation and thanks goes to Brian Fuesz for his initial work on the glass cockpit. Also, the FlightGear development group is thanked for all their help, support, and suggestions.

## References

[1] Bragg, M.B., Perkins, W.R., Sarter, N.B., Basar, T., Voulgaris, P.G., Gurbacki, H.M., Melody, J.W., and McCray, S.A., "An Interdisciplinary Approach to Inflight Aircraft Icing Safety," AIAA Paper 98-0095, Reno, NV, Jan. 1998.

[2] Bragg, M.B., Perkins, W.R., Basar, B., Voulgaris, P.G., Selig, M.S., Melody, J.W., and Sarter N.B., "Smart Icing Systems for Aircraft Icing Safety," AIAA Paper 2002-0813, Reno, NV, Jan. 2002.

[3] Bragg, M.B., Hutchison, T., Merret, J., Oltman, R., and Pokhariyal, D., "Effects of Ice Accretion on Aircraft Flight Dynamics," AIAA Paper 2000-0360, Reno, NV, Jan. 2000.

[4] Melody, J.W., Pokhariyal, D., Merret, J., Basar, T., Perkins, W.R., and Bragg, M.B., "Sensor Integration for Inflight Icing Characterization using Neural Networks," AIAA Paper 2001-0542, Reno, NV, Jan. 2001.

[5] Merret, J., Hossain, K., and Bragg, M.B., "Envelope Protection and Atmospheric Disturbances in Icing Encounters," AIAA Paper 2002-0814, Reno, NV, Jan. 2002.

[6] Sarter, N.B. and Schroeder, B.O., "Supporting Decision-Making and Action Selection Under Time Pressure and Uncertainty: The Case of Inflight Icing," *Human Factors*, in press 2001.

[7] Sehgal, B., Deters, R.W., Selig, M.S., "Icing Encounter Flight Simulator," AIAA Paper 2002-0817, Reno, NV, Jan. 2002.

[8] Deters, R.W., Dimock, G.A., Selig, M.S., "Icing Encounter Flight Simulator with an Integrated Smart Icing System," AIAA Paper 2002-4599, Monterey, CA, Aug. 2002.

[9] Sharma, V. and Voulgaris, P., "Effects of Ice Accretion on Aircraft Autopilot Stability and Performance," AIAA Paper 2002-0815, Reno, NV, Jan. 2002.

[10] FlightGear website, http://www.flightgear.org, 1997–present.

[11] Jackson, B.E., "Manual for a Workstation-Based Generic Flight Simulation Program (LaRCsim) Version 1.4," NASA TM 110164, April 1995.

[12] Ratvasky T., Private Communications, 2001–2002.

[13] McGuirl, J.M. and Sarter, N.B., "Inflight Icing: A Survey of regional Carrier Pilots," Unpublished CSEL Technical Report prepared for NASA Glenn Research Center, Columbus, OH, The Ohio State University, 2001.

[14] National Transportations Safety Board, “Aircraft Accident Report: Unstabilized Approach and Loss of Control, NPA, Inc. d.b.a. United Express Flight 2415, British Aerospace BA-3101, N41OUE, Tri-Cities Airport, Pasco, Washington, Dec. 26, 1989,” PB91-910406, NTSB/AAR-91/06, Washington,D.C.: National Transportation Safety Board, 1990, 62 pgs.

[15] National Transportations Safety Board, “Aircraft Accident Report: In-Flight Icing Encounter and Loss of Control, Simmons Airlines, d.b.a. American Eagle Flight 4184, Avions de Transport Regional (ATR), Model 72-212, N401AM, Roselawn, Indiana, Oct. 31, 1994, Volume 1: Safety Board Report,” PB96-910401, NTSB/AAR-96/01, DCA95MA001, Washington, D.C.: National Transportation Safety Board, 1990, 322 pgs.

[16] National Transportations Safety Board, “Aircraft Accident Report: In-Flight Icing Encounter and Loss of Control, Simmons Airlines, d.b.a. American Eagle Flight 4184, Avions de Transport Regional (ATR), Model 72-212, N401AM, Roselawn, Indiana, Oct. 31, 1994, Volume 2: Response of Bureau Enquetes-Accidents to Safety Board’s Draft Report,” PB96-910402, NTSB/AAR-96/02, DCA95MA001, Washington, D.C.: National Transportation Safety Board, 1990, 274 pgs.

[17] Maurino, D.E., Reason, J., Johnston, N., and Lee, R.L., *Beyond Aviation Human Factors*, Avebury Aviation, Hants, UK, 1995.