NASA/TM—2011-216951 AIAA–2010–7987

Piloted Simulation to Evaluate the Utility of a Real Time Envelope Protection System for Mitigating In-Flight Icing Hazards

Richard J. Ranaudo, Borja Martos, and Bill W. Norton
University of Tennessee Space Institute, Tullahoma, Tennessee

David R. Gingras and Billy P. Barnhart
Bihrle Applied Research, Inc., Hampton, Virginia

Thomas P. Ratvasky
Glenn Research Center, Cleveland, Ohio

Eugene Morelli
Langley Research Center, Hampton, Virginia

October 2011

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Prepared for the
Atmospheric and Space Environments Conference
sponsored by the American Institute of Aeronautics and Astronautics
Toronto, Ontario, Canada, August 2–5, 2010

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

October 2011

Acknowledgments

The development and testing of ICEPro was funded under a federal grant, which was sponsored three-year cooperative research effort with NASA under the NASA Research Announcement NNH06ZEA001N, Appendix B, of the Aviation Safety Program. The objectives of the NRA were defined under the Integrated Vehicle Health Management Project, topic IVHM 3.1, Environmental Hazards, which are caused by the "Effects of Icing on Aircraft State". The successful development, testing, and evaluation of ICEPro would not have been possible without the contributions of key individuals and organizations, which made up the research team. The author wishes to recognize Mr. Thomas Ratvasky, NASA Glenn Research Center, and Dr. Eugene Morelli, NASA Langley Research Center for their guidance and support throughout this project. Mr. Ratvasky's experience and technical expertise with icing related problems were essential during the development and testing phases of ICEPro. Dr. Eugene Morelli provided critically important technical assistance during the integration and application of the Real Time Parameter Identification algorithm, which he and others from his organization had developed over a period of several years (see Refs. 12, 13, 14, and 16). In addition, Mr. David Gingras and Mr. Billy Barnhart, Bihrle Applied Research, who are experts in the field modeling and simulation, successfully designed, developed, integrated and tested the ICEPro system in NASA's ICEFTD. Mr. Barnhart was directly involved during the test and evaluation phase of ICEPro, and along with Mr. Gingras, provided important simulation functionality, and solved numerous technical and integration problems necessary for a successful evaluation. Mr. Borja Martos, UTSI worked diligently with BAR to identify and address issues with ICEPro during its development, and was an invaluable test conductor during the pilot evaluation at ERAU. Mr. Billy Norton, an engineering management doctoral candidate at UTSI developed and conducted the statistical data handling methods, which were essential to the analysis of pilot performance metrics. Lastly, the authors wish to express their sincere appreciation to the faculty and staff of the Embry Riddle Aeronautical University for their support of this testing at their Eagle Works facility in Daytona Beach, Florida.

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University of Tennessee Space Institute
Tullahoma, Tennessee 37388–9700

David R. Gingras and Billy P. Barnhart
Bihrle Applied Research, Inc.
Hampton, Virginia 23666

Thomas P. Ratvasky
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Eugene Morelli
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23681–2199

Abstract

The utility of the Icing Contamination Envelope Protection (ICEPro) system for mitigating a potentially hazardous icing condition was evaluated by 29 pilots using the NASA Ice Contamination Effects Flight Training Device (ICEFTD). ICEPro provides real time envelope protection cues and alerting messages on pilot displays. The pilots participating in this test were divided into two groups; a control group using baseline displays without ICEPro, and an experimental group using ICEPro driven display cueing. Each group flew identical precision approach and missed approach procedures with a simulated failure case icing condition. Pilot performance, workload, and survey questionnaires were collected for both groups of pilots. Results showed that real time assessment cues were effective in reducing the number of potentially hazardous upset events and in lessening exposure to loss of control following an incipient upset condition. Pilot workload with the added ICEPro displays was not measurably affected, but pilot opinion surveys showed that real time cueing greatly improved their situation awareness of a hazardous aircraft state.

Nomenclature

α	Alternate Hypothesis
AOA	Angle of Attack
D-ICES	Dynamic Inversion Control Evaluation System
ICEFTD	Ice Contamination Effects Flight Training Device
ICEPro	Icing Contamination Envelope Protection System
ISP	Icing Severity Parameter
H_0	Null Hypothesis
PCE	Pilot Coupling Event
RTPID	Real Time Parameter Identification

1.0 Introduction

The University of Tennessee Space Institute (UTSI) in partnership with Bihrle Applied Research (BAR) completed a 3-year cooperative research effort with NASA under NASA Research Announcement (NRA) NNH06ZEA001N, Appendix B, of the Aviation Safety Program. The objectives of the NRA were defined under the Integrated Vehicle Health Management (IVHM) Project, topic IVHM 3.1, Environmental Hazards, which are caused by the "Effects of Icing on Aircraft State". This effort culminated in the development of a real time vehicle state assessment system, which was described by Gingras (Ref. 1) and is referred to as the Icing Contamination Envelope Protection system (ICEPro). The algorithms in ICEPro were initially developed and tested in a desktop simulation environment, and then integrated and further developed in the NASA Ice Contamination Effects Flight Training Device (ICEFTD). The two flight models used in simulation to develop ICEPro for testing and evaluation were based upon the characteristics of the NASA Twin Otter icing research aircraft in a no-ice baseline condition, and those representing a failure of the ice protection system (IPS). The failure case was defined by the ice accretions that would form during a 22.5 min FAR 25 Appendix C icing encounter as calculated by LEWICE version 2.0. Most of the data for the simulator came from testing a 6.5 percent scale Twin Otter model in the Wichita State University 7X10 Low Speed wind tunnel and BAR's Large Amplitude Multi-Purpose (LAMP) rotary balance wind tunnel using scaled ice shapes (Ref. 2). Flight data from aircraft testing with failure case ice shapes was also gathered to refine the sub-scale model data so it would match full scale flight test results (Ref. 3).

After development and testing in a desktop environment, ICEPro was integrated with the NASA ICEFTD (Refs. 4 and 5). Researchers from BAR and UTSI completed final development and integration testing to ensure readiness for the planned pilot evaluations. A final check of test readiness was then performed by having two experienced NASA test pilots complete the evaluation profile, and all required pre-test preparation and training. This included a review of: the test plan, NASA web based icing training, standard operating procedures (SOP) for the Twin Otter, the NASA Task Load Index or TLX workload method (Ref. 6), a tutorial on flying with ICEPro displays (only for the pilot using the experimental displays), and post-test survey questionnaire. One NASA pilot was selected to represent the control group and flew with baseline displays. The other was selected to represent the experimental group and flew with the ICEPro modified displays. Before the test began, each pilot was briefed on the entire test process. The test protocol at the time called for minimal training in aircraft handling with hazardous ice formations, somewhat similar to that which a typical pilot would receive in an aircraft transition course. However, once testing began, it became apparent that the flight task was so difficult that without practice, there was a high probability of a random "crash" regardless of the displays used. It was apparent that a different approach would have to be taken. After assessing the pilot's comments from the debriefings, it was therefore decided to modify the test protocol and train the pilots in both groups to proficiency for executing the hazardous approach task using their respective flight displays. Utility benefits could then be assessed by comparing pilot performance, workload, and opinions between control and experimental groups who were flying the same task with the same training and preparation, but with different flight displays. This adjustment in the test plan was an essential change, and would not have been discovered without this pre-test. The NASA pilots also completed the NASA TLX forms and answered all the survey questions during their respective evaluations. A few small changes in the survey questions were also required to eliminate ambiguity problems. After these adjustments were made to the test plan, pilot-in-the- loop (PIL) evaluations of ICEPro were scheduled at the Embry Riddle Aeronautical University (ERAU), Daytona Beach, Florida.

2.0 Background

Ice formations on aircraft can negatively affect performance, stability and control characteristics, and handling qualities. Accidents that have occurred due to these issues have been documented by the National Transportation Safety Board (NTSB) and the Federal Aviation Administration (FAA) over many years. In a recent study (Ref. 7) of aircraft icing accidents and incidents reported between 1978 and 2002, loss of control events were usually preceded by stall and more likely to occur during approach and landing. This is the busiest phase of flight where historically over 50 percent of all accidents occur, and where human error is responsible for approximately 75 percent of those accidents (Ref. 8). Ice contamination, which accretes on a critical airframe surface such as the wings and tail, due to an Ice Protection System (IPS) failure, encountering an exceedance condition, or operator error can have a detrimental effect on aircraft performance, stability and control, and handling qualities. This situation is further exacerbated by the required changes in airspeed and configuration as the pilot slows and configures during the descent, approach, and landing phases. A lateral upset resulted in the fatal crash of American Eagle 4184 after encountering what appeared to be an exceedance icing condition. The NTSB listed the probable cause of the accident as "…the loss of control, attributed to a sudden and unexpected aileron hinge moment reversal that occurred after a ridge of ice accreted beyond the deice boot and ultimately lead to an upset condition" (Ref. 9). The pilots of this aircraft had no forewarning of the impending upset condition and furthermore, were flying on auto pilot at the time of the upset, which masked the rapid build-up in lateral control force as the flaps were raised while descending in the holding pattern. As the upset occurred, the autopilot disengaged and the aircraft rolled sharply to the right. The pilots then attempted to recover the aircraft, but in so doing entered a secondary stall upset, which caused the aircraft to roll inverted and enter a steep dive and crash. In its Tailplane Icing Program (TIP) NASA employed various artificial ice shapes, which were attached to the horizontal tail plane of a research aircraft (Ref. 10). Numerous test maneuvers were conducted where wing flap settings, engine power, and flight speed were varied. The results showed a considerable decrease in longitudinal stability and elevator control effectiveness as a function of increasing wing flap angle, power setting, and airspeed. In the extreme, a tail stall upset would occur, which resulted in an uncontrollable nose down pitching motion. Airframe ice contamination also increases drag, reducing climb performance and is most evident in propeller driven aircraft. Although not a handling issue per se, it can greatly reduce engine out ceiling (Ref. 11), which in multi-engine aircraft and could ultimately result in controlled flight into terrain or CFIT. This is especially a concern if an engine should fail during a missed approach procedure. In cases such as these, wing flap settings must be reduced and speeds increased to ensure a positive rate of climb while avoiding a stall upset. Unfortunately, pilots cannot always determine when the state of the aircraft is adversely degrading, nor are they always able to predict how a configuration change such as raising or lowering the wing flaps, would affect aircraft stability and control. The ICEPro system was therefore developed with the theory that a knowledge-based system, which compares predicted aircraft stability and control characteristics with those existing in real time, could effectively provide envelope protection cues and alerting messages to help the pilot keep the aircraft in a safe condition of flight. The knowledge base consists of the baseline or clean aircraft model, and an ice contamination model with known safe flight envelope limits as demonstrated by either wind tunnel or flight test. Angle of attack (AOA) cues, which are driven by ICEPro, show the pilot safe limits that will protect against either a wing stall or tail stall upset event. Messages, on the other hand, alert the pilot of loss in stability and control as a function of flight configuration and condition, and of configuration limits as a function of icing condition and wing flap setting.

3.0 ICEPro System Description

3.1 System Design and Architecture

During the initial system design stage of the program, the research team decided upon a real time state assessment system architecture, which would incorporate two state estimation methodologies; a Dynamic Inversion Control Evaluation System (D-ICES), which assesses control position from measured aircraft response, and a Real Time Parameter Identification (RTPID) (Refs. 12, 13, and 14) system, which estimates stability and control parameters from manual or automatic flight control system inputs and the resulting aircraft response. ICEPro is controlled by executive logic, which

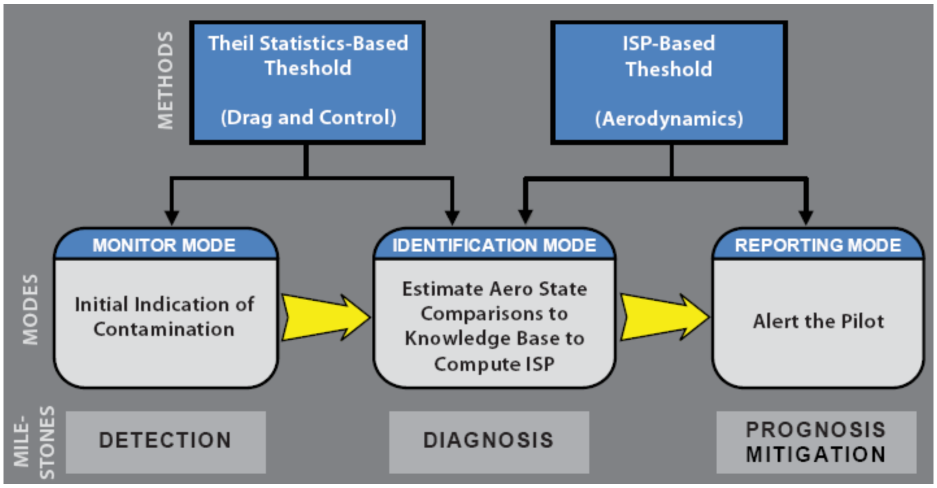

Figure 1.—ICEPro system architecture.

uses D-ICES to compare existing control deflections with those predicted from a knowledge base of the "clean" or un-iced aircraft. As shown in Figure 1, the system architecture consists of three modes of operation, defined as Monitor, Identify or ID, and Report. In the "MONITOR" mode, measured control surface deflections are compared to predicted control surface deflections from the baseline aircraft model in the D-ICES algorithm. If the deflections of the real-time aircraft differ from those of the baseline model by a defined threshold value, ICEPro switches to the "ID" mode. The system logic executes this mode change by using a normalized statistical metric called a Theil (Ref. 15) coefficient, which is calculated from control deflection samples taken in a moving time window. This metric indicates the level of agreement between the actual control deflection and the D-ICES prediction. In this mode, ICEPro diagnoses the degraded vehicle condition by executing a series of optimally-designed control excitations (Ref. 16) for 10 sec to provide information for the RTPID algorithm to estimate stability and control derivatives from measured control surface deflections and vehicle response. An "Icing Severity Parameter" or ISP is calculated based upon the time averaged differences between the a priori clean and iced values. When the ISP exceeds a threshold amount, "Report" mode is entered and flyable cues and alerting messages relating to the severity of the condition are provided on pilot displays. These displays provide a prognosis of the condition and envelope protection limits. This process is iterative, and continues throughout the duration of the flight. If at any time the ISP drops below a predetermined threshold, cueing and messages will disappear and the system returns to the monitor mode. The system also consists of latching and de-latching timers, not shown in the figure, which prevent nuisance cueing and message toggling. It is beyond the scope of this paper to provide specific system design details. These details however, will be discussed in a companion paper by David Gingras, which will be presented at the AIAA Modeling and Simulation Conference, Toronto, Ontario, Canada, August 2 to 5, 2010.

3.2 Functionality Description and Flight Displays

The fundamental function of ICEPro is to perform real time state assessment and provide cues and messages to the flight deck that assist the pilot in keeping the aircraft in a safe operating envelope at all times. Figure 2 shows how those cues and messages are implemented on flight displays.

Airspeed carets provide high and low airspeed limits for the current aircraft configuration and estimated state due to icing. In general, the high speed limit is based upon longitudinal stability and control considerations, and the low speed limit is based on wing stall speed. The carets appear next to the airspeed tape and are marked with a snowflake symbol to indicate that they are estimated by ICEPro. Their position on the tape depends upon wing flap setting and the estimated aircraft state due to icing. Figure 2 shows a notional display of the high speed limit (rectangular wedge caret) corresponding to tail

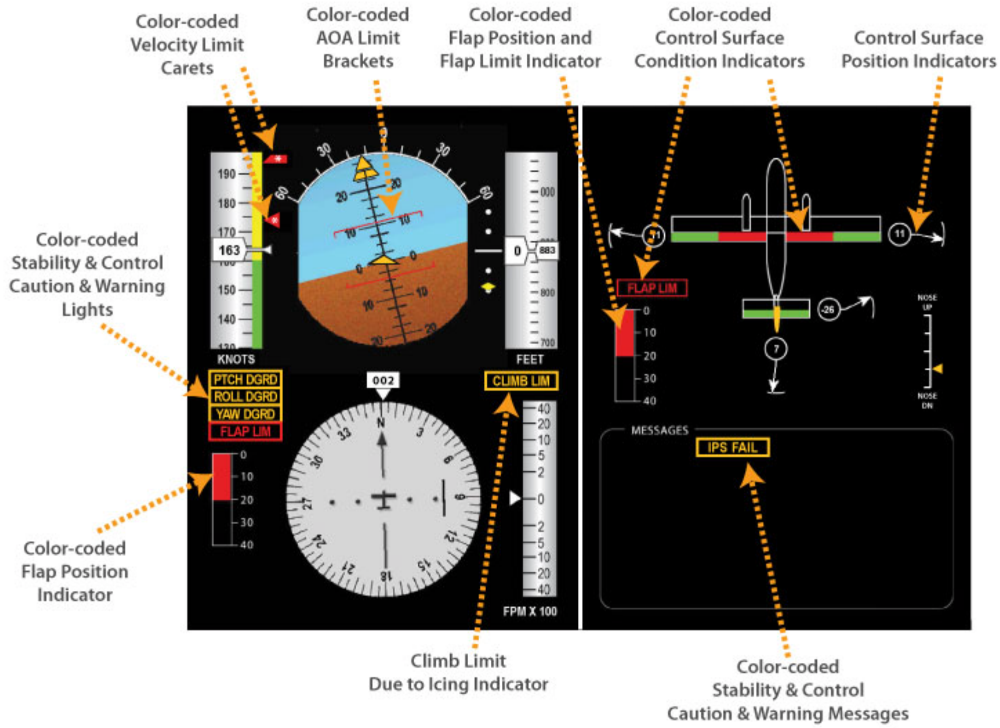

Figure 2.—ICEPro flight displays.

stall upset speed, and the low speed limit (triangular caret) corresponding to the stall speed with wing-flaps in the landing position. When the wing flaps are not in the landing position, the triangular stall speed caret is amber and provides stall warning corresponding to 107 percent of the stall speed.

AOA brackets provide maneuvering limits in pitch for the pilot. These brackets are superimposed on the pitch ladder of the attitude indicator display. There is an upper bracket that indicates the predicted stall AOA for the current configuration and ice contamination state, and a lower bracket that indicates the minimum safe AOA to provide tail stall and/or negative-g protection. The brackets are nominally white when the aircraft is being flown at a safe mid range AOA between the brackets. When the AOA approaches either the upper or lower bracket, both brackets turn amber to indicate caution, and when the AOA is at or beyond the bracket levels, the brackets turn red to warn of an unsafe condition. In addition, whenever the brackets turn amber or red, they flash for several seconds to ensure that the pilot notices the change. The relationship between upper and lower bracket depend upon the AOA limits for the current wing flap configuration.

ICEPro provides a flap position indication that advises the pilot as to the state of the vehicle at the current flap deflection. As flaps are deployed during icing conditions and the system detects degradations in stability and control and/or in the single-engine climb capability, the indicator will change to an amber color, cautioning further deployment of the flaps. As the condition worsens, the indicator turns red, warning the pilot to stop deployment and retract the flaps until the condition is cleared.

Stability and control alerting messages are provided to inform the pilot of an adverse change in the stability and or control in the pitch, roll, or yaw axes. These messages on the Primary Flight Display (PFD) are repeated on the Flight Control Status display, which is shown to the right of the PFD on Figure 2. Thresholds for displaying the alerting messages are activated when pre-established reductions are determined from real time parameter estimates. An amber PITCH DGRD message for example, means that pitch stability or controllability has degraded by 50 percent or more than that of the nominal un-iced aircraft. The message turns red when degradation is 75 percent or greater than nominal. To enhance pilot awareness, the color of the primary or secondary control surface in the affected control axis is also changed to that of the message. This functionality prompts the pilot to return to a previous configuration and flight condition that provided safer flight characteristics.

A climb limit (CLIMB LIM) caution and warning message is a performance-based cue to provide the pilot with an indication of single-engine climb potential given the current state of the aircraft. An amber message indicates that should an engine fail the airplane climb rate for the current flap setting will be less than 100 ft per minute. If the message is red, this indicates that the airplane will be unable to climb or will descend in the event of an engine failure.

Later in development, it was also decided to incorporate a "stick shaker" for stall warning, a STALL message, stick pusher and aural warning for a stall upset and a de-cluttering mode for the primary flight display when flight attitudes became excessive during extreme upset conditions. De-cluttering removes all but primary recovery cues such as AOA and airspeed limits.

4.0 Test Methodology

4.1 Experiment Design

The purpose of the test and evaluation with pilots in the loop was to determine if ICEPro had utility for mitigating a potentially hazardous icing encounter. The independent parameters were the two displays (baseline, and ICEPro with envelope protection), and the dependent parameters were technical performance, workload, and pilot opinion. A non-parametric, independent measures experiment was therefore selected where differences in the dependent variables were analyzed using the Mann-Whitney "U" test (Ref. 17). A critical "U" was determined, based on a one-tailed test where a 95 percent confidence criteria or better was required to correctly reject the null hypothesis (H_0). H_0 assumed that there was no difference between the two groups for the tested variable, therefore the level of significance or alpha level required to reject the null hypothesis was chosen to be $\alpha = 0.05$. The experiment was planned for an evaluation by 30 pilots with relatively similar flight experience. All were ERAU instructor pilots with a median flight experience of approximately 1300 flight hours. Each possessed commercial, multi-engine, and instrument ratings, but none had any specific experience in actual icing conditions or any prior training in aircraft handling and upset recovery due to a hazardous icing condition. The 30 pilots were randomly divided into a control group (baseline flight displays and no ICEPro system) and an experimental group (displays modified with ICEPro cues and messages). A scheduling problem resulted in a total of 29 pilot evaluations and unequal sample sizes between the control and experimental groups ($n_c = 14$ and $n_e = 15$). This disparity was accounted for by the MWU methodology as provided for in Reference 17.

4.2 ICEFTD Simulator Description

The aircraft model and sub-system components for the ICEFTD simulator were assembled in BAR's commercial off the shelf (COTS) proprietary simulator development environment, D-Six (Bihrle Applied Research, Inc.). The simulator provides highly representative flight characteristics of the Twin Otter icing research aircraft. Although originally designed as a pilot training device, the ICEFTD's ability to accurately represent aircraft icing characteristics made it a very useful research tool with several advantageous features. One is its capability for accurately representing flight characteristics beyond stall AOA, which permits pilots to experience post-stall gyrations and tail stall hard-over's that occur during upset conditions. Another is the pitch control system, which can provide control force gradients and deflections that closely match those recorded from flight tests of the NASA Twin Otter during upset events. Lastly, an "aircraft emulator" was designed and integrated in order to represent the same sensor feedback and output response as that of the aircraft. Much of the functionality testing during development focused on refining the system logic to fine tune thresholds and minimize nuisance messaging. Figure 3 is an overview of the ICEFTD as modified for this test. The items in red font are those which support ICEPro operation.

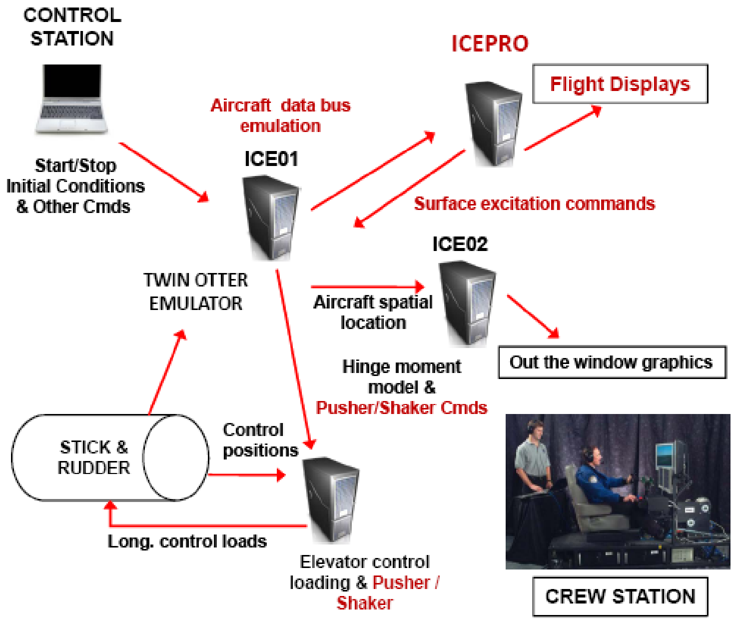

Figure 3.—ICEFTD configuration for test and evaluation of ICEPro.

The ICEFTD simulator also provided excellent three-screen graphics of a visual scene, which was an essential element of the final approach and missed approach task in this evaluation. A video recording camera system was also employed for each pilot evaluation run in the event a replay of the pilot's actions needed to be observed. During testing, the evaluation pilot wore a headset and was completely enclosed in the simulator by a system of curtains (not shown in the figure). This isolated the pilot from any outside disturbances or distractions, and enhanced the fidelity of the simulation environment. A member of the test team operated the simulator and performed data acquisition and processing tasks from a remote console. A second member communicated with the pilot while acting as test conductor and air traffic control (ATC).

4.3 Pre-Test Pilot Proficiency Training

Before performing the evaluation tasks for data collection, each pilot was subjected to approximately 1.5 hr of flight training. Pilots were trained for the evaluation task using the respective flight displays depending on whether they were in the control or experimental group. Training began by having each pilot execute the evaluation approach task profile as shown in Figure 4 in a no-ice or baseline configuration under instrument meteorological conditions (IMC). The IMC condition for training and testing was set at 400 ft and 1 nautical mile (NM) visibility. The white boxes in the figure describe the flight condition and events during the task and the green shaded boxes show the commands given by the test conductor, who acted as ATC at various stages during its execution. The missed approach procedure (MAP) with an engine failure was initiated by the test conductor at the approximate position as shown in red font. Pilots practiced the approach task according to the SOP, which specified speeds, configurations, and performance standards throughout the profile. This phase of training was important in order for the test team to determine that each evaluation pilot possessed the requisite instrument flight skills to satisfactorily perform the task. The next phase of training was conducted up and away under visual meteorological conditions (VMC) to familiarize pilots and develop their skill in dealing with aircraft characteristics due to the failure case icing condition. This training emphasized recognition of impending upset conditions and the effects of wing flap configuration and flight speed on aircraft handling and control characteristics. Pilots in the control group were taught how to most effectively use their baseline flight displays to control the aircraft and recognize and recover from upset conditions. Pilots in the experimental group received the same training emphasis, but were taught how to integrate their scan and

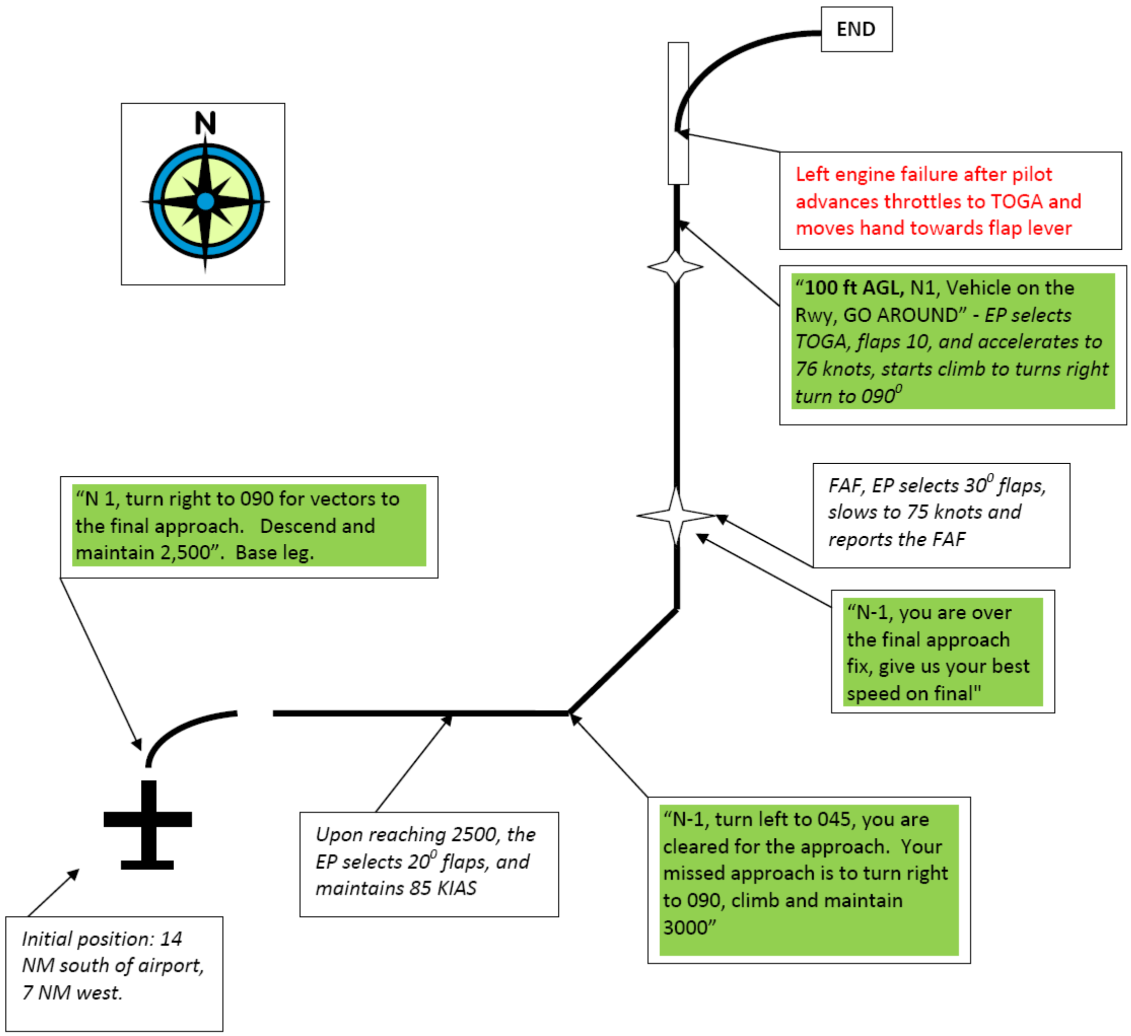

Figure 4.—Evaluation profile approach task flown by each pilot group during ICEPro testing and evaluation.

control strategy with envelope protection cues to facilitate safe flight control and upset recoveries. During this training, evaluation pilots were also instructed to fly with both hands on the yoke. For some pilots this was a learning experience because nearly all of them were used to one handed operation in aircraft with relatively light control forces. Once the up and away training was completed, each of the pilots practiced the approach procedure with the hazardous failure case icing condition as would be performed in the actual evaluation. A certain amount of time was also spent having the pilots practice the missed approach procedure under iced conditions. This was the most difficult task to perform because of high pitch control forces and the requirement to null the asymmetric thrust with high rudder forces when an engine was failed. Pilots had to practice this maneuver several times before they could consistently accomplish it in a proficient manner and not lose control. Evaluation pilots were continually reminded to fly according to the SOP, which was intentionally designed to place the aircraft near the edges of the flight envelope at all times. This protocol forced considerable attention to precise aircraft control throughout the approach task, which was essential for making a good utility assessment of ICEPro. The evaluation profile approach task for both groups required considerable mental concentration, physical strength and very aggressive control inputs to prevent or recover from upset conditions. All pilots, regardless of size or gender, were able to effectively perform the approach task where pitch control forces reached 90 to 100 lbf at times. In general, most pilots only required one practice approach before they were ready to begin the evaluation phase. In addition to the flight training, pilots were briefed on and practiced completing the NASA TLX workload form. Following this training, pilots were critiqued by the test team, and then given a short break before they began their evaluation runs.

4.4 Flight Evaluations

The evaluation phase required that a total of three satisfactory approach tasks be performed by each pilot. The test conductor sat behind the simulator cab and acted as ATC and was able to view the evaluation pilot through a small opening in the rear curtain. During each evaluation run, the pilots were completely enclosed in the simulator cab, and no coaching or extraneous discussions were permitted. As shown in Figure 4, the approach task consisted of "radar vectors" to intercept a precision approach procedure. The pilot would execute the approach according the SOP, and "break out" of the clouds at 400 ft above ground (AGL), and continue the descent to the runway on a visual glide path. At approximately 100 ft AGL, "ATC" would instruct a missed approach procedure, which the pilot would acknowledge and then initiate. As soon as both power levers were fully advanced, the test conductor would fail an engine, and the pilot would continue the procedure while raising the wing flaps from full down to 10°. The test would be terminated when the evaluation pilot was stabilized on the missed approach heading. Once complete, the evaluation pilot would fill out an electronic TLX form, which automatically computed the numerical workload score, and receive a short debriefing from the test team. The pilot would then re-enter the simulator for the next evaluation run. The entire evaluation process for each pilot including the pre-test training exercises and three evaluation runs took approximately 3 hr, which seemed to be the limit before fatigue became a factor affecting pilot performance. After testing was completed for each pilot, they were asked to fill out a post-test survey questionnaire, included in Appendix A. This questionnaire consisted of four sections using a Likert (Ref. 18) style format: Part I provided pilot demographic and experience information; Part II asked about situational awareness; Part III asked for the experimental group's assessment of ICEPro integration; and Part IV asked general questions about workload factors.

4.5 Data Acquisition and Handling

Pilot flight performance data parameters, which were available through a flight data file that was resident in D-Six, were sampled at 10 Hz. MATLAB (The MathWorks, Inc.) routines were used to collect and reduce these data for further analysis. For the final approach segment of the task, the Theil coefficient was used to evaluate how closely the pilot's flight path and airspeed agreed with that of a perfectly flown approach. A Theil coefficient was calculated for measured lateral and vertical deviations from the centerline of the approach path, and the airspeed error from the required 75 kn indicated airspeed (KIAS) approach speed. MATLAB routines were also used to record the number of times the stick shaker and pusher fired, and number and depth of tail stall AOA exceedance events over the duration of the entire flight task. In addition to these performance data, other parameters were recorded during each run to provide a more complete picture of the pilot's control strategy which was also useful when training and de-briefing the evaluation pilots. These included time histories of pressure altitude (H_P), pitch attitude (θ), pitch rate (q), normal acceleration (n_Z), elevator position (δ_e), elevator control force (F_e), and wing flap setting (δ_F). Pilots completed the NASA TLX immediately after each data run, and then completed the survey questionnaire at the termination of the evaluation session.

The pilot performance data quantified how well the pilot flew the approach task, how many stick shaker and pusher events occurred, and the number of times and extent to which the tail stall AOA was exceeded by 5° or more. It should be noted that reaching a tail stall AOA, which was one of the measured parameters, did not always result in an upset as long as the pilot immediately recognized the condition and promptly arrested the negative pitch rate. The added 5° margin took into account pilot reaction time and aircraft dynamic response to the controls. Therefore, tail stall upsets were defined by the number of times the pilot *reached or exceeded the 5° margin*, and the maximum negative AOA achieved in the event. This latter metric was also used to define "upset risk", since the deeper the stall, the greater the chance of an upset from which recovery was less probable. In addition to pilot performance data, the numerical scores of the TLX workload assessments and the numerical results from the Likert-type post-test questionnaires were analyzed by the MWU process. The TLX analysis was of interest to understand if the added information of the ICEPro displays adversely affected workload. The post-test survey analysis was used to assess if there was a real and positive difference in hazardous aircraft state awareness, and perception of workload between the two groups. Additionally, a section of the survey provided non-comparative information on how well the experimental group felt the ICEPro was integrated with flight displays.

The utility evaluation of ICEPro was based upon assessing real differences between the control and experimental groups. The MWU analysis process began by rank ordering the scores of each group, and computing a “U” value based on the rank sums. In this one directional test, the “U” for the experimental group had to be greater than 144 to ensure a 95 percent probability for correctly rejecting H_0. A cumulative probability p was calculated from the z score and was compared to $\alpha = 0.05$, the requirement for accepting the alternate hypothesis. If this probability was less than 0.05, the null hypothesis was rejected. A negative z score (number of standard deviations) of more than magnitude 1.69 (i.e., less than –1.69) was required to produce the cumulative probability which met this requirement. The parameters which were assessed included all quantified measures of pilot performance, TLX workload, and subjective opinions from the survey questionnaires.

An assessment of recovery from tail stall upsets was also performed. In many cases, when a tail stall event was encountered, a series of pitch oscillations would ensue from which the pilot would have to recover. An analysis of repeated events was performed to determine if the experimental group could recover from these oscillations using ICEPro cueing sooner than the control group, and thereby be less prone to entering an out of control condition. A pilot coupling event (PCE) represents a hazardous situation, which if not arrested quickly, could progress to a loss of control. In this context, the risk of an unrecoverable upset was associated with the number of repeated tail stalls in a PCE scenario, and the depth of each stall beyond the 5° margin previously discussed. A time window analysis was therefore used to analyze the number of tail stalls occurring within a continuous 5, 10, 15, and 20 sec span, while the pilot was attempting a recovery. Search scripts in MATLAB were used to analyze the beginning and ending of each PCE, and total the number and severity of each tail stall within the PCE. The results were then reported in a tabular format for both groups, and analyzed for significance by the MWU method. An important outcome of this analysis was to assess the utility of ICEPro AOA cues for minimizing the recovery time from a PCE, and thereby reduce risk of a loss of control situation.

5.0 Results and Discussion

5.1 Pilot Demographics

All evaluation pilots were instructor pilots in the ERAU professional pilot training program. Thirty pilot volunteers were broken down into two groups—a control group who flew baseline displays, and an experimental group who flew with ICEPro modified displays. The 29 ERAU instructor pilots held FAA commercial licenses with multi-engine and instrument ratings. The demographic data was collected in Part I of the post-test survey questionnaire, and is discussed in Section 5.6. Due to a scheduling problem, the control group consisted of one less pilot that the experimental group. The demographics of the groups were as follows:

- Subjects and gender
  - 14 control group (12 male, 2 female)
  - 15 experimental group (12 male, 3 female)

- Median flight hours

Control group		Experimental group	
Total	1350	Total	1250
Multi-engine	122	Multi-engine	100

Icing related experience and training as related from Part I of the post-test survey questionnaire:

- 75 percent had no prior in-flight icing experience
- 89 percent did not feel that their prior icing related knowledge/experience would have prepared them to perform the test scenario (training was required in order for pilots to execute the flight task)
- 72 percent agreed that the NASA videos/web based training gave more information about icing than they had known before (viewing NASA web based training videos was a pre-test requirement)
- Mixed responses were given for icing related flight training being focused on IPS operation (this depended on the types and classes of aircraft in which pilots had been previously trained)

5.2 Pilot Control Performance

Pilot control performance assessment from the control and experimental groups are summarized in Figure 5. Results highlighted in *green* indicate that the significance or real difference criterion for the assessed parameter was met, and the performance of the experimental group was better than that of the control group. Results highlighted in *blue* indicate that the assessed parameter showed better performance by the experimental group, but the result did not meet the real difference criterion. Results highlighted in *orange*, indicate that there was no difference between the performance of the two groups, and results highlighted in *magenta* indicate that the experimental group did not perform as well as the control group. In general the cumulative pilot performance for the two most critical events, pusher activation and tail stall, met the real difference criterion. These events were considered most important from a safety of flight standpoint because a wing or tail stall upset had occurred, and potential for loss of control was very high unless the pilot promptly applied the correct sequence of recovery controls. The shaker activation event indicated that the control group had slightly better performance than the experimental group, but this finding can be misleading without considering important aspects of shaker implementation and pilot use of this functionality in a human factors context. This is explained in the following discussion of the results, which were tabulated in Figure 5. The first column of the figure identifies the parameter or event that was evaluated during the approach and missed approach task, the second column indicates the number of standard deviations (z) required in meeting the real difference criterion, the third column indicated the cumulative probability (p), and the last column provides a performance assessment between the experimental and control group based upon the analysis.

5.2.1 Shaker Events—Stall Warning

The results of the pilot performance for avoiding stick shaker events as shown in Figure 5 indicate that, cumulatively, the control group had a slightly better performance than the experimental group. Shaker firings typically occurred in banked turns if speed got too low, during positive pitch overshoots incited by a tail stall induced PCE, and when pilots made an overly aggressive stick pusher recovery. The following discussion places these results into perspective and discusses factors that may have affected their outcome. The control group flew with basic aircraft displays and a simple stick shaker functionality, which always provided a 7 percent stall speed margin based upon a clean wing; i.e., no-ice. Therefore, when the shaker fired during the approach task in the icing condition, the actual margin to stall was less than 7 percent. On the other hand, the experimental group flew with ICEPro generated displays, which provided real time AOA cues and shaker functionality that maintained a 7 percent stall speed margin for the icing condition. Experimental group pilots could avoid shaker events if they remained below the upper alpha limit as shown in Figure 2. The control group had no AOA information on their basic flight displays. In order to avoid shaker activation, they had to closely maintain the SOP required airspeeds throughout the entire task.

Pilot control performance by run number and cumulative	*z* score: $z < -1.69$ for 95% confidence in H_0 rejection	Probability: $p < 0.05$ required to satisfy α (alternate hypothesis)	Group performance: Exp. versus control Positive real difference (PRD), Better (B), Worse (W), Same (S)
Shaker events			
Run 1	1.0474	0.8575	W
Run 2	–0.2837	0.3799	B
Run 3	–0.5892	0.2705	B
Cumulative runs	0.0873	0.5434	S
Pusher events			
Run 1	–0.0655	0.4652	S
Run 2	–1.2875	0.0952	B
Run 3	–2.1822	0.0137	PRD
Cumulative runs	–1.7457	0.0385	PRD
Stall Messages No stall messages appeared for the experimental group			
Tail stall events			
Run 1	–1.2657	0.0989	B
Run 2	–1.8330	0.0318	PRD
Run 3	–1.7894	0.0350	PRD
Cumulative runs	–2.1822	0.0137	PRD

Legend	
(green)	Meets 95% confidence for rejecting H_0
(blue)	Experimental group better over control group but < 95% confidence for rejecting H_0
(orange)	No difference between experimental and control group
(pink)	Experimental group performance worse than control group

Figure 5.—Summary of pilot control performance

Notably, the control group was technically at greater risk when the shaker fired because their stall speed margin was less than 7 percent. A study of the frequency of shaker events is helpful in order to better understand the results of Figure 5. Table 1 provides the number of recorded shaker events per run for each group of pilots.

TABLE 1.—NORMALIZED SHAKER EVENTS

Control group (14 pilots)			Experimental group (15 pilots)		
Run	Shaker events	Normalized	Run	Shaker events	Normalized
1	87	6.21	1	113	7.53
2	92	6.57	2	86	5.73
3	87	6.21	3	72	4.80
Cum	266	6.33	Cum	271	6.02

During run one, 14 control group pilots experienced 87 shaker events, whereas 15 experimental group pilots experienced 113 shaker events. On average, the control group experienced 6.21 events per pilot, and the experimental group experienced 7.53 events per pilot. The corresponding MWU analysis for run one in Figure 5 clearly shows better (but not significant) performance from the control group. During the subsequent runs, however, the experimental group's performance got better, and this is reflected in the analysis for runs two and three in Figure 5. If all three runs are considered cumulatively, the normalized ratio between the two groups is slightly better for the experimental group, but the cumulative results of the statistical analysis shown in Figure 5 slightly favors the performance of the control group. Regardless, the differences between control and experimental groups as shown in Figure 5 and Table 1 are very small. What is important to observe here is that the experimental group did a much better job of avoiding shaker events during subsequent runs, while the control group's performance remained nearly constant. This was likely due to increased proficiency in using ICEPro AOA cues, which was not fully realized during pre-test training. Unfortunately, practical limits on pre-test training were necessary in order to conduct all required evaluations within time and program cost constraints.

5.2.2 Pusher Events—Wing Stall Upsets

Table 2 summarizes the number of pusher events per run for each group. Pusher events were generally precipitated by the same factors that incited shaker events and occurred when the pilot could not arrest an angle of attack increase, which resulted in a stall upset. This was particularly evident when the missed approach procedure was executed. Here, pilots immediately advanced the throttles to full power, raised the wing flaps to 10° and the nose to the takeoff attitude in one coordinated motion. As soon the power levers reached the full power stop and the evaluation pilot reached for the wing flap lever, the left engine was failed by the test conductor, and the pilot then had to null the yaw and adjust pitch so as to maintain a 76 KIAS climb speed. This was a very dynamic maneuver, and in many cases it precipitated a PCE. As in the case of the shaker events, the experimental group of pilots improved with each evaluation run, whereas the control group actually got worse. The raw data in Table 2 supports the statistical assessment that the ICEPro displays resulted in better pilot control performance and lower risk of an upset due to either wing or tail stall.

TABLE 2.—NORMALIZED PUSHER EVENTS

Control group (14 pilots)			Experimental group (15 pilots)		
Run	Pusher events	Normalized	Run	Pusher events	Normalized
1	12	0.86	1	13	0.87
2	16	1.14	2	10	.67
3	19	1.16	3	6	.40
Cum	47	1.05	Cum	29	.64

5.2.3 Stall Messages

A "STALL" message was incorporated into the PFD in the event the pilot attempted to override the pusher and thereby remain in a stall upset condition. This was a functionality associated with ICEPro displays, and appeared to be unnecessary as all the experimental pilots promptly applied recovery controls to reduce the AOA below the upper bar when the pusher fired. No stall messages appeared during any of the runs flown by the experimental group.

5.2.4 Tail-Stall Upsets and Recoveries

Tail stall upsets resulted when pilots flew too fast, exceeding the speeds specified at various segments of the flight task, or when they allowed the angle of attack to get too low. This condition was greatly aggravated with increasing wing flap deflections, and was most sensitive during the final approach and missed approach procedure when the flaps were 30º down. As described previously, a tail stall was defined as reaching a negative angle of attack that was 5° below that where the tail had technically reached a stall condition. This margin was determined experimentally, as it appeared that if a pilot immediately applied recovery controls before reaching this negative angle of attack, recovery would be prompt and the chance of a PCE minimized. When a tail stall occurs in an aircraft equipped with mechanical controls, such as the one simulated in this test, the pilot feels an immediate increase in pull force and notes a rapid build-up in negative pitch rate. In order to arrest the condition, the pilot must quickly exert very high pull forces (on the order of 90 to 100 lbf) to reverse the downward motion of the nose. If successful, the nose starts back up; but, as it does, pitch forces immediately lighten and a positive pitch overshoot can easily occur. This can precipitate a PCE, which can develop into a loss of control situation should a negative angle of attack be reached, which the pilot is not able to physically overcome. Pre-test pilot training acquainted both control and experimental group pilots with these characteristics, and the basic methods for recovery. The control group, of course, did not have the AOA displays of the experimental group and therefore did not know their margins to either a wing or tail stall upset. They practiced tail stall upset recoveries by keeping the pitch divergence to a minimum. The experimental group, on the other hand, was taught to use the ICEPro displays to facilitate recovery by adjusting pitch during a PCE to remain within the safe envelope defined by the AOA bars. When pitch rate was negative, the pilot would attempt to pull the nose up but remain below the high AOA bar. If the pitch rate was positive, the pilot would push the nose down, but remain above the low AOA bar. If done properly, this would result is a very expeditious recovery—normally within one or two cycles. Of note, this was also the reason why there were fewer pusher events as the experimental group tended to be better at avoiding stall angle of attack than the control group. The learning bias evident in the shaker and pusher data seem to indicate that had more time been available for the experimental group to practice with the ICEPro displays, their performance during these events would have been better. Runs 2, 3, and cumulative of the tail stall event in Figure 5 clearly show positive real difference in the performance of the experimental group and provide better than 95 percent confidence for correctly rejecting H_0.

5.3 Pilot Precision Approach Performance

The final approach segment required the pilots to intercept and accurately fly a precision approach to the minimum descent altitude of 200 ft. As shown in Figure 2 the flight displays for both groups did not provide computed steering or a flight director format. Therefore, the pilots had to fly what is termed “raw data” and null localizer and glide slope errors by controlling heading and pitch attitude. As described earlier, this task was also performed in IMC until reaching the imposed ceiling of 400 ft above ground level. When the pilots “broke out” of the cloud at this altitude, they continued their descent to 100 ft and were directed to execute a missed approach. The difficulty in flying the approach task was largely due to control aspects discussed earlier. Some pilots were very smooth and precise throughout the task, and were able to execute it without too much difficulty. This was because they did not allow the attitude of the aircraft to vary much beyond that required to maintain a given flight condition. Generally, these were pilots who had very efficient instrument scans, and who made very small but immediate corrections when required. Pilots whose instrument scans were less efficient and allowed large pitch or roll variations to occur were more prone to get into a pitch axis PCE. This event greatly affected glide slope, course, and airspeed errors, and was reflected in the Theil coefficient values for each of those parameters. Figure 6 provides the results of the MWU analysis of the precision approach errors between the control and experimental groups. It should be noted, that both groups of pilots generally flew the approach procedure within ATP standards (Ref. 19) as required in the SOP. The Theil coefficient values, which were used in the MWU analysis, were basically a means of quantifying the pilot’s performance with respect to a perfectly flown approach.

As shown in Figure 6, the control group had better cumulative performance in minimizing localizer and airspeed errors. The experimental group on the other hand had better cumulative performance in minimizing glide slope error, but did not meet the significance criteria required to infer that there was a real difference between the two groups. It would appear, after considering the results from Figure 5 and Figure 6, that pilots who had the advantage of ICEPro displays tended to prioritize aircraft control over the preciseness at which they flew the localizer and the required airspeed. This is perhaps why the control group, who flew more precise airspeed, had significantly more tail stall upset events than the experimental group and was considered to be at greater risk of entering an out of control situation.

Pilot precision approach performance by run number and cumulative	***z* score:** $z < -1.69$ for 95% confidence in H_0 rejection	**Probability:** $p < 0.05$ required to satisfy α (alternate hypothesis)	**Group Performance: Exp. versus Control** Positive real difference (PRD), Better (B), Worse (W), Same (S)
Localizer			
Run 1	0.6328	0.7436	W
Run 2	0.2619	0.6116	W
Run 3	0.0436	0.5260	W
Cumulative	0.1528	0.5692	W
Glide slope			
Run 1	–1.4402	0.0718	B
Run 2	0.5674	0.7221	W
Run 3	–1.4621	0.0689	B
Cumulative	–0.4364	0.3233	B
Airspeed control			
Run 1	1.8330	0.9681	W
Run 2	1.9640	0.9764	W
Run 3	1.4402	0.9281	W
Cumulative	1.9421	0.9752	W
Legend			
(green)	Meets 95% confidence for rejecting H_0		
(blue)	Experimental group better over control group but < 95% confidence for rejecting H_0		
(orange)	No difference between experimental and control group		
(magenta)	Experimental group performance worse than control group		

Figure 6.—Pilot precision approach performance.

5.4 Exposure to Risk of an Out of Control Event

A number of tail stalls, which were encountered in the course of the approach procedure, resulted in PCEs before the pilot was able to stop the oscillations and recover to a stable and normal flight condition. This event was described earlier in Section 4.5, and under "Tail-stall upsets and recoveries," Section 5.2.

If a quick recovery from a tail stall event (TSE) could not be facilitated by the pilot, there was a risk that repeated oscillations result in a PCE which would deteriorate into an out of control situation. Therefore, the numbers of repeated tails-stalls during PCEs were summed for each group during the final approach segment in four time duration windows of 5, 10, 15 and 20 sec. The methodology began by identifying an initial tail-stall event (TSE), which met the criterion (negative tail-stall AOA plus 5°). If another TSE occurred within 5 sec it would be counted with the first tail stall and considered a PCE. If in this event, TSEs continued to occur within 5 sec of the one previous, they would be added to the PCE until the duration of time between a repeat TSE was greater than 5 sec. This methodology was then repeated for time intervals of 10, 15, and 20 sec. The exposure to risk of reaching an out of control situation was therefore greater during a PCE based upon the number of repeat TSEs in any of the four time frames, the amount of time it took the pilot to recover, and the maximum negative pitch attitude reached during the event. The results of this analysis are provided in Table 3.

TABLE 3.—EXPOSURE TO RISK BASED UPON PILOT COUPLING EVENTS

Group	Time interval between repeat TSEs (sec)	Total number of PCEs	Mean duration of PCEs in the time interval (sec)	Mean max negative pitch
Control	5	16	15.16	–12.23
Experimental		4	8.66	–8.8
Control	10	69	18.54	–12.06
Experimental		29	17.98	–11.12
Control	15	84	23.08	–12.32
Experimental		36	23.22	–11.37
Control	20	90	27.64	–12.44
Experimental		41	25.85	–11.23

The most significant events occurred during the 5 sec interval. By using their ICEPro driven displays, the experimental group had 25 percent fewer PCEs, their events were approximately half as long in duration, and the maximum nose down attitude during the event was about 3.5° less than that of the control group. In effect, the experimental group could arrest a PCE quicker, with fewer oscillations than the control group. Most important however, was the maximum depth of the tail stall, which was measured by the maximum negative pitch attitude achieved during the recovery attempt. The more negative the attitude, the higher the negative column forces, and the more difficult it was for the pilot to arrest the negative pitching moment. Though not shown here in the data, some pilots had to use in excess of 90 to 100 lbf to arrest the negative pitching moment, which was more likely to cause a positive pitch overshoot, and sometimes result in pusher activation. As previously mentioned, the test profile was intentionally designed to place pilots on the edge of a TSE during the approach, and as a result, most pilots in both groups experienced them, especially when momentarily distracted from their instrument cross-check. However, when a TSE occurred and especially when it deteriorated into a PCE, the experimental group was able to effectively utilize their AOA cues to damp the oscillations more quickly than the control group. They accomplished this recovery while minimizing their time at an unsafe negative AOA, and thereby were at less risk of reaching an out of control situation.

5.5 Workload

After completing each evaluation run, evaluation pilots were asked to complete a TLX workload assessment for the entire task. The flight profile was intentionally designed to place the each group of pilots very near the edges of the safe flight envelope especially during the final approach and missed approach segments. Further, the tasks were flown in IMC, and both the cognitive and physical aspects of workload were quite high for both groups, especially when recoveries from TSEs or PCEs were required. Because the experimental group had to integrate more information when performing the flight task than the control group, there was a concern that their workload could be adversely affected because the ICEPro displays provided much more information than the basic displays, and had to be integrated into the pilot's scan along with the instrument flying task. The control group did not have the additional information and thus had less cognitive workload. An analysis was conducted on each of the three runs for both groups, and the results shown in Figure 7 indicate that overall, the experimental group reported less total workload. Run 2 for example, taken by itself did meet the significance criteria and indicated that ICEPro displays made a real difference in reduced workload. However, on average for all runs, the results did not meet the significance criteria. Observation of both groups of pilots indicated that as they flew each successive profile, they became more comfortable with the task, and tended to report lower workload. In spite of the lower workload, it was also apparent that, by the second run, fatigue began setting in; this affected pilot concentration and control performance. The entire evaluation was conducted over an approximate 3 hr period with strategically inserted rest breaks, but it was apparent that the performance of the pilots from both groups seemed to peak by the second evaluation and decrease on the third run. The results of the post-test survey questions, which are discussed in the next section, provide further insight into these findings.

Pilot workload by run number and cumulative	*z* score: $z < -1.69$ for 95% confidence in H_0 rejection	Probability: $p < 0.05$ to satisfy α (alternate hypothesis)	Group Performance: Exp. versus Control Positive real difference (PRD), Better (B), Worse (W), Same (S)
TLX Workload			
Run 1	–0.5237	0.2926	B
Run 2	–1.8985	0.0274	PRD
Run 3	–1.4621	0.0689	B
Average all runs	–1.0911	0.1328	B

Legend

Green	Meets 95% confidence for rejecting H_0
Blue	Experimental group better over control group but < 95% confidence for rejecting H_0
Orange	No difference between experimental and control group
Magenta	Control group performance better than experimental group

Figure 7.—Workload assessment.

5.6 Post-Test Survey Results

The questions in all four parts of the survey solicited pilot opinions to help gain insight of the two pilot groups with respect to their icing experience, perception of situation awareness, how well ICEPro was implemented, and workload issues associated with the flight task. Descriptive analysis was used for responses to Part I—Demographics and Part III—ICEPro Implementation. Parts II—Situation Awareness, and Part IV—Workload, were analyzed via the MWU methodology for real differences. The survey questions solicited either agreement, or frequency of occurrence. A Likert five-answer format was used with numbers 1 to 5 assigned to the answers from left to right. For the MWU analysis of Parts II and IV, the “direction” of the numbered response for each question, i.e., 1 to 5, or 5 to 1, was defined to indicate better performance. The survey questionnaire is provided in Appendix A for the reader’s reference, and histograms of the responses to questions in Parts I, II and IV are provided in Appendix B. Descriptive-only assessments of experimental group pilot opinions are provided for Part III.

5.6.1 Part I—Demographics

The two pilot groups were intentionally selected from a relatively homogeneous sample. All pilots were essentially General Aviation (GA) instructor pilots who shared common experience with training, ratings, and types of aircraft flown. All pilots except one were staff instructors at ERAU and subscribed to the same operational and flight standards as defined by the University’s professional pilot training program. There was only one outlier in the control group, and that individual’s flight hours were not included in the standard deviation calculations as this individual’s flight time skewed the data considerably. With the elimination of that pilot’s flight hours, the standard deviation of the control group was 1054 hr, and the standard deviation of the experimental group was 698 hr. As shown in Figure B.1 nearly all pilots had minimal experience with aircraft icing or icing related training before participating in this test.

5.6.2 Part II—Situation Awareness

Figure 8 and Appendices A and B summarize the situational awareness responses to the questions.

Pilot post-test survey questionnaire results	*z* score: $z < -1.69$ for 95% confidence in H_0 rejection	Probability: $p < 0.05$ required to satisfy α (alternate hypothesis)	Group Performance: Exp. versus Control Positive real difference (PRD), Better (B), Worse (W), Same (S)
Part II—Situational Awareness			
1. Flight displays were adequate to determine if airframe icing was having an effect on aircraft characteristics.	–3.0987	0.00008	PRD
2. Knew minimum safe speed for a given wing flap setting within 5 kn.	–2.2242	0.0072	PRD
3. Knew how to adjust pitch attitude to avoid a wing stall or a tail stall upset.	–2.5750	0.0047	PRD
4. Knew wing flap settings for safe rate of climb in event of an engine failure.	–2. 5968	0.0044	PRD
5. Had to rely on aircraft control response to determine icing effects on pitch, yaw, and roll.	–4.4298	0.0000	PRD
6. Confident that the final approach airspeed would prevent stall.	–0.3273	0.3634	B
7. Able to avoid aircraft handling problems or tail stall upsets when selecting wing flaps down.	1.1129	0.8717	W
8. Colored bands on airspeed tape useful to safely fly the aircraft during the entire flight.	–2.7714	0.0026	PRD
9. Relied on stick shaker to prevent inadvertently stalling.	–0.1746	0.4221	B
10. Always knew when approaching a wing or tail stall condition.	–1.8985	0.0274	PRD

Legend	
(green)	Meets 95% confidence for rejecting H_0
(blue)	Experimental group better over control group but < 95% confidence to reject H_0
(orange)	No difference between experimental and control group
(magenta)	Experimental group performance worse than control group

Figure 8.—Situational awareness post-test questionnaire results.

aircraft control response. From the responses to question 8 the experimental group of pilots felt the colored bands on the airspeed tape were useful for safely flying the aircraft during the entire flight, while the control group did not. The histogram of the responses, Figure B.3, clearly reflects this difference, but the result was somewhat confusing since both groups had the same color bands on their airspeed tape (Figure 2), and a real difference was not expected. One explanation however, may have been that the ICEPro speed carets, when overlaid on the baseline PFD display speed tape, provided better low and high speed awareness in relation to the non-iced aircraft condition. Another possibility is that the experimental group misinterpreted the question and thought the "color bands" referred to the ICEPro speed carets. In any case, the wording of the question could have been better to ensure that no misinterpretation of the nomenclature was made. Question 10 indicated that the experimental group felt they had significantly better awareness when approaching a flight condition that could lead to a wing or tail stall than the control group. Many of the experimental pilots verbally commented during their test runs that the real time computed AOA brackets were most useful in that respect. The responses to questions 6 and 9 respectively, indicated that the experimental group was more confident that their final approach airspeed would avoid wing stall, and that they did not have to rely as much on the shaker to avoid stalling. These results, although better for the experimental group, did not meet the significance criteria. This better but not significantly better result may have been due to the fact that the experimental group knew that they could safely fly to just below the AOA upper bracket and avoid the shaker firing. If the brackets started flashing coincident with the aircraft reference symbol and the shaker did fire, they could immediately reduce AOA and avoid stall. The combination of AOA and shaker gave the experimental group good low speed and incipient stall awareness. The control group on the other hand, had to rely on basic (clean aircraft) shaker settings and the likewise basic (clean aircraft) airspeed bands on their PFD to avoid stalling.

Fortunately for the control group, the failure case icing configuration in the simulation model resulted in a very small stall speed increase and concurrent stall AOA decrease. As a result, if the shaker fired for the control group, or if they flew into the amber stall warning band on the airspeed indicator, they were generally able to react with a decreased pitch input in time to avoid stall. Had a more severe ice shape been modeled and the stall margin been less, or even negative, the control group responses may have been different as they could have stalled before the shaker fired. The responses to question 7 indicated that the experimental group felt less able to avoid handling problems or tail stall upsets while extending the wing flaps than the control group. Referring to Figure B.3, it is apparent that the greatest number of responses from the control group agreed that they could manage their control inputs to avoid handling problems, while there were an equivalent number of disagreement responses from the experimental group. This result was somewhat puzzling because it was apparent from the data in Figure 5 that quantitatively, the experimental group was significantly better than the control group in avoiding tail stalls. One possible explanation is that the experimental group was provided with displays that clearly showed the effects of wing flap extension on the safe AOA envelope, but were required by the test protocol to ignore those indications and extend the wing flaps regardless. This could well have led to their response choice because they *expected* handling problems as wing flaps were extended, and knew that they were unavoidable. The question may have been poorly worded in that respect.

5.6.3 Part III—ICEPro Integration

The experimental group was asked fifteen questions regarding the integration of ICEPro displays. Since these questions only affected that group, a descriptive statistical approach was taken in the analysis of the data. The primary goal of these survey questions was to understand if the implementation of real time state assessment into flyable pilot cues did in fact provide utility of ICEPro for the pilot. The key findings that follow list the percentage of responses on either side of a “neutral” opinion.

1. 40 percent agreed, 40 percent disagreed, that messages were not useful and cluttered the display
2. 53 percent agreed, 33 percent disagreed that combining visual, aural and tactile cues was important
3. 60 percent agreed, 40 percent disagreed that bars were useful to fly safely
4. 70 percent agreed, 20 percent disagreed that it was difficult to understand relation between AOA bars and Hi/Lo airspeed carets
5. 40 percent agreed, 40 percent disagreed that synoptic page was more useful than messages for state assessment
6. 47 percent frequently or always, 40 percent never or infrequently favored using airspeed carets over AOA bars for safe flight
7. 40 percent agreed, 47 percent disagreed that decluttering did not affect ability to recover from stall
8. 40 percent agreed, 47 percent disagreed that the “red” CLM and FLP LIM needed less flap setting for engine out performance.
9. 47 percent agreed, 40 percent disagreed that “control buzzing” made aircraft control difficult
10. 60 percent agreed, 30 percent disagreed that baseline airspeed tapes and carets were confusing
11. 60 percent frequently or always, 40 percent never or infrequently flew in middle of AOA bars
12. 47 percent frequently or always, 30 percent never or infrequently felt that AOA bars immediately captured attention when flashing.
13. 40 percent frequently or always, 47 percent never or infrequently felt airspeed cues were helpful for maneuvering/approach.

14. 60 percent frequently or always, 40 percent never or infrequently felt low α cue helped avoid tail stall upset
15. 67 percent agreed, 20 percent disagreed that they immediately noticed when CLM and FLAP LIM messages were on at the same time

Summarizing these key findings, the experimental group felt that the AOA brackets were very useful in all phases of flight, and were effectively able to use the brackets to keep the aircraft in a safe flight envelope. But many had difficulty understanding the relationship between angle of attack and airspeed. None of the participating pilots had experience with flying angle of attack prior to this test, and it is felt that this response was largely the result of this lack of experience. More pilots felt that presenting both the baseline airspeed along with the ICEPro generated airspeed carets was confusing. The original design intent of the ICEPro displays was to present the computed real time speeds as “advisory” information. This way, the pilot would always have a reference to the baseline aircraft, which would prove useful if a system anomaly was encountered. There was a concern for the manner in which this would be done to avoid confusion and the survey seemed to bear this concern out. Along those same lines, pilots were essentially ambivalent as to the usefulness of the ICEPro speed carets when maneuvering and flying the approach task as shown in Figure 6. A majority of pilots felt that the integration of visual, aural, and tactile cues was important, but providing redundant messages on two displays was not necessary. Lastly, one major concern was the assessment of the multi-axis control excitation or “buzzing”, which was commanded by the ICEPro logic for aircraft state assessment. Some pilots were bothered by the buzzing, and some were not. It appeared that because it was expected, pilots accommodated to this as they would if having to fly through turbulence. In any case, there did not seem to be a strong opinion one way or the other regarding control buzzing.

5.6.4 Part IV—Workload

Workload assessments via the NASA TLX format were gathered after each run for each pilot. Post-test questionnaires were solicited in an attempt to understand some of the important factors that influenced the scores that pilots gave to workload assessment. The survey answers from the control and experimental was assessed via the MWU methodology. Figure 9 provides the results from the survey questionnaire.

Pilot workload was not measurably affected by ICEPro cueing. The data indicated the following:

1. Controlling vertical speed on glide slope was more difficult for experimental group (60 versus 43 percent). It appears that the control group prioritized safe flight over strict airspeed control.
2. Flight control inputs were more physically demanding for the control group (73 versus 60 percent), possibly due to the fact that the control group was not aware of the magnitude of angle of attack divergence.
3. The control group reported that it took more concentration and effort for flying MAP safely (87 versus 80 percent). The results however did not meet the significance criterion, but did show that the experimental group did better.
4. Staying on glide slope without pitch upset was more difficult for control group (79 versus 67 percent). This was likely because the control group made corrections without knowledge of AOA limits. On the other hand, the experimental group had a real time display of AOA limits and could remain within those limits while correcting to the glide path. By “respecting” these limits, the experimental group tended to give greater priority to remaining in a safe flight conditions and were less aggressive in maintaining a precise vertical flight path. It should be noted however, that both groups flew the approaches within ATP standards as previously discussed.
5. Maintaining glide slope detracted from localizer control. This affected the experimental group more than the control group (64 versus 47 percent). This is thought to be a result of AOA cueing, which captured the pilot’s attention.

Pilot post-test survey questionnaire results	***z* score:** $z < -1.69$ for 95% confidence in H_0 rejection	**Probability:** $p < 0.05$ required to satisfy α (alternate hypothesis)	**Exp. versus Control** Positive real difference (PRD), Better (B), Worse (W), Same (S)
Part IV—Workload			
1. It was difficult to control vertical speed when on glide slope.	0.7856	0.7902	W
2. Operating the flight controls to avoid an upset condition when on final approach was a physically demanding effort.	–0.5455	0.2852	B
3. I felt it took a considerable amount of concentration and effort to safely execute the missed approach procedure.	–1.2002	0.1108	B
4. Keeping the aircraft on the glide slope without experiencing a pitch upset was a very demanding task.	–0.8074	0.2034	B
5. On final approach I spent so much time trying to fly the glide slope that I was unable to maintain good localizer course control.	0.5674	0.7221	W

Legend	
(green)	Meets 95% confidence for rejecting H_0
(blue)	Experimental group better over control group but < 95% confidence for rejecting H_0
(orange)	No difference between experimental and control group
(magenta)	Control group performance better than experimental group

Figure 9.—Pilot workload survey results.

In summary, the workload was not measurably affected by the addition of ICEPro system. Pilots seemed to accommodate to those displays rather quickly during their training, and appeared to use them quite effectively to perform the flight task. TLX data showed clearly that the flight task was very demanding for both groups of pilots, and the physical difficulty of it far outweighed other workload dimensions.

6.0 Conclusions and Recommendations

A pilot-in-the-loop simulator evaluation was conducted to assess the utility of ICEPro for mitigating a hazardous icing encounter. Most of the results of this testing were statistically quantified for real differences between a control and experimental group by the Mann-Whitney “U” test, which is a non-parametric, independent measures analysis of data used to define pilot control performance, pilot opinion, and workload. Other data, which was not compared between two groups, was analyzed descriptively. The conclusions from this test indicate that the experimental group of pilots, who flew with ICEPro displays, demonstrated significantly better control performance in dealing with aircraft handling problems under icing conditions and had better awareness of a hazardous aircraft state. Pilot workload was not affected by the additional display information provided by ICEPro, but pilot opinions of the implementation of that system indicate that improvements could be made. Based on the findings of this test, future testing with ICEPro should include the effects of environmental uncertainties, such as in-flight turbulence and wind gusts, on the quality-of-state assessment. Additionally, the flight displays in this test were not optimized from a human factors standpoint, nor were they coupled in any way with flight guidance. Based upon the opinions extracted from the pilot survey, pilot control performance and state awareness might be improved by addressing those issues in future testing.

Appendix A.—Post-Test Survey Questionnaire

Part I. Demographics

Name: ________________________ ☐ Male ☐ Female

Pilot Number: __________

Total Flight Hours: __________

Multi – Engine Hours: _________

FAA Ratings: Commercial ☐ Multi ☐ CFI ☐ CFII ☐

Aircraft Flown and Hours in Type:

____

____

Icing related training and experience:

1. In my all my prior flying experience, I encountered in-flight icing

Never Rarely Sometimes Very often Always

2. I felt that my prior icing related knowledge and experience would have adequately prepared me to perform this test scenario without the familiarization training I received on aircraft handling characteristics.

Strongly Disagree Disagree Undecided Agree Strongly Agree

3. The NASA videos and web based training materials provided me with information about icing that I had never known about before.

Strongly Disagree Disagree Undecided Agree Strongly Agree

4. Before this test, my icing related flight training was mostly focused on how to operate the ice protection system.

Strongly Disagree Disagree Undecided Agree Strongly Agree

Part II. Situation Awareness

1. My flight displays were adequate for me to determine when airframe icing was having an effect on aircraft characteristics.

Never Rarely Sometimes Very often Always

2. I felt as though I knew the minimum safe speed I could fly for a given wing flap setting within 5 knots.

Never Rarely Sometimes Very often Always

3. I knew how to adjust my pitch attitude to avoid a wing stall or a tail stall upset.

Never Rarely Sometimes Very Often Always

4. I wasn’t always sure which wing flap settings would allow a safe rate of climb in the event of an engine failure.

Strongly Disagree Disagree Undecided Agree Strongly Agree

5. I relied solely on aircraft control response to determine how icing affected pitch, yaw, or roll characteristics.

Strongly Disagree Disagree Undecided Agree Strongly Agree

6. I was confident that the final approach airspeed I chose to fly after I departed the final approach fix would prevent me from stalling.

Strongly Disagree Disagree Undecided Agree Strongly Agree

7. While I was putting the flaps down during the approach and landing, I felt I could effectively manage my control inputs and airspeed to avoid aircraft handling problems or tail stall upsets.
Strongly Disagree Disagree Undecided Agree Strongly Agree

8. The various colored bands on the airspeed tape were useful for me to safely fly the aircraft during the entire flight.
Never Infrequently Sometimes Frequently Always

9. I relied upon the stick shaker to prevent me from inadvertently stalling.
Never Rarely Sometimes Very Often Always

10. I could always tell when I was approaching a wing or tail stall condition.
Strongly Disagree Disagree Undecided Agree Strongly Agree

Part III. Implementation of Envelope Protection Cueing (Experimental ICEPro Group Only)

1. I felt that it was important to combine the visual cues from ICEPro with aural alerts, and tactile feedback from the stick shaker.
Strongly Disagree Disagree Undecided Agree Strongly Agree

2. The ROL DGRD, PTCH DGRD, or YAW DGRD messages on the PFD did not provide useful information, and only cluttered the display.
Strongly Disagree Disagree Undecided Agree Strongly Agree

3. When flying at slow speeds, I could easily use the AOA bars as a good pitch control reference for safely flying the airplane.
Strongly Disagree Disagree Undecided Agree Strongly Agree

4. I had difficulty understanding the relationship between the AOA bars and the high and low speed carets on the airspeed tape.
Strongly Disagree Disagree Undecided Agree Strongly Agree

5. The color coded flight control surfaces on the flight control synoptic were more useful than the messages for assessing degraded control state.
Strongly Disagree Disagree Undecided Agree Strongly Agree

6. I favored using the airspeed carets rather than the AOA bars to remain within a safe operating condition.
Never Infrequently Sometimes Frequently Always

7. When I unintentionally got into an upset condition, the disappearance of all ICEPro messages except the AOA bars on the PFD did not affect my ability to recover the airplane. (Answer only if a wing stall or tail stall upset occurred).
Strongly Disagree Disagree Undecided Agree Strongly Agree

8. When I extended the wing flaps and the red CLIMB LIM and FLAP LIM messages came on together, I immediately knew if an engine failed I would have to reduce my flap setting in order to climb.
Strongly Disagree Disagree Undecided Agree Strongly Agree

9. The occasional “buzzing” of the flight controls by ICEPro made flying the aircraft very difficult.
Strongly Disagree Disagree Undecided Agree Strongly Agree

10. I tended to confuse baseline airspeed limits with the airspeed limits (carets) that were posted by ICEPro.
Strongly Disagree Disagree Undecided Agree Strongly Agree

11. I tended to fly so as to keep my pitch attitude in the middle of the AOA bars when they were presented by ICEPro
Never Infrequently Sometimes Frequently Always

12. When the AOA bars started flashing, they immediately captured my attention.
Never Infrequently Sometimes Frequently Always

13. I felt that the airspeed carets from ICEPro were useful for helping me determine safe flight speeds when maneuvering during approach and landing.
Never Infrequently Sometimes Frequently Always

14. The low AOA cue on the PFD enabled me to avoid a tail stall upset.
Never Infrequently Sometimes Frequently Always

15. I immediately noticed when the CLIMB LIM and FLAP LIM messages were on at the same time.
Strongly Disagree Disagree Undecided Agree Strongly Agree

Part IV. Workload

1. I found it difficult to control vertical speed when on glide slope.
Never Infrequently Sometimes Frequently Always

2. Operating the flight controls to avoid an upset condition when on final approach was a physically demanding effort.
Never Infrequently Sometimes Frequently Always

3. I felt it took a considerable amount of concentration and effort to safely execute the missed approach procedure.
Strongly Disagree Disagree Undecided Agree Strongly Agree

4. Keeping the aircraft on the glide slope without experiencing a pitch upset was a very demanding task.
Strongly Disagree Disagree Undecided Agree Strongly Agree

5. On final approach I spent so much time trying to fly the glide slope that I was unable to maintain good localizer course control.
Never Infrequently Sometimes Frequently Always

Appendix B.—Results of Survey Questions from Parts I, II, and IV

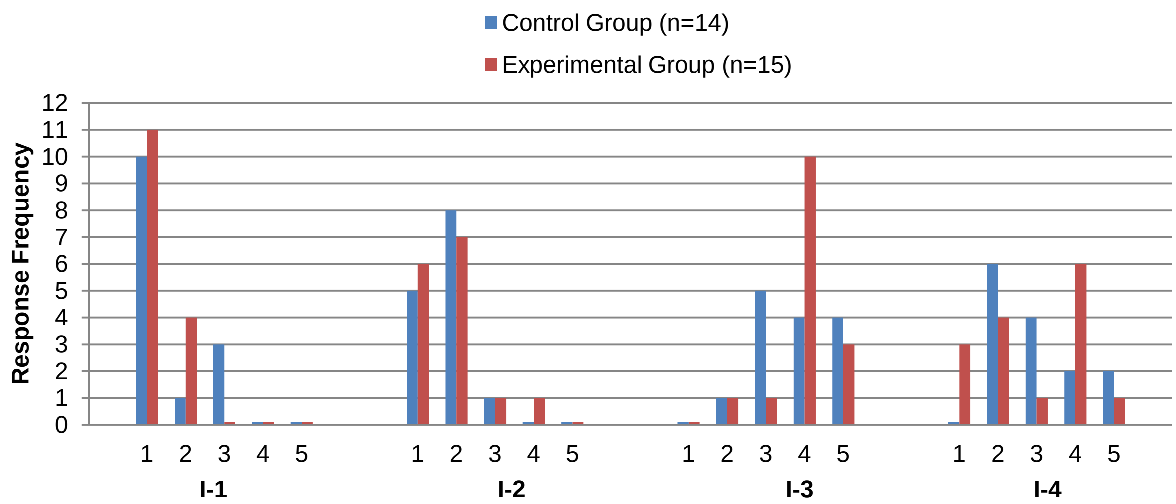

Figure B.1.—Pilot demographics—Part I Survey questions 1 to 4.

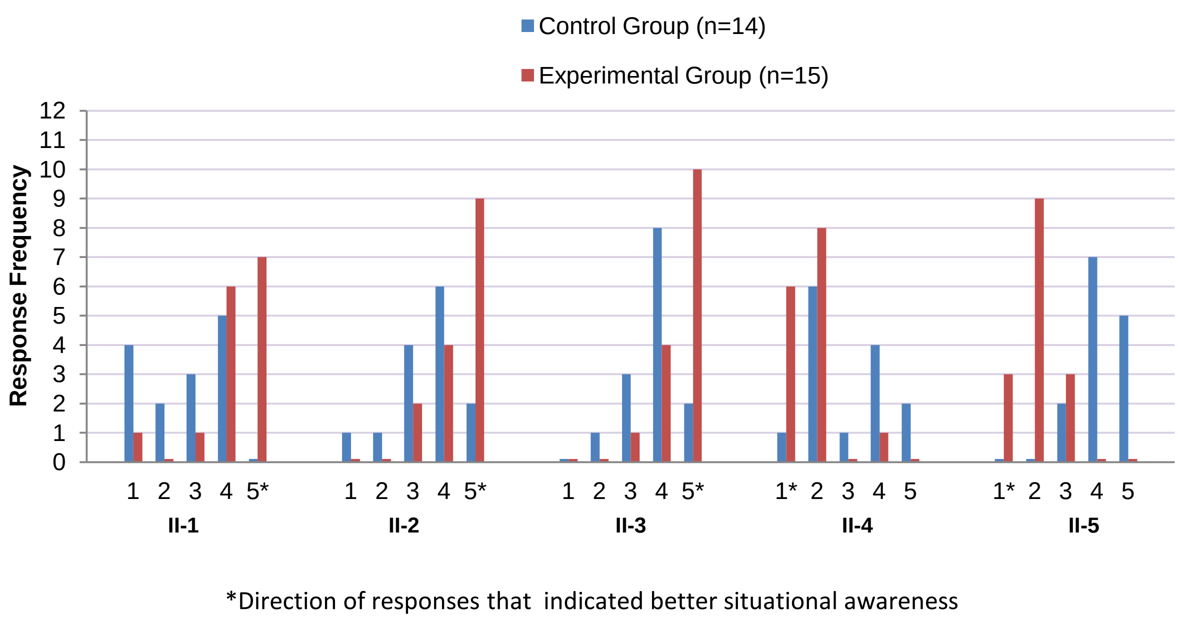

Figure B.2.—Situational Awareness—Part II Survey questions 1 to 5

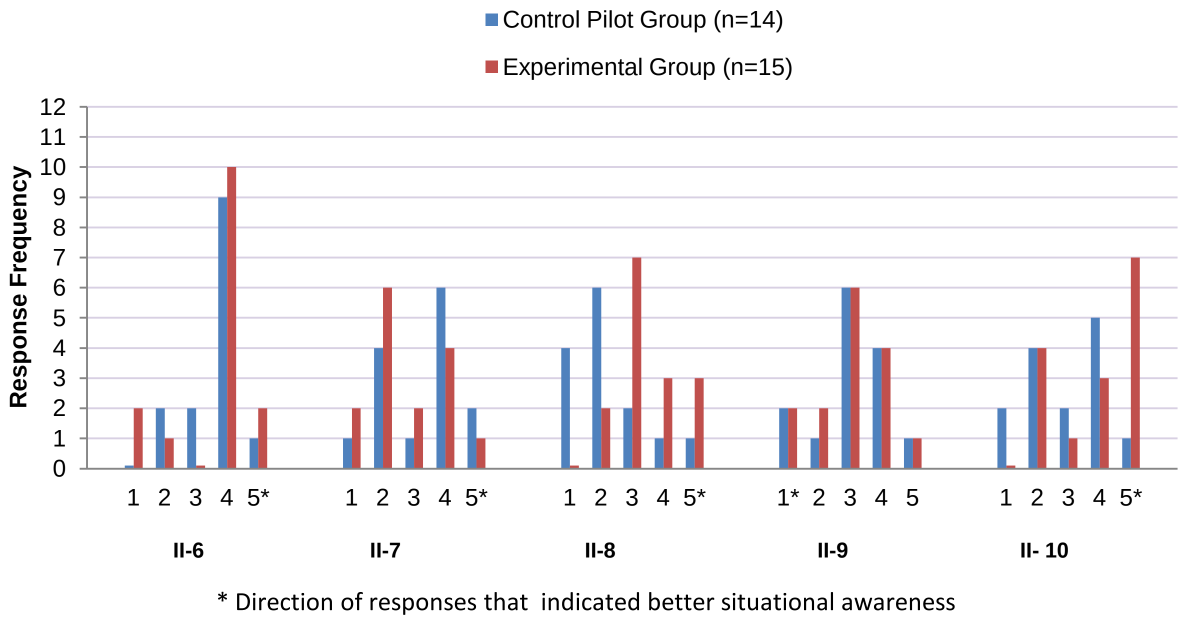

Figure B.3.—Situational Awareness—Part II Survey questions 6 to 10

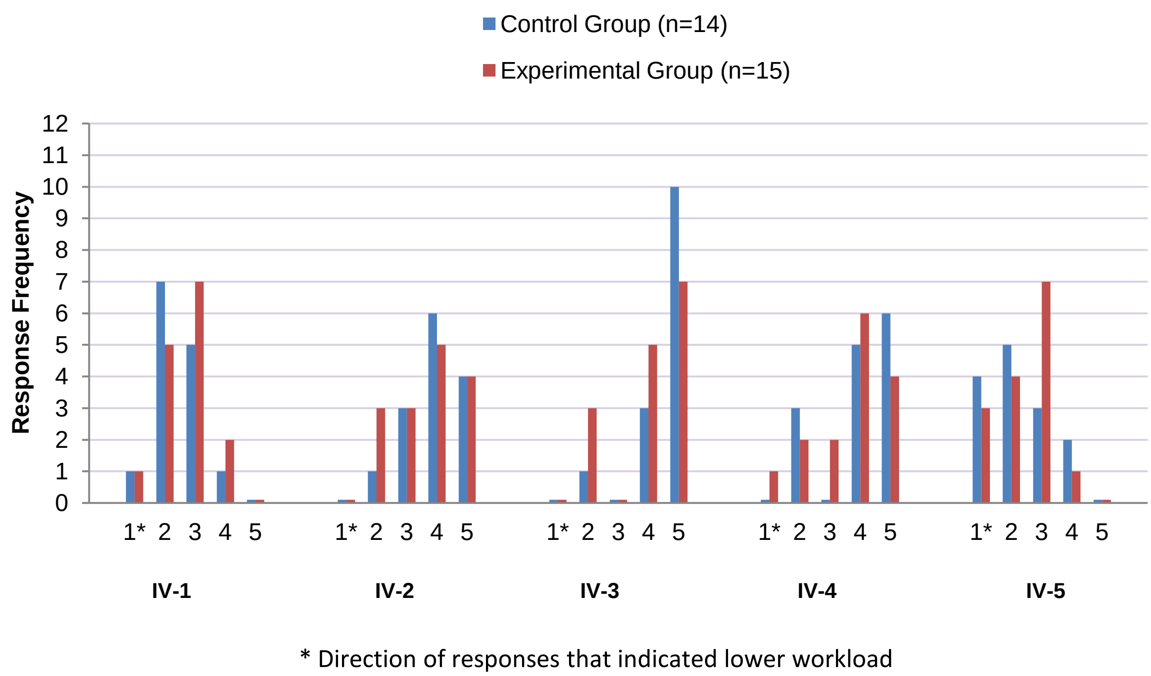

Figure B.4.—Workload—Part IV Survey questions 1 to 5.

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REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-10-2011

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Piloted Simulation to Evaluate the Utility of a Real Time Envelope Protection System for Mitigating In-Flight Icing Hazards

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Ranaudo, Richard, J.; Martos, Borja; Norton, Bill, W.; Gingras, David, R.; Barnhart, Billy, P.; Ratvasky, Thomas, P.; Morelli, Eugene

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 645846.02.07.11.02

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17556

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2011-216951

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 05 and 08
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The utility of the Icing Contamination Envelope Protection (ICEPro) system for mitigating a potentially hazardous icing condition was evaluated by 29 pilots using the NASA Ice Contamination Effects Flight Training Device (ICEFTD). ICEPro provides real time envelope protection cues and alerting messages on pilot displays. The pilots participating in this test were divided into two groups; a control group using baseline displays without ICEPro, and an experimental group using ICEPro driven display cueing. Each group flew identical precision approach and missed approach procedures with a simulated failure case icing condition. Pilot performance, workload, and survey questionnaires were collected for both groups of pilots. Results showed that real time assessment cues were effective in reducing the number of potentially hazardous upset events and in lessening exposure to loss of control following an incipient upset condition. Pilot workload with the added ICEPro displays was not measurably affected, but pilot opinion surveys showed that real time cueing greatly improved their situation awareness of a hazardous aircraft state.

15. SUBJECT TERMS
Aircraft icing; Flight safety; Flight simulation training; Ice protection system

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	35	STI Help Desk (email:help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(include area code)* 443-757-5802