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General Aviation Pilot Performance Following Unannounced In-Flight Loss of Vacuum System and Associated Instruments in Simulated Instrument Meteorological Conditions

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16. Abstract

Forty-one instrument-rated pilots were exposed to an unannounced failure of attitude and heading instrumentation during flight in single-engine general aviation aircraft: 25 in a Piper Archer PA-28 and 16 in a Beechcraft Bonanza A36. The PA-28 flights consisted of three groups: (1) Group A — a failure of the attitude indicator (AI) and directional gyro (DG), (2) Group B — same as Group A but received 30 minutes of partial-panel instruction in a personal-computer-based aviation training device (PCATD) prior to the flight, and (3) Group C – same as group A but had a failure-annunciator light (vacuum) on the panel. The A36 flights consisted of two groups: (1) Group A – a failure of the AI only, (2) Group B – a failure of the AI and the horizontal situation indicator (HSI). All of the PA-28 pilots maintained control of the aircraft, and 68 percent of them flew successful partial-panel approaches, and likely would have survived if it had been an actual emergency. However, 25 percent of the Bonanza pilots could not maintain control, and the evaluator had to assume control of the aircraft. Use of the PCATD prior to the data flight reduced the time required to recognize a failure while airborne (mean A&C = 7.6 min., mean for B = 4.9 min.), but there were no other observed differences in performance between the Archer groups. Recommendations are presented regarding both training and instrumentation.

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General Aviation Pilot Performance Following Unannounced In-Flight Loss of Vacuum System and Associated Instruments in Simulated Instrument Meteorological Conditions

BACKGROUND

There has been a concern with instrument flight and loss of attitude awareness for at least the last 50 years. There are two primary situations where loss of attitude awareness may lead to a fatal accident. The first is when a non-instrument-rated pilot inadvertently or intentionally enters instrument meteorological conditions (IMC), is unable to maintain the attitude of the aircraft, and ultimately enters either a spiral dive or increasingly severe oscillations that ultimately lead to aircraft structural failure. The AOPA Foundation, Inc., funded a study at the University of Illinois Institute of Aviation that was reported by Bryan, Stonecipher, and Aron (1954) in which a procedure was developed to help visual-flight-rules (VFR) pilots who had inadvertently wandered into IMC to return to visual meteorological conditions (VMC). Baseline data were collected at the beginning of the study to determine with what frequency pilots without instrument experience would enter potentially flight-terminating conditions. The 20 pilots ranged in age from 19 to 60 years, had no previous instrument experience, and had a minimum of experience with the Beechcraft Bonanza. Total pilot time ranged from 31 to 1625 hours. In their first exposure to simulated instrument conditions (created by wearing blue goggles in a cockpit with orange plexiglas covering the front and side windows), 19 of the 20 entered a "graveyard spiral" within an average of 3 minutes after losing their contact view of the outside world. The 20th placed the aircraft into a whip-stall attitude. These results were obtained with cockpit instrumentation sufficient to conduct instrument-referenced flight.

The second contributing situation is the one in which instrument-rated pilots in IMC lose their attitude reference through vacuum/pressure system or instrument failure. The majority of the 207,000 airplanes in the general aviation (GA) fleet have vacuum-powered attitude indicators (AIs) and heading indicators. Many of those same airplanes are not equipped with back-up or secondary attitude indicators or a back-up vacuum pump. Therefore, instrument-rated pilots must demonstrate the ability to fly airplanes in "partial-panel" (loss of vacuum instruments) conditions as part of their initial and recurrent training. This usually entails maintaining controlled flight using indications from the pitot/static system instruments (airspeed indicator, vertical speed indicator, and altimeter), electric gyro instruments (turn coordinator), and magnetic instruments (compass). Inasmuch as partial-panel flying is usually simulated by covering up the supposedly "failed" instruments, pilots do not have the opportunity to experience a realistic vacuum failure, in which they would have to detect and diagnose the failure - unless it is an actual emergency. This type of mechanical failure (vacuum system or related instruments) has been documented as a causal factor in only about three accidents per year, which is 11% of all documented spatial disorientation accidents. However, these accidents result in fatalities approximately 90% of the time (Landsberg, 2002; data from the Air Safety Foundation, ASF, database of National Transportation Safety Board accident reports). If one was to look at the combination of a VFR pilot entering IMC and experiencing a vacuum-system failure, thus losing any attitude reference, it is not difficult to imagine the fatality rate being even higher (little data exist, however, on this specific combination of factors). That is to say, if pilots who flew primarily by visual reference had difficulty flying by reference to a full set of instruments, it is likely that they would be completely unable to continue under partial-panel conditions.

This study is a continuation of a study conducted for the AOPA/ASF by Martinez (2000) and administered by Flight Safety International (FSI) in 2000. Martinez reported on pilot performance following the failure of an aircraft vacuum system in single-engine Cessna 208 and Cessna 210 simulators, with motion disabled. Beringer and Ball (2001) reported a similar study in fixed-base single-engine Cessna 172 and Piper Malibu simulators, with results comparable to Martinez'.

In the Martinez study, 66.7 % of the 24 test flights resulted in loss of control and 50 % of the flights ended in a crash. Beringer and Ball's results from a sample of 60 pilots showed that 27 % of the 11 pilots flying the Malibu with the electric horizontal situation indicator (HSI) would have exceeded performance limitations of the aircraft or struck the ground. A simulated vacuum-driven directional gyro (DG) was depicted in place of the HSI to represent the majority of low-end GA aircraft for one group, and 83 % of those 12 pilots lost control, exceeded performance limitations of the aircraft, or would have struck the ground. When a back-up AI was depicted in place of the turn coordinator (TC), 33 % of the pilots in that group were unsuccessful in continuing the flight. Best performance was obtained with a back-up AI, HSI and turn coordinator (only 8 % loss). The Cessna 172 pilots, with a warning flag on the AI, fared better, with only one (8 %) loss of control. However, differences in stability between the Malibu simulator and the Cessna simulator (more stable in roll) placed limitations on interpretation. Beringer and Ball recommended replacing the DG and very-high-frequency omni range (VOR) heads with an HSI, freeing up an instrument location for a back-up electric AI.

The Air Safety Foundation, in coordination with the FAA Civil Aerospace Medical Institute (CAMI), developed the present study to collect baseline aircraft data evaluating pilots' skills in dealing with an unannounced vacuum failure in flight for comparison with results obtained in flight simulators. The following sections describe the details of the effort and the results obtained.

METHOD

Participants

Forty-one volunteer pilots (40 males, 1 female) were selected from approximately 300 applicants who responded to an announcement on the ASF Web site. The primary goal in the selection process was to choose a wide variety of pilots, regarding demographics and flight experience. Pilots participated without monetary compensation. Table 1 presents demographic data for both the Archer and the Bonanza pilot groups.

Equipment

Aircraft. The two aircraft used were a simple (Piper Archer PA-28) (see Figure 1) and a complex (Beechcraft Bonanza A36; see Figure 2) airplane. Each was equipped with all Federal Aviation Regulation - FAR - required items for a single-pilot IFR flight. Polarized material was placed across the lower portion of the windscreen and left side window of each aircraft (see Figure 3) so that approximately the lower two-fifths of the windscreen was covered. The Francis hood used to simulate IMC (see inset, Figure 3) contained the same polarized material in the eye openings, oriented 90° to

Table 1. Pilot demographic data by group.

ARCHER (n=25 males)				
Variable name	*Mean*	*Median*	*Minimum*	*Maximum*
Age (years)	50	53	20	79
Total Pilot-in-Command time (hours)	4,358.0	1,477	161.0	24,750.0
Total instrument time (hours)	1,528.0	283	20.0	14,000.0
Total instrument time in the last 90 days	3.9	3	0.0	9.7
Years since rating received	19.2	19	0.3	58.0
BONANZA (n=15 males, 1 female)				
Age (years)	46	44	32	62
Total Pilot-in-Command time (hours)	1,714.0	1,397.0	195.0	5,495
Total instrument time (hours)	294.0	212.0	45.0	816
Total instrument time in the last 90 days	4.7	2.5	0.0	25
Years since rating received	13.2	12.9	1.2	32

Figure 1. Archer instrument panel.

Figure 2. Bonanza instrument panel.

Figure 3. Polaroid material across windscreen of Piper Archer with (inset) Francis hood.

the windshield material. This arrangement allowed the pilots to see inside the cockpit, but eliminated the outside view immediately above the glare shield.

The PA-28 flights consisted of three groups (Table 2): (1) Group A - a failure of the AI and the DG, (2) Group B - same as Group A but received 30 minutes of partial-panel instruction in a personal-computer-based aviation training device (PCATD) prior to the flight, and (3) Group C – same as group A but had a failure-annunciator light (vacuum) on the panel. The A36 flights consisted of two groups (see Table 2): (1) Group A – a failure of the AI only, (2) Group B – a failure of the AI and the HSI.

Data recording. Several forms of data were recorded for each flight. Flight performance data were recorded via a Cambridge Aero Instruments GPS Navigator and Secure Flight Recorder. This generated a plan-view map and vertical-profile view of the flight path for the purpose of assessing average and maximum flight-path deviations. A color digital video recording was also obtained during the flight with audio of all intercom/radio communications. The field of view of the camera, which was attached to the cabin headliner behind and to the right of the front left seat, included the subject pilot, key flight instrumentation, and the forward view out of the windscreen. Additionally, the pilot and evaluator each completed a post-scenario questionnaire at the conclusion of the flight .

Table 2. Operational instruments available for each pilot group. X indicates feature was present.

Pilot Group	AI	DG	HSI	TC	Compass	Annunciator Light	Vacuum gauge
Archer A			N/A	X	X		X
Archer B			N/A	X	X		X
Archer C			N/A	X	X	X	X
Bonanza A		N/A	X	X	X	X	X
Bonanza B		N/A		X	X	X	X

Archer implementation of vacuum failure. Prior to each flight, an airframe and powerplant (A&P) mechanic disengaged the aircraft's engine-driven vacuum system. Therefore, the AI and DG were fully operational only via the standby vacuum system. During the flight, the evaluator disengaged the standby system via a switch in the cockpit, thereby failing the vacuum-driven instruments in a realistic manner.

Bonanza implementation of vacuum failure. Prior to each flight, an A&P mechanic disabled the aircraft's engine-driven instrument air pressure pump. The AI was powered by the standby system. The HSI is electrically powered, so no maintenance was required before the flights for that instrument. During the flight, the evaluator disengaged the standby air pressure system and HSI via their individual circuit breakers in the cockpit. It is important to note that, because the AI was vacuum-driven and the HSI was electric, this was not a "real world" failure. It would be rare for both vacuum systems *and* one electric instrument to fail during flight.

Procedures and Tasks

Each scenario began with a pre-flight interview and briefing involving the volunteer pilot and the evaluator. Safety information for the flight was discussed, and each volunteer completed a consent form and a flight-experience questionnaire. The pilot was briefed about proper aircraft operation, including airspeed and power settings, and the flight plan was discussed. The volunteers were told they would be evaluated on their execution of IFR procedures. The autopilot was turned off for the duration of each flight.

After the briefing and pre-flight inspection of the airplane, the pilots departed the Frederick Municipal Airport (FDK) in Frederick, Maryland. The evaluator acted as an air traffic controller (ATC), giving the pilot heading vectors for the instrument landing system (ILS) Runway 23 approach at FDK. The purpose of this first approach was to allow the volunteer to practice flying in simulated IMC and to allow the flight data recorder to establish a baseline for the pilot's performance under normal conditions. The approach was discontinued at approximately 800 feet above ground level (AGL). At that time, "ATC" issued a clearance for the pilot to climb to 3,000' and fly a heading of 270° to the Eastern WV Regional/Shepherd Airport (MRB) in Martinsburg, West Virginia.

During the climb after the ILS approach, at a specific standardized point (point D in Figure 4), the aircraft vacuum/pressure pump (and HSI in the Bonanza) was disengaged without the pilot's knowledge, leading to the eventual loss of the aircraft's attitude and heading indicators. The pilot's task was to maintain control of the aircraft, select the best option(s) to pursue, navigate accurately, communicate effectively with ATC, and complete the flight with a safe landing at either the destination or an alternate airport.

The simulated weather conditions were such that FDK was the best alternate airport. "ATC" provided vectors to a point that provided the pilot an intercept heading and altitude to the ILS Runway 23 approach at FDK. If requested by the pilot, "ATC" provided no-gyro vectors above 2,500'. No-gyro vectors consisted of the direction of turn, and when to start and stop that turn. The evaluator took control of the airplane if the pilot at any time maneuvered to a bank angle approaching 60 degrees and increasing, if the aircraft's airspeed was approaching Vne (never-exceed speed) and increasing, if the aircraft was approaching a stall condition, or for any other reason deemed necessary for the safety of the flight. All flights were conducted in weather conditions that would allow the scenario to be completed in VFR conditions. The evaluator acted as pilot in command for each flight relative to flight safety issues.

RESULTS

Response to the vacuum-failure event required two tasks to be performed. First, the pilot had to recognize that a failure of some kind had occurred and correctly diagnose it and, second, the pilot then had to successfully control the aircraft using the flight data remaining. The following sections consider each component in turn.

Recognition Time

Time to detect/recognize the failure was measured from the time the failure was initiated to the first verbal report by the participant of something being "wrong." Although some pilots attempted adjustments to the AI prior to verbal reporting, the only consistent scoring point that could be used was the verbal report.

The PA-28 pilots averaged a higher recognition time, with an average of 6.9 minutes for the entire group. (See Table 3.) The pilots who flew partial-panel on the PCATD prior to their flight recognized the instrument failure more quickly; however, the differences among the Archer groups did not attain statistical significance [$F\ (2,21)=2.54,\ p>0.1$] (4.9 minutes, vs. 7.6 for the other groups). Neither can comparisons be made between the two aircraft because of potential differences in the rate at which the vacuum/pressure-driven instruments in each failed. The

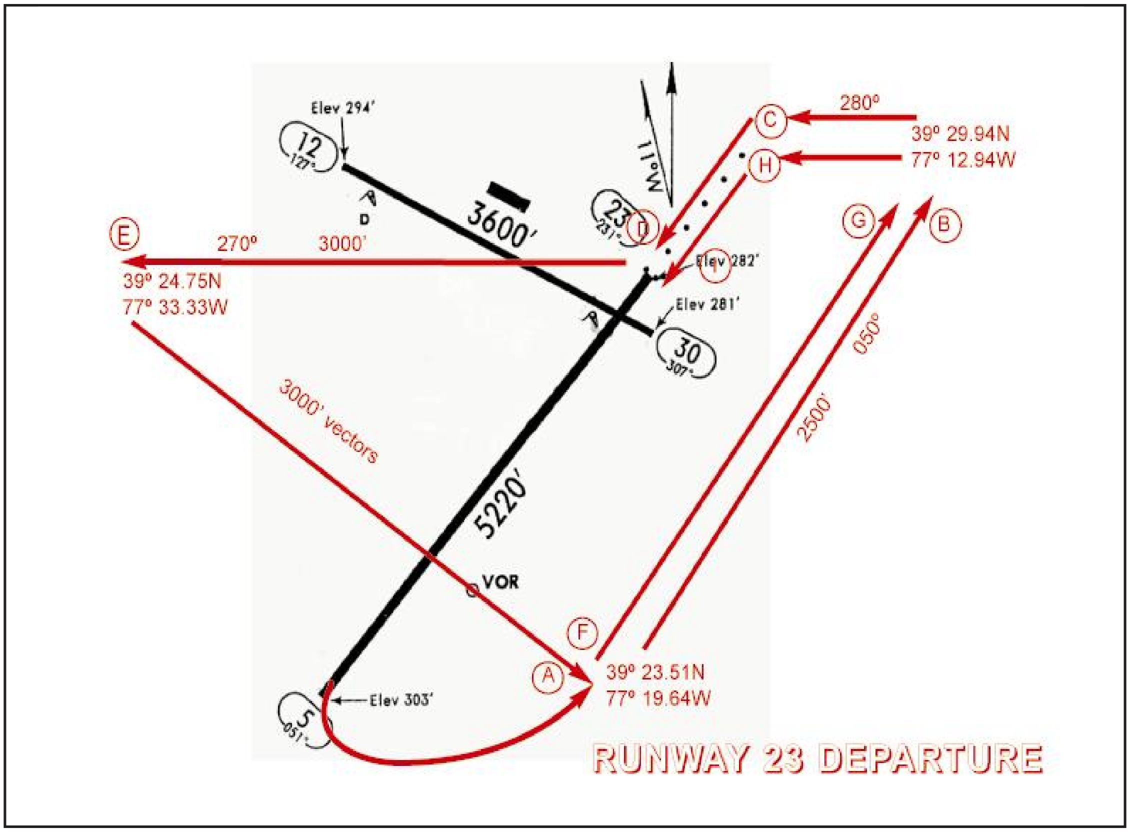

Figure 4. Scenario chart showing point (D) where vacuum/pressure system was disengaged and intended flight paths.

Bonanza pilots who experienced a failure of the HSI as well as the AI recognized the failure in an average of 2.6 minutes, which was significantly faster than the average 4.6 minutes for those pilots who had only an AI failure [F (1,14)=6.372, p<. 05]. The HSI was equipped with a warning flag to announce instrument failure, and this undoubtedly aided pilots in the Bonanza B group.

Flight Performance Data

Outcomes of all flights were categorized as follows:

Category 1: The pilot had no problem controlling the aircraft. The deviation was less than 20 degrees and 200 feet.

Category 2: The aircraft remained under the pilot's control, but with more effort than the category 1 pilots. The deviation was between 20 and 40 degrees inclusive and 200 to 400 feet.

Category 3: The aircraft was barely under control – the pilot was struggling significantly.

Category 4: The evaluator had to take control of the aircraft. Had this been a real instrument failure in IMC, the flight likely would have resulted in a crash.

Archer. All of the PA-28 pilots were able to maintain control of the aircraft under partial-panel conditions. However, some became disoriented and were not able to successfully execute an approach and landing to the airport. Thirty-two percent of the pilots did not successfully complete the approach (i.e., 68 % were successful). An example of the horizontal and vertical-profile plots obtained from each flight is depicted in Figure 5.

Archer Procedures. Upon noticing the vacuum system failure, 28 percent of the PA-28 pilots declared an emergency to "ATC" (the experimenter). At the next level of urgency, 68 % notified ATC of the problem without declaring an emergency, but one pilot (4 %) gave "ATC" no notification of the problem. Distraction played a significant role in that 28 % of the pilots covered the failed instruments to prevent distraction or being mislead by the now-failed indicators. The remaining 72 % did not do so and tended to include the failed instruments in their scan, indicating to the experimenter that this was a distracting situation.

Bonanza. Twenty-five percent of the A36 pilots lost control of the aircraft. All four of those pilots (3 males, 1 female) were in Bonanza Group B (loss of AI and

HSI). Two of these four were experienced Bonanza pilots, thus the effect is not solely attributable to lack of familiarity with the aircraft type. Sixty-nine percent of the pilots were able to successfully complete a partial-panel approach, including two of the pilots who had lost aircraft control but were given a second chance to fly the aircraft partial panel.

Bonanza procedures. None of the A36 pilots declared an emergency to "ATC," choosing instead to simply notify "ATC" of the problem and request assistance. One pilot (6 %) covered the failed instruments – that pilot had no problem controlling the aircraft, and is classified as a Category 1 flight. Flight performance outcomes for each group are summarized in Table 4.

The distribution of loss-of-control flights was such that a chi-square analysis was not appropriate given the number of cells having expected and/or observed frequencies less than five. The distribution of failed approaches by aircraft type was amenable to such an analysis, but there was no significant effect attributable to aircraft type.

Table 3. Mean recognition time per pilot group.

Pilot Group	**Average time to recognize failure (minutes)**
Archer A	7.3
Archer B	4.9
Archer C	7.9
Bonanza A	4.6*
Bonanza B	2.6*

Note:
* The only significant difference was between these means. Archer A pilots used standard Archer instrumentation.

Archer B pilots received 30 minutes of partial panel PCATD training prior to their flight.

Archer C pilots had a vacuum annunciator light as a warning when the vacuum system failed.

Bonanza A pilots experienced an AI failure.

Bonanza B pilots experienced both AI and HSI failures.

Response to Warning Indicators/instruments

Only one (12.5 %) of the Archer pilots in Group C (vacuum annunciator light available) actually noticed the light. Only one (4 %) out of all of the Archer pilots noticed the vacuum gauge at the onset of the emergency. The others simply used it to verify the system failure once the instruments were tumbled. Previous studies (Beringer and Ball, 2001) listed the vacuum-low annunciator light as one of the first failure indications detected by the participants in the conditions where it was available. The present finding is not too surprising, given that the pilots were wearing the Francis hood, which greatly limits peripheral and parafoveal vision, and that the vacuum gauge was located on the right side of the cockpit, well out of the area of vision when viewing the primary instrument cluster. It should also be noted that the vacuum annunciator light was small and not very bright. This suggests that some attention may need to be given to indicator placement and conspicuity.

Pilot Experience Variables

Several questionnaire forms were administered to gather experience data from each pilot. Questions assessed experience with the specific model of aircraft to be flown, certificates/ratings, date of instrument rating, pilot-in-command hours (total and last 90 days), instrument hours (total, last 12 months, last 90 days, and "actual"), instrument training in the last 90 days (last date of partial-panel training, amount of partial-panel training, description of that training), hours flown annually, number of approaches in the last

Table 4. Frequency of outcome by aircraft group. Subscripts indicate number of pilots in that category who failed to complete the instrument approach in partial-panel conditions.

Pilot Group	**Category 1:** Successful partial panel	**Category 2:** Required more effort	**Category 3:** Barely controlled	**Category 4:** Safety pilot took over	**Total sample size**
Archer A	6_1	5_2	1	0	12
Archer B	3_2	2_1	0	0	5
Archer C	4	4_2	0	0	8
Bonanza A	1	2	1_1	0	4
Bonanza B	4	2_1	2_1	4_2	12

Figure 5. Example plan-view (top) and vertical profile (bottom) plots of a flight.

90 days, and experience using GPS equipment. Only two observations are worth noting. The PA-28 pilots who had more than three instrument flight hours during the 90 days preceding their flight (40 %) were noticeably more proficient. Nine (75 %) flew Category 1 flights and three (25 %) flew category 2 flights. However, it should be noted that no significant correlations were found between pilot experience variables and performance variables, including categorization, for the PA-28 sample. This is undoubtedly due to the small sample size. The only pilot-experience variable that showed a significant correlation with performance (Spearman's rho) was total pilot-in-command (PIC) hours (rho = -.622, p=.01). Practically speaking, a higher PIC total was associated with a greater likelihood of obtaining a better (lower-numbered) category of performance.

Simulator and Training Benefits

Pilots reported that flying the partial-panel trial was a beneficial experience and that they felt better prepared to handle this type of emergency situation in actual IMC after having participated in the study. Those who flew the Elite PCATD flight simulator prior to their aircraft flights indicated that the training helped them. Specifically, they said that they were better prepared to handle an emergency and were already "warmed up" to fly after the training-device practice. Recommendations related to training included encouraging flight schools to have at least one aircraft configured to present vacuum-system failures in flight, providing students with the opportunity to detect and diagnose this failure in a realistic-onset environment. This was proposed in contrast with the present practice of having the instructor place covers over instruments to be deemed "failed" during practice. In addition, it was the majority opinion that pilots need more practice flying with partial-panel instrumentation.

Limitations on Interpretation of the Data

A number of factors could have affected the outcome of the airborne trials and should be considered when interpreting the data. Each is listed and discussed briefly below:

Artificial termination of flight: The evaluator terminated any flight at the onset of unsafe conditions. Therefore, it was not possible to determine if a crash would have actually occurred. For the four A36 losses of control, it is likely that the flight would have been fatal.

Source of participants: As volunteers, the pilots may not have been an accurate representation of the 309,000 instrument-rated pilots in the US. It is likely that volunteers were more proficient than average general-aviation pilots.

Experience with test aircraft: The pilots had no flight time in the actual study aircraft (8121K and 7236W) prior to the experiment. However, most pilots are familiar with PA-28 aircraft and have flown them as part of their initial flight training. That may be why a higher percentage of the PA-28 pilots were able to control the aircraft during the loss of horizon reference as compared with the Bonanza groups.

Simulated IMC and safety pilot: The scenario was simulated single pilot IMC, actually flown under VFR conditions with a safety pilot. The pilots likely would perform differently if they had actually been alone during a real emergency (more may have declared an emergency; fewer may have pressed the limits of the performance envelope).

Compound systems failure, Bonanza: The A36 had a pressure-air-powered attitude indicator (AI), but an electric horizontal situation indicator (HSI). Therefore, there was not an actual pressure-air-system failure, but instead, two individual instrument failures. That may have resulted in more confusion for the pilots flying the scenario who were familiar with redundant systems, although none of the A36 pilots mentioned this issue during the post-flight briefing.

Supplemental visual cues: Pilots may have received some supplemental cues to aircraft attitude from shadows playing across the cockpit or from occasional fragmentary outside-world views when the head was tilted (polarizing fields not fully orthogonal). This could have improved their performance slightly as a group.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study reflect to some degree the simulator data obtained by Beringer and Ball (2001). On one hand, the results with the simple airplanes (Cessna 172 and Piper PA-28) were very similar in that pilots flying that simulator and aircraft were largely in control of the flight to completion. It was also true that virtually all of the recorded losses of control occurred with the complex aircraft (Malibu simulator and Bonanza A-36 aircraft; only one loss was recorded in the Skyhawk simulation). These results, taken together, suggest that we are likely to see more problems associated with high-performance aircraft than with the simpler fixed-gear, fixed-pitch-propeller aircraft when vacuum failures are encountered. However, it should also be noted that the loss rate using the airborne platform (Bonanza) was far lower, for equivalent instrument equipage, than that found in the Malibu simulator. Given the factors listed that may have compromised, to some degree, the outcomes of the airborne observations and the simulator trials, we believe that the likely rate at which serious controlling difficulties may be encountered in actual aircraft lies somewhere between the two figures.

Unfortunately, no airborne assessment of the efficacy of a back-up attitude indicator was obtained. Nonetheless, it is reasonable to believe, based upon the simulator data, that the percentage of complex-airplane pilots experiencing serious difficulties after loss of the horizon reference could be further reduced with the proper instrumentation. The presence of the functioning electric HSI after the vacuum failure appeared to greatly reduce the difficulty of maintaining control in the Bonanza, and this was consistent with data from the Beringer and Ball simulator study.

Given the results to date, as represented in the cited simulator studies and the airplane study reported herein, the following recommendations are submitted for consideration:

Training: Attention should be given to any training wherein detection and diagnosis can be practiced in as realistic a setting as possible. This should include simulators, aviation training devices, and/or aircraft with vacuum systems specially adapted for the removal of power from at least one attitude instrument on the trainee's side.

Warnings indicators: Attention should be given to the location and design of indicators for system or instrument failure. Vacuum-failure indicators should be located as close to the primary panel as possible and should be very conspicuous. Attitude indicators should be flagged to indicate loss of power, whether electrical or air. This can also be done by referencing gyro RPM and indicating whenever it drops below the minimum deemed necessary for reliable operation.

Instrumentation: Three levels of instrumentation modification are suggested in order of increasing cost/complexity:

1) Given that a reliable heading reference has been demonstrated to be useful in maintaining control, one option is to replace the directional gyro with a heading indicator that is independent of the attitude indicator's power source and that will continue to function, obviating the need for referencing a fluid-filled compass. This also brings the heading indicator into the primary panel/scan and reduces both scanning requirements and the need to compensate for the known behaviors of a fluid-filled compass.

2) Integrating instrumentation can also produce decluttering benefits and free up space for additional instrumentation. Thus, another option is to install an HSI in place of a directional gyro and a VOR head, providing multiple indications within one instrument, reducing required scan, and opening up an instrument location on the panel.

3) It is also likely that a back-up attitude indicator would be useful in reducing pilot workload based upon the simulator-study results. This must be independently powered relative to the primary attitude indicator, and each should be flagged to indicate instrument or power-system failure. This option, however, is not directly addressed by data in this study.

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