Aircraft Loss of Control: Problem Analysis for the Development and Validation of Technology Solutions

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Aircraft loss of control (LOC) is a leading cause of fatal accidents across all transport airplane and operational classes. LOC can result from a wide spectrum of precursors (or hazards), often occurring in combination. Technologies developed for LOC prevention and recovery must therefore be effective under a wide variety of conditions and uncertainties, including multiple hazards, and the validation process must provide a means of assessing system effectiveness and coverage of these hazards. This paper provides a detailed description of a methodology for analyzing LOC as a dynamics and control problem for the purpose of developing effective technology solutions. The paper includes a definition of LOC based on several recent publications, a detailed description of a refined LOC accident analysis process that is illustrated via selected example cases, and a description of planned follow-on activities for identifying future potential LOC risks and the development of LOC test scenarios. Some preliminary considerations for LOC of Unmanned Aircraft Systems (UAS) and for their safe integration into the National Airspace System (NAS) are also discussed.

Nomenclature

AAIB = UK Air Accidents Investigation Branch
AAIU = Irish Air Accident Investigation Unit
ASN = Aviation Safety Network
ATLAS = Aviation Team Looking Ahead at Safety
ATSB = Australian Transport Safety Bureau
BEA = French Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile
BFU = German Bundesstelle für Flugunfalluntersuchungin

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CAST = Commercial Aviation Safety Team
DoD = Department of Defense
ICAO = International Civil Aviation Organization
LOC = Loss of Control (in-flight)
NAS = National Airspace System
NASA = National Aeronautics and Space Administration
NextGen = Next Generation Airspace Operations Concept
NIA = National Institute of Aerospace
NTSB = National Transportation Safety Board
SME = Subject Matter Expert
TSB = Canadian Transportation Safety Board
UAS = Unmanned Aerial System

I. Introduction

Aircraft loss of control (LOC) is a leading cause of fatal accidents across all transport airplane and operational classes.[1, 2, 3] The development and validation of technologies for LOC prevention and recovery poses significant challenges. Aircraft LOC can result from a wide spectrum of precursor events and hazards, often occurring in combination [4], which cannot be fully replicated during evaluation. Technologies developed for LOC prevention and recovery must therefore be effective (i.e., resilient) under a wide variety of conditions and uncertainties, including multiple LOC precursors and hazards, and the validation process must provide some measure of assurance that the new vehicle safety technologies do no harm – i.e., that they themselves do not introduce new safety risks.

Onboard systems technologies have been developed by NASA as part of a holistic approach for LOC prevention and recovery.[5, 6] A validation framework involving analysis, simulation, and experimental testing has also been developed by NASA for safety-critical integrated systems operating under hazardous conditions that can lead to LOC [7, 8], and a preliminary set of LOC test scenarios [9] was developed based on a limited set of flight accidents. Preliminary analysis results have been reported [10] for a comprehensive set of transport aircraft accidents over a recent 15-year period (1996 – 2010), including a methodology for the identification of worst-case combinations of causal and contributing factors and how they sequence in time. This analysis, when complete, will be used in the development of a set of LOC test scenarios that can be used in the validation of onboard systems technologies for LOC prevention and recovery. Since enhanced engineering simulations are required for batch and piloted evaluations under realistic LOC precursor conditions, these test scenarios also serve as a high-level requirement for defining the simulation enhancements needed for generating realistic LOC test scenarios.

Since publication of the preliminary analysis results for transport aircraft (see Ref. 11), the analysis process has been substantially refined and is being applied to the transport accidents and incidents identified in Ref. 11 as well as for the analysis of unmanned aircraft systems (UAS) mishaps (i.e., accidents and incidents). Refinement of the methodology includes the addition of LOC precursors, the addition of flags for quickly identifying key issues of interest for LOC, the identification of potential research solutions for each accident (if applicable), and the capture of specific comments for each precursor. Each precursor comment is taken from the accident report and specifies why each precursor is included in the sequence. This paper provides a detailed summary of this refined analysis methodology and provides some examples to illustrate it. Section II presents an overview of recent definitions for transport aircraft LOC as well as the refined LOC problem definition used in performing the analysis. Section III provides a detailed description of the refined LOC accident analysis process, which is illustrated via selected example cases. Individual hazards occurrences are also summarized in Section III for the mishaps analyzed to date. Section IV describes the analysis products resulting from this work as well as follow-on research to identify future potential LOC risks and develop hazards-based test scenarios for use in the development and validation of technology solutions for LOC prevention and recovery. Section V presents a discussion of the importance of LOC prevention and recovery for future resilient and autonomous systems as well as some preliminary considerations based on this work for the safe integration of UAS into the National Airspace System (NAS). Section VI provides a summary of the paper and some concluding remarks.

II. Aircraft Loss-of-Control (LOC) Problem Definition

LOC can be described as motion that is: outside the normal operating flight envelopes; not predictably altered by routine pilot control inputs; characterized by nonlinear effects, such as kinematic/inertial coupling; disproportionately large responses to small state variable changes, or oscillatory/divergent behavior; likely to result in high angular rates and displacements; and characterized by the inability to maintain heading, altitude, and wings-level flight.[11] LOC also includes situations in which the flight path is outside of acceptable tracking tolerances and cannot be predictably controlled by pilot (or autoflight system) inputs.[12] LOC is therefore fundamentally a dynamics and control problem. It is important to note that LOC need not be unrecoverable, but *if left unaddressed it may become unrecoverable*. LOC is also a complex problem in that there are many causal and contributing factors that can lead to LOC (see Refs. 5 & 11). The primary causes include: entry into a vehicle upset condition; reduction or loss of control power; changes to the vehicle dynamic response in relation to handling/flying qualities; and combinations of these causes. There are numerous factors that have historically led or contributed to LOC. These can be grouped into three major categories: adverse onboard conditions, external hazards and disturbances, and abnormal flight conditions (or vehicle upsets). LOC causal and contributing factors within these categories are summarized in Fig. 1. Adverse onboard conditions include vehicle problems (i.e., impairment, failures, or damage) and inappropriate crew response. External hazards and disturbances consist of inclement weather conditions, atmospheric disturbances, and obstacles that require abrupt maneuvering for avoidance. Vehicle upset conditions include a variety of off-nominal or extreme flight conditions and abnormal trajectories. The complexity of LOC is clearly illustrated in Fig. 1, particularly considering that many LOC accidents involve combinations of the causal and contributing factors that are listed.

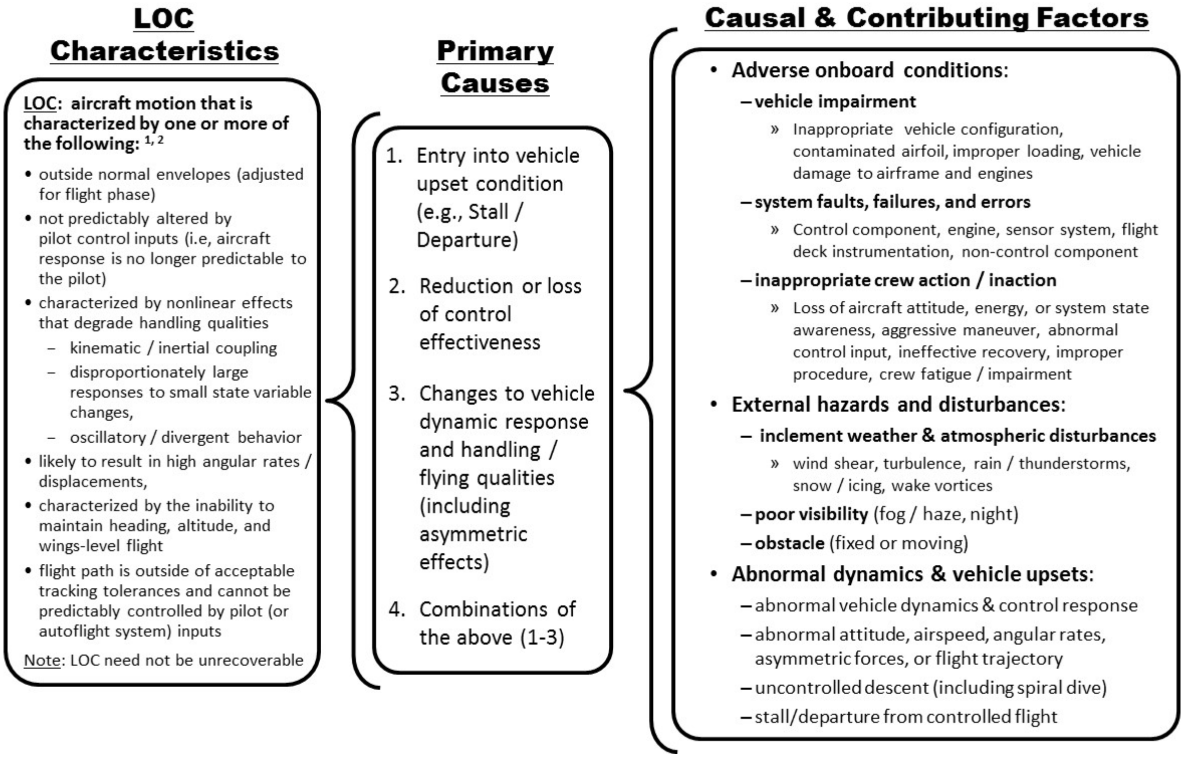


Figure 1. LOC key characteristics, primary causes, and causal & contributing factors.

Onboard systems of the future must therefore be developed to provide LOC prevention and recovery capabilities under a wide variety of hazards (and their combinations) that can lead to LOC. An integrated system concept for accomplishing this was presented in Ref. 6. The validation of technologies developed for loss of control (LOC) prevention and recovery, such as that of Ref. 6, poses significant challenges. The validation process must provide some measure of assurance that the new vehicle safety technologies are effective and that they do no harm – i.e., that they themselves do not introduce new safety risks. Moreover, a means of assessing hazards coverage must also be included in the validation framework. A validation framework involving analysis, simulation, and experimental testing was previously developed for safety-critical integrated systems operating under hazardous conditions that can lead to LOC (see Refs. 8 & 9), and a preliminary set of LOC test scenarios was developed (see Ref. 10) based on a limited accident set.

III. LOC Accident Analysis Methodology and Example Cases

This section presents a detailed methodology for the analysis of aircraft accidents and incidents, with the purpose of developing technology solutions for LOC prevention and recovery. The accident / incident set includes inflight LOC (LOC-I) accidents as categorized by the CAST/ICAO Common Taxonomy Team[13] as well as other LOC accidents (e.g., resulting from control component failures and/or vehicle damage sufficient to alter vehicle dynamics and control characteristics) related to the definition of Section II but not typically included in the LOC-I accident category. Refinement of the analysis methodology includes the addition of LOC precursors, the addition of flags for quickly identifying key issues of interest for LOC, the identification of potential research solutions for each accident (if applicable), and the capture of specific comments for each precursor. Each precursor comment is taken from the accident report or supporting information and specifies why each precursor is included in the sequence. In some cases, consensus comments by the analysis team have been added to enhance clarity. This section provides a detailed summary of this refined analysis methodology and provides some examples to illustrate it.

A. Accident Set Definition

Air carrier upset accidents were reviewed for the period 1996 through 2010. All reported mishaps to airplanes certified under Transport Category or Commuter Category were considered. The following databases were reviewed:

- Australian Transport Safety Bureau (ATSB) [14]
- UK Air Accidents Investigation Branch (AAIB) [15]
- Canadian Transportation Safety Board (TSB) [16]
- French Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile (BEA) [17]
- German Bundesstelle für Flugunfalluntersuchungin (BFU) [18]
- Irish Air Accident Investigation Unit (AAIU) [19]
- National Transportation Safety Board (NTSB) [20]
- International Civil Aviation Organization (ICAO) [21]
- Ascend Fleets from Flightglobal [22]
- Aviation Safety Network (ASN) [23]
- Aircraft Accident Report DVD [24]

Database coded event fields and narratives were queried for event categories and/or keywords such as “loss-of-control,” “upset,” “unusual attitude,” “stall,” “crash out of control,” and “uncontrolled descent.” All resulting database records and accident reports were reviewed by the authors to determine applicability to the study. Military airplanes and accidents resulting from criminal or deliberate activities (e. g., Egyptair 990) or pilot incapacitation (e. g., Helios 522) were culled from the list. Test operations were not considered nor were engine-out ferry flights, although positioning flights were included.

The full accident / incident set is provided in Appendix A. Some general statistics associated with the LOC accident / incident set of this study are summarized below in terms of number of events (or mishaps) and fatalities (onboard and ground) relative to phase of flight, aircraft type, operation, and five-year intervals.

Table 1. LOC Events and Fatalities Relative to
a.) Five-Year Intervals, b.) Phase of Flight, c.) Aircraft Type, and d.) Operation

a.) LOC Events by 5-Year Intervals

Time Period	Events	Onboard Fatalities	Ground Fatalities
1995-2000	102	3007	81
2001-2005	101	2143	135
2006-2010	75	2104	19
Total	278	7254	235

b.) LOC Events by Phase of Flight

Flight Phase	Events	Onboard Fatalities	Ground Fatalities
Takeoff and Initial Climb	85	1511	94
Climb	44	1767	33
Cruise	43	2008	78
Descent	17	157	0
Holding	2	0	0
Approach	47	805	23
VFR Pattern	2	5	0
Circling	3	175	0
Landing	18	39	0
Go-Around	10	116	0
Missed Approach	7	671	7
Total	278	7254	235

c.) LOC Events by Aircraft Classification

Aircraft Classification	Events	Onboard Fatalities	Ground Fatalities
Wide-body Turbojets	38	2224	17
Narrow-body Turbojets	83	3850	170
Business Jets	57	187	15
Turboprop Transports	45	620	31
Piston Transports	5	34	0
Commuter Airplanes	50	339	2
Total	278	7254	235

d.) LOC Events by Type of Operation

Operation	Events	Onboard Fatalities	Ground Fatalities
Scheduled Airlines	147	5900	170
Non-Scheduled Airlines	85	1206	52
Non-Revenue Operations	29	78	6
Executive Transportation	17	70	7
Total	278	7254	235

B. Accident Analysis Methodology

The accident analysis methodology was based on the sequential precursor model, which defines an accident as a series of connected events that ultimately lead to an undesired outcome. If a precursor event can be eliminated by an intervention, the accident/incident can be prevented. For this study, the methodology was designed to identify dominant precursors for each accident and the associated temporal sequencing. In contrast to typical root cause analysis, the precursors were selected by identifying all relevant hazards that sequentially led to the mishap (as opposed to the primary / root cause) to better understand LOC more holistically as a multiple-hazards event and thereby enable the development of research and technology interventions that are effective across a wide spectrum of key LOC hazards and their combinations (as opposed to developing separate technologies that target a single hazard). The precursors, shown in Table 2, were defined by the team based on the previous accident analysis of references 5-6 and were further updated during the analysis process. The wording of each precursor was carefully defined to correlate with terminology typically seen in accident reports and to minimize ambiguities. Some precursors, such as those under "Vehicle Upset," were derived from recent references (e.g., Refs. 4,12) and further, more specific definitions may warrant additional research. An important distinction with this analysis was that the goal was to identify potential technology interventions that merit further research, rather than the root cause or specific near-term interventions. Therefore some accidents were included in the database that did not clearly fit the specific definition of a LOC event but contained important precursor information that added substantially to the analysis or should be considered for future analysis.

Table 2. LOC Precursors / Hazards Set Used in the Accident Analysis

Precursor Categories	Subcategories	Precursors / Hazards
Adverse Onboard Conditions	Vehicle Impairment	Improper Maintenance Action/Inaction/Procedure Inappropriate Vehicle Configuration Contaminated Airfoil Smoke/Fire/Explosion Improper Loading: Weight/Balance.CG Airframe Structural Damage Engine Damage (FOD)
	System & Components Failure/Malfunction	System Design/Validation Error/Inadequacy System SW Design/Verification Error/Inadequacy Control Component Failure/Inadequacy Engine F/M Sensor System F/M Flight Deck Instrumentation Malfunction/Inadequacy System F/M (Non-Control Component)
	Crew Action/Inaction	Loss of Attitude State Awareness/SD Loss of Energy State Awareness Lack of Aircraft/System State Awareness Aggressive Maneuver Abnormal/Inadvertent Control Input Improper/Ineffective Recovery Inadequate Crew Resource Monitoring/Management Improper/Incorrect/Inappropriate Procedure/Action Fatigue/Impairment/Incapacitation
External Hazards & Disturbances	Inclement Weather & Atmospheric Disturbances	Thunderstorms/Rain Wind Shear Wind/Turbulence Wake Vortex Snow/Icing
	Poor Visibility	Fog, Haze Night
	Obstacle	Fixed Obstacle Moving Obstacle
Abnormal Vehicle Dynamics & Upsets	Abnormal Vehicle Dynamics	Uncommanded Motions, Oscillatory Response (Includes PIO) Abnormal Control for Trim/Flight and/or Control Asymmetry Abnormal/Counterintuitive Control Response
	Vehicle Upset Conditions	Abnormal Attitude Abnormal Airspeed/Energy Abnormal Angular Rates Undesired Abrupt Response Abnormal Flight Trajectory Vmc / Departure Stall / Departure

The analysis was based solely on publicly-available formal accident reports and associated supporting documents when available. For example, knowledge of sub-system design and performance specific to the aircraft was included when appropriate to clarify the precursor or temporal sequencing. Each accident was reviewed and precursors identified in a consensus format and the results were recorded in a spreadsheet document to facilitate data analysis.

An illustration of the analysis spreadsheet used in the analysis process is provided in Appendix B. The team based the precursor analysis on the published information verbatim and did not inject additional analysis or conclusions. In some cases the accident reports were very limited, which resulted in minimal identified precursors. The temporal sequencing was established by assigning a number to the precursors and in some cases a precursor may have occurred more than once. In most cases, the ending precursor was under the category of "Vehicle Upset Conditions". Because some precursors were somewhat broad in definition, the associated text that was used to justify that precursor was included in the database for completeness and further analysis.

As part of the database, three broad technology categories were flagged for potential relevance to the accident, 1) crew distraction, 2) human-machine interface, and 3) mitigation through research including training. These categories, though not specific precursors, were included due to numerous important and recent studies to address these areas but which were not necessarily addressed in the accident reports. In addition, comments were included to highlight important aspects of the accident that were not necessarily included in a precursor.

Once the precursor sequences are identified, an analysis can be performed to identify worst-case precursor combinations and precursor sequences. "Worst case" in this context is in terms of the number of accidents and fatalities. Worst case precursor combinations are identified using three-dimensional scatter plots with the three dimensions corresponding to the three precursor categories identified in Table 2. The preliminary analysis results documented in Ref. 10 illustrated these scatter plots at the sub-category and precursor levels. An example from Ref. 10 is included in Appendix C for convenience. Worst-case precursor sequences can be identified using pivot tables in Excel. All sequences associated with an initiating precursor can be drawn with the number of associated accidents and fatalities for each sequence. Examples from Ref. 10 of worst case sequence identification are also included in Appendix C. Individual precursor statistics can also be computed, as illustrated in Ref. 10 and summarized for the mishaps analyzed to date in Subsection III-D.

C. Accident Analysis Example

To illustrate the potential use of the database and analysis methodology, an analysis of eight accidents and incidents involving blocked pitot tubes or static port is presented. Table 3 provides a summary of these accidents and incidents.

Table 3. LOC Accidents and Incidents from the Data Set Involving Blocked Pitot Tubes

Accident No.	Date	Location	Airline	Flight No.	Aircraft	Phase of Flight	Fatalities
2	2/6/1996	Dominican Republic	Birgenair	301	B-757-225	En Route	189
14	10/2/1996	Peru	AeroPeru	603	B-757	Climb	70
37	10/10/1997	Uruguay	Austral Lineas Aereas	2553	DC-9	En Route	74
62	4/7/1999	Ceyhan, Turkey	THY Turkish Airlines	5904	B-737	En Route	6
142	10/20/2002	Baltimore, Maryland	Icelandair	662	B-757	En Route	0
188	5/12/2005	Missouri	Midwest Airlines		MD-90	Initial Climb	0
254	1/28/2009	Ghana	Astraeus for Ghana Airways		B-757	Cruise	0
260	6/1/2009	Atlantic Ocean (Near Sao Paulo Archipelago)	Air France	447	A-330	En Route	228

A description of the sensor system failure causes, symptoms, and outcomes is summarized below for the above mishaps.

1 Causes of the Sensor System Failure:

  a Four sensor system failure events were caused by pitot icing.

  Pitot icing can affect all onboard air data systems, the pilot, copilot, and standby systems and all flight control systems that use air data. These include autopilots, flight directors, and some flight control functions.

  Three of the failures were caused by inoperative pitot heat (either switched off or failed). One was caused by atmospheric conditions that were worse than pitot design requirements

  b Three failure events were caused by a single blocked pitot tube.

  A single blocked pitot tube affects a single air data system, usually the pilot's or copilot’s systems. In this case, there will be disagreement between the cockpit indications.

  Two failures occurred after pitot covers were left off overnight.
  One failure was caused by an internal blockage.

  c One failure event was caused by static ports being taped over by the maintenance crew.

  Blocking all static ports affects all onboard air data systems, the pilot, copilot, and standby systems and all flight control systems that use air data. These include autopilots, flight directors, and some flight control functions.

2 Symptoms of the Sensor System Failure:

  a Seven failure events resulted in flight crew confusion with misleading or conflicting cues and warnings. It was not clear to the flight crews what was happening. Attempts to isolate the failed systems appeared to be ineffective because the selection logic for airspeed/altitude input to autopilots or flight directors was not clear. The pilots did not understand what the effect of changing altitude had on their indications. Confusing warnings, such as MACH/SPD TRIM and RUDDER RATIO were shown with no previous training documented for the flight crews. Simultaneous overspeed and stall warnings were presented.

  b One failure event resulted in the copilot, who was flying, seeing zero airspeed and immediately applying stall recovery which was intended for low altitude stalls and had the effect of causing loss of one slat which precluded recovery.

3 Differences between accidents and incidents

  a Four accidents showed extreme confusion (as described above) in the flight deck. The crews were still trying to sort out the situation when they crashed, killing all onboard.

  b Three incidents showed the same confusion in the flight deck with the same indications. Fortunately for all onboard, the crew finally reverted to basic pitch and power control and safely recovered the airplanes.

Further analysis of these mishaps can be accomplished by identifying the precursor sequences and worst-case combinations associated with each accident and incident. Figure 2 illustrates the accident sequence determined for the Birgenair accident of 1996, which corresponds to Accident No. 2 in Table 3. The blocks in the sequence represent accident precursors (or hazards) that led to this accident. The comments below each box are taken from the accident report to reflect the team rationale for inclusion of each precursor. These comments provide specific information from the accident or incident for each precursor / hazard in the sequence.

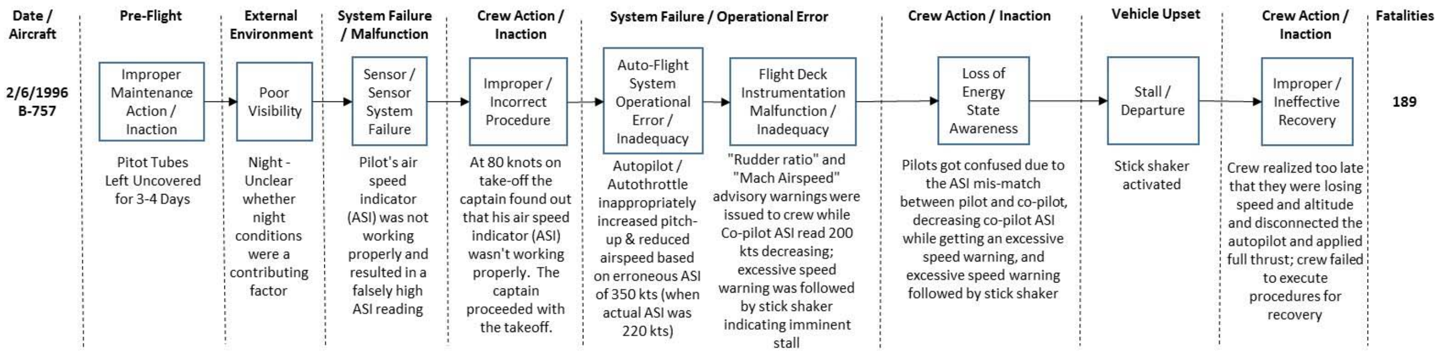
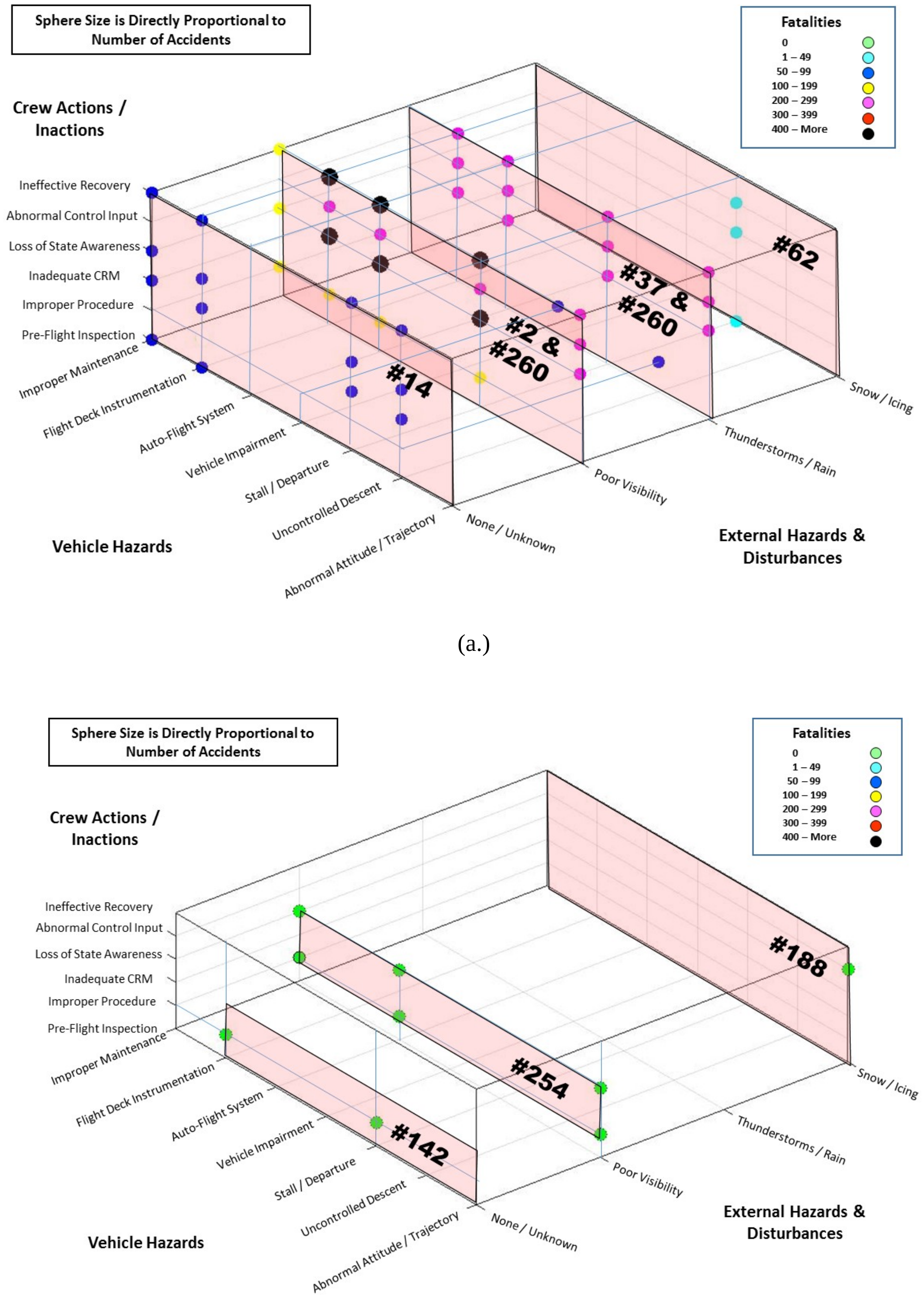


Figure 2. LOC accident sequence for Birgenair 301 (2/6/1996).

The precursor sequences developed for the eight blocked pitot tube or static port mishaps of Table 3 are provided in Appendix D. Some initial observations in analyzing the precursor sequences include the following:

1) What started the event?
    a. 37.5% (3/8) of the events started with an “Improper Maintenance Action/Inaction.” This means that 37.5% of these mishaps may have been able to be avoided with proper ground crew actions or adequate preflight by the flight crew – assuming the other hazards and hazards combinations could be mitigated successfully.
    b. 50% (4/8) of the remaining mishaps seem to have pitot tube icing as an initiating precursor (under snow, thunderstorm, or other icing conditions).
    c. The remaining event (1/8) started with a pitot tube sensor failure, though reasons for the blockage could not be determined.
2) What do the fatality cases all have in common?
    a. Three of the five (or 60%) are characterized by “Improper/Ineffective Recovery.” This precursor could potentially be added to mishap #62 as well, but information is limited for this case. Adding it would make 4/5 (or 80%).
    b. One aircraft suffered structural damage that resulted in an inability to control the aircraft. The pilots likely could not make a proper recovery given the damage.
    c. All of the fatal events experienced a serious vehicle upset condition, with 80% (4/5) involving stall / departure and the fifth event involving uncontrolled descent.
    d. Three of the five fatal accidents (60%) involved flight deck instrumentation and/or auto-flight system issues (operational errors, inadequacy, etc.).
    e. In 4/5 cases (80%) there were also a “Loss of Awareness” issue in either aircraft / system state, energy, or attitude.
3) What’s different about the nonfatal incident cases?
    a. All three of these incidents (142, 188, and 254) led to vehicle upsets, although only one event involved vehicle stall, and the pilots were able to recover the aircraft.
    b. There were still pilot issues as all three had either an “Improper/Incorrect Procedure” or “Abnormal Control Input.”
    c. Only one of the three (#254) had a “Lack of Aircraft System State Awareness,” but this was limited to the mode switching that was occurring in the background.

In general, the fatal accidents appear to be more complicated (i.e., involving more precursors) than the nonfatal incidents. A comparison of event complexity can be performed by analyzing the worst case precursor combinations using 3-D scatter plots. Figure 3 shows the precursor combinations for the fatal accidents (Figure 3a) and nonfatal incidents (Figure 3b). The axes represent Vehicle Hazards, External Hazards & Disturbances, and Crew Action / Inaction. These axes were selected to identify the hazards combinations involved in these mishaps, and to enable a more detailed identification of the specific hazards involved. Since all of these mishaps involved a sensor system failure (resulting from a blocked pitot tube or static port), this precursor is assumed and not included in Figure 3. The planes along the External Hazards and Disturbances axis are used to identify the precursor combinations for each mishap. The nodes (or spheres) in Figure 3 identify hazard combinations, where sphere size is proportional to the number of accidents and sphere color relates to the number of fatalities (as indicated by the legend of Figure 3).



(a.)

(b.)

Figure 3. Three-Dimensional (3-D) Scatter Plots Showing Precursor Combinations for (a.) Fatal Accidents and (b.) Nonfatal Incidents

Considering the fatal accidents first, it is easy to see from Figure 3a that there are many hazards combinations occurring for #2, #37, #260, and #14. Mishap #62 is the least complex in terms of hazards combinations, but this event involves snow/icing conditions, loss of state awareness by the crew, abnormal control inputs, and entry into stall. Mishap #14 involves multiple ineffective crew actions (improper pre-flight inspection, inadequate crew resource management, loss of state awareness, and ineffective recovery), flight deck instrumentation issues, and two serious upset conditions (stall / departure and uncontrolled descent). Accidents #2, #37, and #260 are the most complex, with #260 being both the most recent fatal accident and the most complex. All three of these events involve both flight deck instrumentation and autoflight system issues (operational errors, inadequacies, etc.), multiple crew hazards (including loss of state awareness, abnormal control inputs, and ineffective recovery), and stall / departure. Mishap #2 occurred under poor visibility conditions, #37 occurred under thunderstorms / rain conditions, and #260 involved both of these external hazards. Mishap #37 also involved vehicle impairment that resulted from an inappropriate configuration that led to structural damage and abnormal vehicle dynamics and control.

By comparison, the nonfatal incidents of Figure 3b are much less complex involving fewer hazards combinations. Incident #188 is the simplest event involving a single combination of snow / icing, abnormal control input, and abnormal attitude / trajectory. Incident #142 is slightly more complicated. Although there is no involvement by External Hazards & Disturbances, it does involve flight deck instrumentation and stall / departure, but only involves improper procedure by the crew. The final incident, #254, occurred under poor visibility conditions, involved the auto-flight system, two crew hazards (improper procedure and loss of state awareness), and abnormal attitude. The only stall event was not complicated further by inclement weather or poor visibility, nor by multiple instances of ineffective crew involvement. The other two incidents never entered into more severe vehicle upset conditions (such as stall / departure or controlled descent).

It is noted that very few incident investigations get the level of attention given to fatal accidents, but it would be difficult to quantify this difference (e.g., length of the report, length of the investigation, number of parties to the investigation, etc.) and thereby determine any potential impact this may have on complexity findings. It is also noted that the flight crews of the incidents were able to “break the chain” of events and thereby avert an accident. However, this could be either a cause or effect of less complexity. That is, less complex events may be easier for crews to identify and correct before they become an accident, or breaking the chain earlier in the sequence of events could prevent progression to a more highly complex event. Regardless, it is worth noting that the complexity of some circumstances make it less likely that crews will be able to correctly identify and correct the situation before it progresses too far.

The comments and flags included in the analysis process can also provide some insight into key issues and potential methods for mitigating through research. Tables of this data are contained in Appendix D. In three of the five fatal accidents, the crew was distracted or overwhelmed by conditions related to the pitot system failure (with one of these accidents exacerbated by the presence of cabin crew in the cockpit). Four of the five fatal accidents involved potential human-machine interface issues, with the accident report for the fifth accident lacking enough information to make this determination. In some cases the auto-flight system flew the aircraft into stall (due to the erroneous airspeed indications), and flight deck instrumentation provided little information for improved situation awareness and no guidance on appropriate actions to take. Moreover, in some instances multiple conflicting warnings and alerts were sounding simultaneously – which further confused the crew. In contrast, none of the non-fatal incidents involved crew distraction. Although the onboard systems provided similar opportunities for confusion or to further exacerbate the situation, the comparatively less complex hazards profile enabled the pilots to successfully recover to a safe flight condition.

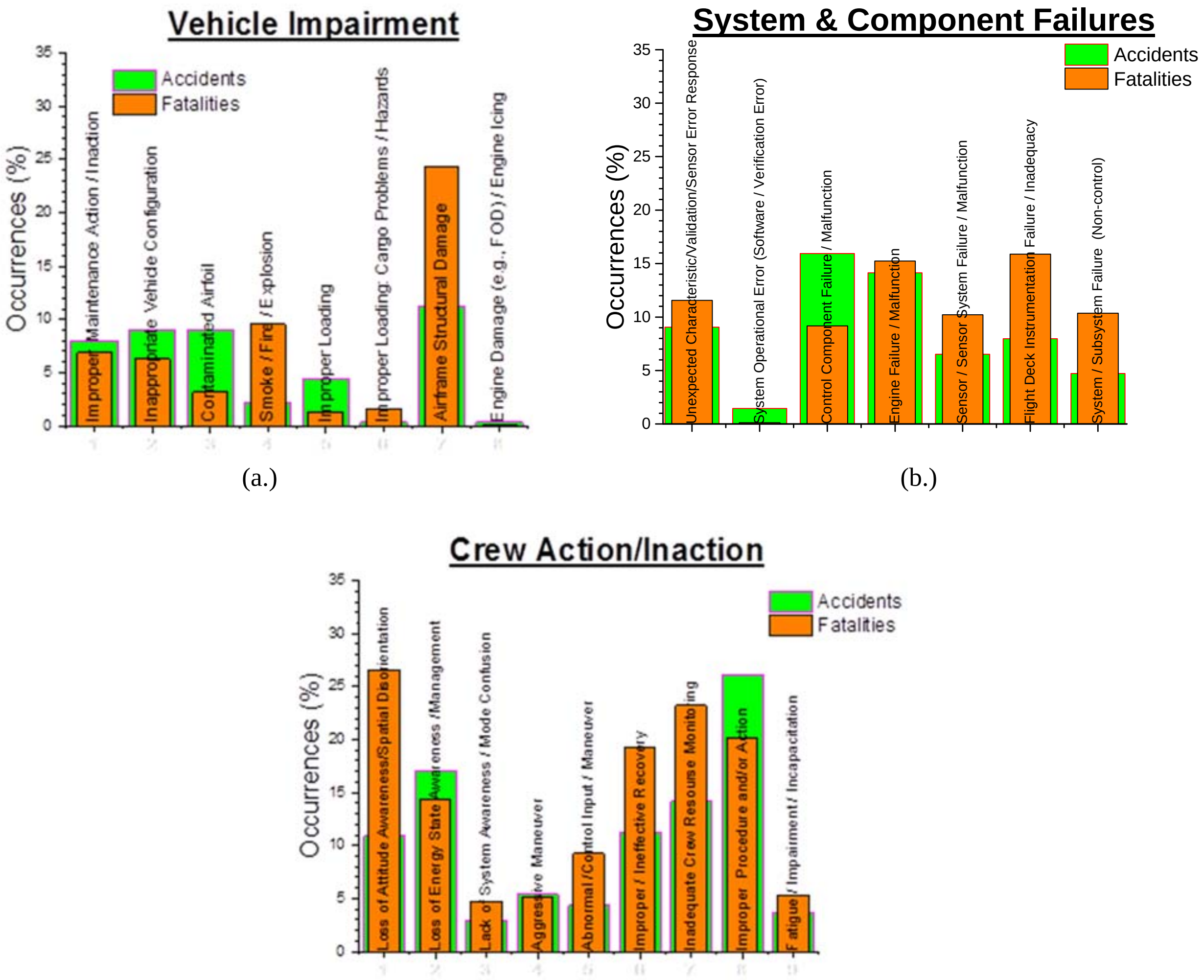
Comparing the fatal and nonfatal mishaps of this study, it can be concluded that there is a level of hazards complexity at which pilots (or any human) become confused and are unable to respond effectively. Moreover, current systems are essentially designed for nominal conditions and either disengage or respond inappropriately (adding additional confusion to the situation). Some potential mitigation strategies to prevent these kinds of mishaps in the future are provided in the tables of Appendix D for each mishap, and summarized here as follows:

1. Improved pilot training relative to diagnosing and mitigating onboard system failures (including sensor system failures and use of alternate instrumentation);
2. Improved crew training under unexpected and abnormal conditions (including multiple hazards events) and in the implications of existing protections associated with system operational modes;
3. Sensor integrity management system capable of detecting, identifying and mitigating sensor system failures (including blocked pitot tube or static ports and common mode sensor failures);
4. Improved algorithms and displays that provide improved situational awareness to the systems and crew under multiple hazards conditions;

5. Resilient flight control system capable of ensuring flight safety under multiple hazards (including system failures, external disturbances, and inappropriate control inputs by the crew and/or autoflight systems);
6. Resilient upset recovery system capable of providing guidance for and/or automatic recovery from upset conditions (including stall) under multiple hazards conditions.

D. Individual Hazards Occurrences

To date, the team has analyzed 122 of the 278 mishaps in the set using the analysis approach described herein. Individual occurrences of the precursors / hazards, arranged by the categories identified in Table 2, in the accident data analyzed to date are shown in Figures 4, 5 and 6 for Adverse Onboard Conditions, External Hazards & Disturbances, and Abnormal Vehicle Dynamics & Upsets, respectively.



(a.) (b.)

(c.)

Figure 4. Percent Occurrence of Hazards from Adverse Onboard Conditions Resulting from (a.) Vehicle Impairment, (b.) System & Component Failures, and (c.) Crew Actions / Inactions.

Relative to hazards from Adverse Onboard Conditions (see Figure 4), airframe structural damage has occurred in approximately 25% of the mishaps analyzed to date, and system and component failures have occurred in a large percentage of mishaps and are fairly evenly distributed at 15% each involving control component failures, engine failures, and flight deck instrumentation malfunctions, with system operational errors, sensor system failures, and system failures (non-control components) occurring in approximately 10 – 12% of the accidents and incidents. Crew actions / inactions are dominated by loss of attitude and energy state awareness at approximately 27% and 17%, respectively, improper procedure at approximately 27%, inadequate crew resource monitoring or management at approximately 23%, and improper or ineffective recovery at about 19%.

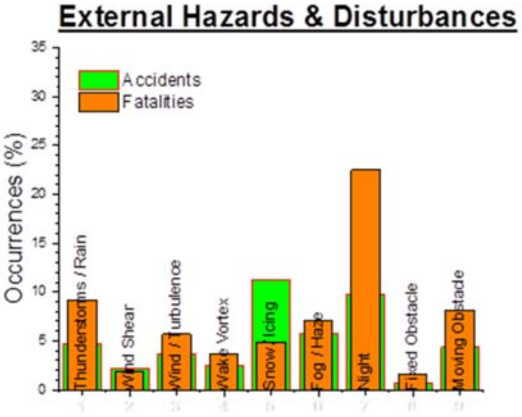


Figure 5. Percent Occurrence of Hazards from External Hazards & Disturbances.

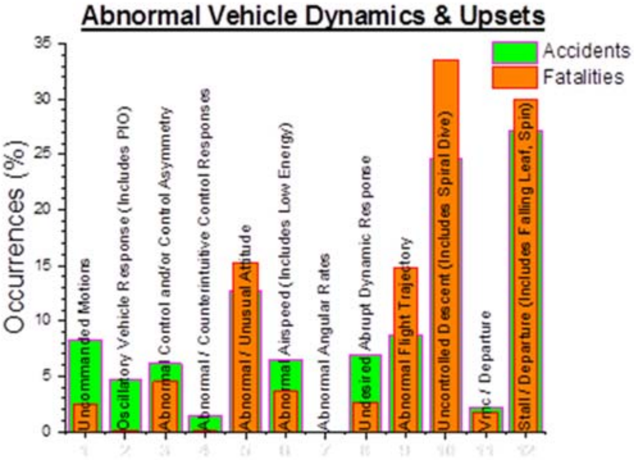


Figure 6. Percent Occurrence of Hazards from Abnormal Vehicle Dynamics & Upsets.

External Hazards and Disturbances (see Figure 5) are dominated by night visibility issues at approximately 22%, with snow or icing occurring in a little more than 10% of the mishaps evaluated to date. Other key external hazards include thunderstorms / rain at 9%, moving obstacles at 8%, and visibility issues related to fog or haze at 7%.

Hazards associated with Abnormal Vehicle Dynamics and Upsets (see Figure 6) are dominated by uncontrolled descent (which occurred in approximately 34% of the mishaps analyzed thus far) and stall / departure (which occurred in approximately 30%). Other key hazards related to vehicle upset conditions include abnormal / unusual attitude and abnormal flight trajectory (each occurring in approximately 15% of the mishaps analyzed to date). Hazards related to abnormal vehicle dynamics occurred less frequently, with uncommanded motion occurring in approximately 8.5% of the mishaps analyzed thus far, followed by abnormal control and/or control asymmetry (6%), oscillatory vehicle response (4%), and abnormal or counterintuitive control response (2%).

Overall (i.e., looking at the entire set of plots in Figures 4 – 6), it appears that a relatively high percentage of the accidents analyzed to date have involved the human element, Crew Action / Inaction. There is also a significant contribution of poor visibility under night conditions within the External Hazards & Disturbances category, and of events involving uncontrolled descent and stall / departure under the Vehicle Upsets sub-category. This may indicate the need for improved systems that better account for human involvement and provide improved man/machine interfaces.

IV. Accident Analysis Products and Follow-On Research

Analysis products will be made available from the process of Section III, and follow-on research is planned for the identification of future potential safety risks related to LOC and the development of LOC test scenarios based on the current and future hazards sets and their analysis. The analysis products and follow-on research are described in the following subsections.

A. Aircraft Accident Analysis Products

A goal of this effort is to facilitate further research on LOC as well as the development of technology solutions for LOC prevention and recovery. The authors therefore plan to make the data and analysis files available online so that the LOC analysis of this study can be openly investigated and additional LOC studies can be performed by other groups. Data files include the aircraft accident dataset described in Section III-A, accident summaries used in the analysis, and the full accident reports that have been obtained. Analysis products from the work described in Section III-B include the analysis spreadsheet used to identify precursor sequences for the accidents in the data set, the spreadsheets used to organize the data for generating worst-case precursor combinations and sequences, and the references sited as being applicable to potentially addressing each accident or incident. We also hope to develop an intelligent interface with links that enable querying the analysis results of this study. For example, clicking on a worst-case precursor combination sphere shown in Fig. B-1 would enable seeing lower level combinations (such as those shown in Fig. B-2) as well as a listing of which accidents and incidents from the set are represented in that combination.

B. Future Potential Risks

In developing technology solutions for LOC prevention and recovery, it is not only important to understand current causal and contributing factors (or precursors) but also future potential risks. The identification of future potential LOC risks is more difficult than current risks because there is no data that can be analyzed. Future potential LOC risks will be identified by the authors by considering current trends and future directions. A preliminary set of future potential LOC risks was identified in Ref. 10, and is repeated here for convenience in Table 4.

Table 4. Potential future LOC risks listed by trend from Ref. 10.

No.	Current Trend / Future Direction	Potential LOC Risk Factors
1	Increased Automation without Improved Crew Interfaces	Increase in Inappropriate Crew Response
2	Future Vehicle Configurations without Identification of Upset Characteristics	Increased Incidents of Vehicle Upsets
3	Increased System Complexity without Comprehensive Evaluation Process	Increase in System Faults / Failures / Errors / Insufficiencies
4	High-Density Operations in Terminal Area	Increase in Wake Vortex Encounters
5	High-Density Operations in Terminal Area	Increase in Pilot Workload
6	Increase in Flight Deck Automation	Decrease in Manual Piloting Skills
7	All-Weather Operations	Increase in Snow/Icing Encounters
8	All-Weather Operations in Terminal Area	Increase in Wind Shear / Turbulence Encounters
9	High-Density Mixed-Vehicle Operations	Increased Incidence of Near-Miss and Mid-Air Collision Events
10	New Vehicle Materials with Lack of Long-Term Data on Aging and Damage Tolerance	Increase in Damage-Initiated LOC Events

Some of the trends / directions identified in Table 4 result from the NextGen Operations concept [25, 26] being developed for the next generation of the air transportation system. Specifically, future directions 4, 7, 8, and 9 relate to NextGen Operations. Although NextGen operations will ultimately improve safety, any change has the potential to introduce unintended risks. The intention here is to identify these future potential risks in an effort to proactively address these in technology solutions that are effective mitigations of both current and future LOC risks.

Another current trend / future direction is the introduction of Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS). In this case, LOC risks can relate to the UAS as well as manned vehicles as a result of unexpected near-miss events involving UAS. Relative to Table 4, future direction 9 includes risks associated with UAS operation near airports and we are already experiencing an increase in this risk[27, 28, 29]. Other risks related to UAS LOC pertain to ground infrastructure and loss of life in developed areas. These will directly relate to intended use cases for UAS by industry, government agencies, and academia, and the effectiveness (and far-sightedness) of regulations for UAS in the NAS developed by the FAA. This is an expanding market with many use cases already identified and many more to come. Some current potential use cases for UAS include search and rescue support, border patrol, infrastructure inspection, and package delivery. These and future potential use cases will need to be studied to identify future potential risks related to safety and security (including LOC).

Increasing levels of autonomy in civil aviation[30] is another current trend / future direction that could potentially impact future LOC risk. This risk relates to future direction 3 in Table 4.

C. LOC Test Scenarios

Once the accident / incident analysis of section III and the future potential risks identified as discussed in Section IV-B are completed, a comprehensive set of hazards-based LOC test scenarios will be developed based on the current and future analysis results. It is anticipated that the test scenarios will include multiple precursor hazards, including adverse vehicle conditions, inappropriate crew response, external hazards and disturbances, and vehicle upset conditions. The test scenarios will include recommended evaluation methods, and flight conditions. The test scenarios will be developed with traceability to the current and future hazards sets for use in resilience testing. This traceability enables the evaluation of hazards coverage and technology effectiveness in providing that coverage. Figure 7 illustrates this concept.

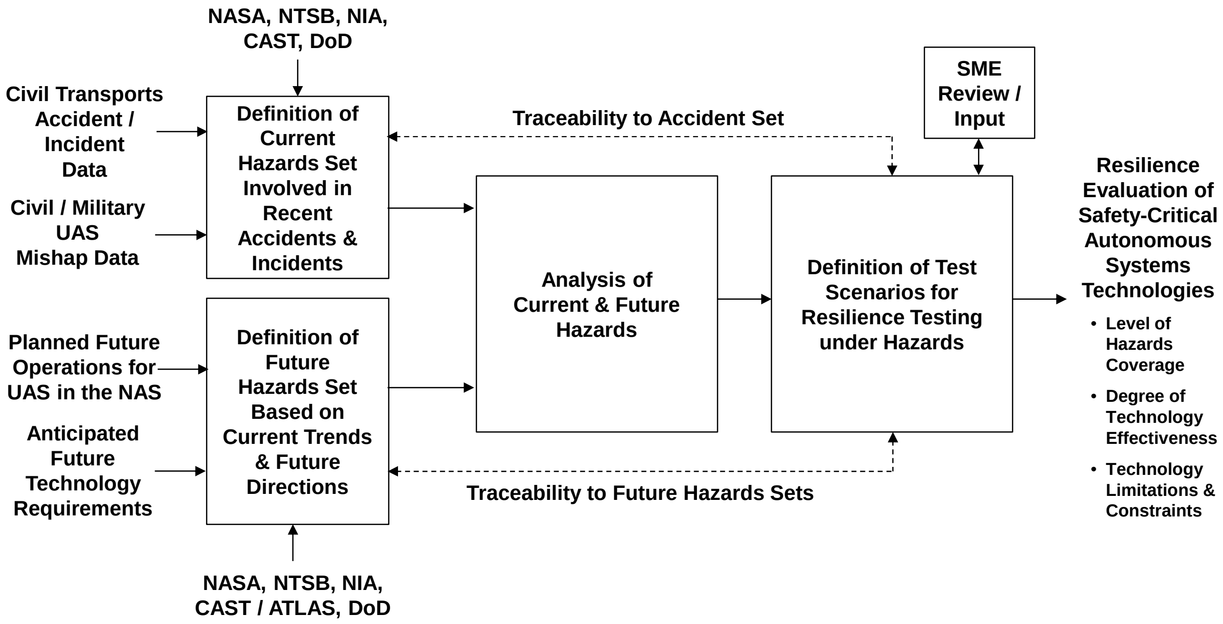


Figure 7. Resilience Evaluation Concept for Determination of Effective LOC Hazards Coverage.

A preliminary set of hazards-based test scenarios was developed in Ref. 10 to support the validation of safety-critical systems developed for LOC prevention and recovery. The authors intend that the hazards-based test scenarios to be developed as part of this study can be utilized as a universal set of test scenarios for resilience testing of technologies for future safety-critical autonomous and semi-autonomous vehicle systems.

V. LOC and Resilience Implications for Future Aircraft Systems

LOC prevention and recovery is a key requirement for future resilient and autonomous aircraft systems as well as for the safe integration of UAS into the National Airspace System (NAS). Research and technology development needs are discussed in the following subsections.

A. LOC Prevention and Recovery for Future Resilient Autonomous Aircraft Systems

LOC prevention and recovery is a critical capability for future safety-critical autonomous and semi-autonomous aircraft systems. In particular, current and future LOC hazards and the hazards-based test scenarios described in Section IV provide a rich set of conditions for evaluating resilience under uncertain, unexpected, and hazardous conditions. Figure 8 illustrates the importance of resilience for key aviation goals within the NASA Aeronautics Research Mission Directorate (ARMD) that will enable transformative capabilities in the future aviation system. More detailed technology development and validation requirements for resilient autonomous and semi-autonomous systems are provided in Appendix E.

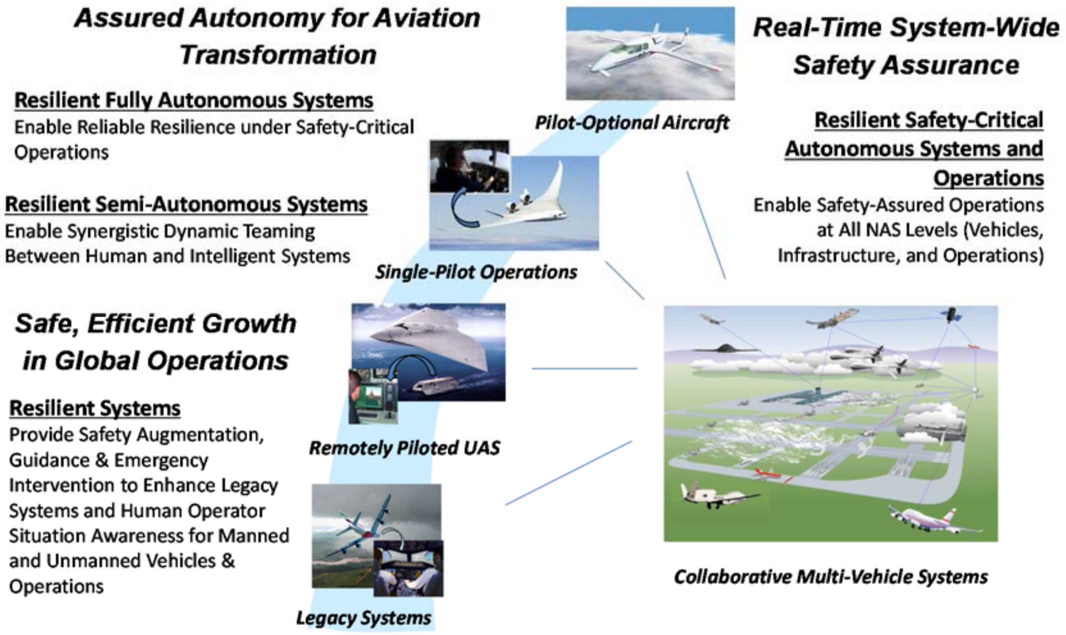


Figure 8. Importance of Resilience for Future Safety-Critical Autonomous Aircraft Systems.

B. LOC Implications for Safe UAS Integration into the National Airspace System (NAS)

Research is currently underway in analyzing UAS accidents and incidents utilizing the LOC analysis methodology of Section III to UAS. As discussed in Section IV, future potential safety risks associated with UAS operation in the NAS and hazards-based test scenarios for evaluating system resilience will also be developed with a focus on UAS relative to LOC as well as to a broader set of hazards. Figure 9 depicts the current strategy for safety/risk analysis research.

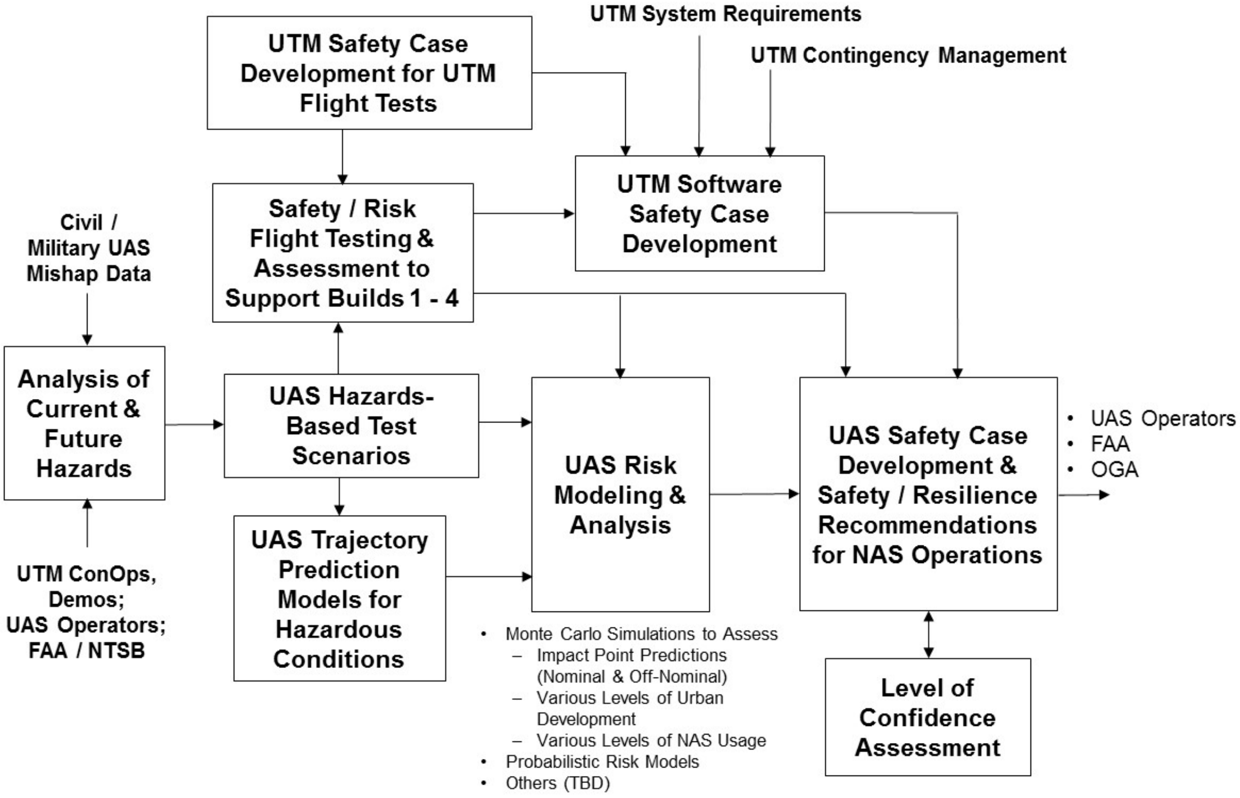


Figure 9. UAS Safety / Risk Analysis for NAS Operations.

An analysis of current hazards will be based on an analysis of civil and military UAS mishaps similar to the approach described in Section III. Future hazards will be identified based on concepts of operation for UAS Traffic Management (UTM) Systems, UTM flight demonstrations, use cases identified by UAS operators, and relevant information obtained from the FAA and NTSB. Hazards-based test scenarios will be developed with traceability to the current and future hazards as described in Section IV. Risk modeling and analyses will utilize trajectory prediction models developed for off-nominal conditions (including LOC hazards). Monte Carlo simulation techniques will be utilized to characterize impact point predictions under nominal and off-nominal conditions, various levels of urban development, and various levels of NAS usage. Probabilistic risk models are also being considered for evaluating the effectiveness of contingency management strategies at the UTM system as well as the vehicle level. Flight testing will be performed to introduce safety risks and evaluate the effectiveness of contingency responses. Safety cases will be developed at various levels of UTM system development, including in support of flight demonstrations, for assessing UTM software, and more broadly for UAS operation in the NAS. A level of confidence assessment will provide a measure of the level of confidence associated with the UAS safety case to be developed.

VI. Conclusion

This paper presented an analysis approach to evaluate LOC accidents and incidents for the purpose of developing technology solutions that enable LOC prevention and recovery under a wide spectrum of relevant hazards. The analysis approach identifies precursor / hazards sequences, worst case hazards combinations, and key attributes (e.g., crew distraction and human-machine interface issues) associated with each LOC accident or incident. This analysis process was illustrated for eight accidents and incidents (from a defined set of accidents and incidents over a recent 15-year period) involving blocked pitot tube or static ports. Five of these mishaps were fatal accidents, and the remaining three mishaps were non-fatal incidents. The analysis developed precursor sequences and hazards combinations to compare and contrast the fatal with the non-fatal mishaps. An evaluation of the precursor sequences included a number of observations, including the initiating event (3/8 started from an "Improper Maintenance Action / Inaction," 4/8 were initiated from pitot tube icing, and 1/8 was undetermined) and common features of the fatal and non-fatal mishaps. The fatal accidents had the following key features: 1.) 3/5 were characterized by "Improper / Ineffective Recovery;" 2.) 5/5 experienced a serious vehicle upset condition, with 4/5 involving a "Stall / Departure," and 1/5 entering into an "Uncontrolled Descent;" 3.) 3/5 involved flight deck instrumentation and/or auto-flight system issues (e.g., operational errors or inadequacies); and 4.) 4/5 cases also involved "Loss of Awareness" by the crew associated with the aircraft / system, energy, or attitude state. The non-fatal incidents involved vehicle upsets, but only one entered into a stall. Only one non-fatal incident involved "Loss of Awareness." There were still pilot issues for the non-fatal incidents, but these involved fewer occurrences and varieties of crew error.

In general, the fatal accidents appear to be more complicated (i.e., involving more precursors and precursor combinations) than the nonfatal incidents. A comparison of event complexity was performed by analyzing the worst case precursor combinations using 3-D scatter plots. The fatal accidents involved numerous multiple hazards combinations, and the non-fatal incidents were clearly less complex. Comments and flags identifying key attributes of each mishaps were also evaluated. In three of the five fatal accidents, the crew was distracted or overwhelmed by conditions related to the pitot system failure (with one of these accidents exacerbated by the presence of cabin crew in the cockpit). Four of the five fatal accidents involved potential human-machine interface issues, with the accident report for the fifth accident not having enough information to make this determination. In some cases the auto-flight system flew the aircraft into stall (due to the erroneous airspeed indications), and flight deck instrumentation provided little information for improved situation awareness and no guidance on appropriate actions to take. Moreover, in some instances multiple conflicting warnings and alerts were sounding simultaneously – which further confused the crew. By comparison, none of the non-fatal incidents involved crew distraction. Although the onboard systems provided similar opportunities for confusion or to further exacerbate the situation, the comparatively less complex hazards profile enabled the pilots to successfully recover to a safe flight condition.

Comparing the fatal and nonfatal mishaps of this study, it can be concluded that there is a level of hazards complexity at which pilots (or any human) become confused and are unable to respond effectively. Moreover, current systems are essentially designed for nominal conditions and either disengage or respond inappropriately (adding additional confusion and complexity to the situation). Some potential mitigation strategies to prevent these kinds of mishaps in the future include: 1.) Improved pilot training relative to diagnosing and mitigating onboard system failures (including sensor system failures and use of alternate instrumentation); 2.) Improved crew training under unexpected and abnormal conditions (including multiple hazards events) and in the implications of existing protections associated with system operational modes; 3.) Sensor integrity management system capable of detecting, identifying and mitigating sensor system failures (including blocked pitot tube or static ports and common mode sensor failures); 4.) Improved algorithms and displays that provide improved situational awareness to the systems and crew under multiple hazards conditions; 5.) Resilient flight control system capable of ensuring flight safety under multiple hazards (including system failures, external disturbances, and inappropriate control inputs by the crew and/or autoflight systems); and 6.) Resilient upset recovery system capable of providing guidance for and/or automatic recovery from upset conditions (including stall) under multiple hazards conditions.

Percent occurrences of individual hazards were also summarized for the 122 mishaps analyzed to date from the set of 278 mishaps. Hazards related to Vehicle Upsets associated with uncontrolled descent and stall / departure have occurred in 34% and 30% of the mishaps analyzed thus far. Hazards related to Adverse Onboard Conditions include Vehicle Impairment (with airframe structural damage dominating at 25%), System & Component Failures (fairly evenly distributed at 10-15% across six of the seven hazards contained therein), and Crew Action / Inaction (with loss of attitude state awareness, improper procedure, inadequate crew resource monitoring / management, ineffective recovery, and loss of energy state awareness all occurring most often ranging from 17% to 27%).

Further work will include the identification of future potential LOC hazards and the development of hazards-based test scenarios for the resilience evaluation of future semi-autonomous and autonomous systems developed for LOC prevention and recovery. This work is highly relevant to UAS and their safe operation in the NAS. An approach for assessing UAS safety and risk was also discussed.

Appendix A: Accident / Incident Set

No	Date	Aircraft	Registr'n	Ident	Loc'n	Light	Wea	Fat	Dam	Phase	Occurrence	Result
1	1/7/1996	DC-9	N--922VV	VJA 558	KBNA	D	V	0	S	Landing	Uncommanded Spoiler Extension	Hard Landing
2	2/6/1996	B-757	TC-GEN	ALW 301	MDPP	N	U	189	D	Climb	Instrument Failure	Uncontrolled Descent to Ground/Water
3	2/12/1996	GAF-24	N-224E	N-224E	MTPP	D	V	10	D	Initial climb	Undetermined	Uncontrolled Descent to Ground/Water
4	2/19/1996	CE-550	D-CASH	PWF ASH		U	U	10	D	Approach	Icing Stall	Uncontrolled Descent to Ground/Water
5	2/22/1996	MD-11	B-152	CAL 4	RCTP	U	U	0	U	Initial climb	Pilot Induced Oscillation (PIO)	Upset
6	5/11/1996	DC-9	N-904VJ	VJA 592	KMIA	D	V	110	D	Climb	Structural Failure - Fire/Explosion	Uncontrolled Descent to Ground/Water
7	6/5/1996	MD-80	N-224AA	AAL 873	KABQ	D	V	0	M	Landing	Atmospheric Disturbance	Hard Landing
8	6/9/1996	B-737	N-221US	EW09 51	KRIC	N	V	0	N	Approach	Uncommanded Bank	Upset
9	6/14/1996	A-320	N-347NW	NWA 395	KBOS	D	V	0	N	Climb	Flight Control System	Uncommanded Pitch
10	6/21/1996	A-340	D-AIBE	DLH 436	KDFW	U	U	0	U	Climb	Unexpected Control Gains	Cabin Injuries
11	7/13/1996	MD-11	N-1768D	AAL 68D		D	V	0	N	Descent	Attempt To Override Autopilot	Cabin Injuries
12	7/17/1996	B-747	N-93119	TWA 800	KJFK	T	V	230	D	Climb	Structural Failure - Fire/Explosion	Uncontrolled Descent to Ground/Water
13	7/20/1996	DC-6	N-313RS	NAC 33	PARS	D	V	4	D	Cruise	Structural Failure - Fire/Explosion	Uncontrolled Descent to Ground/Water
14	10/2/1996	B-757	N-52AW	PLI 603		N	I	70	D	Climb	Spatial Disorientation	Collision W/Terrain
15	10/22/1996	B-707	N-751MA	MIRA 1M	SEMT	U	U	4	D	Climb	Stall	Collision W/Obstacle
16	10/31/1996	FO-100	PT-MRK	TAM 402	SBSP	D	V	96	D	Initial climb	Asymmetric Thrust/Drag	Collision W/Obstacle
17	11/7/1996	B-727	5N-BBG	ADK 86		U	U	144	D	Approach	Aggressive Maneuver	Uncontrolled Descent to Ground/Water
18	11/12/1996	B-747	HZ-AIH	SVA 763		U	U	312	D	Climb	Structural Failure - Midair	Uncontrolled Descent to Ground/Water
19	11/12/1996	Il-76	UN-76435	KZA 1907		U	U	37	D	Descent	Structural Failure - Midair	Uncontrolled Descent to Ground/Water
20	12/9/1996	DC-3	N-75142	D7T 142	KBOI	N	V	2	D	Initial climb	Stall	Collision W/Terrain
21	12/10/1996	An-74	RA-74037	VSA 037	UERR	N	U	0	D	Initial climb	Thrust Reverse-Unwanted	Collision W/Terrain
22	12/21/1996	An-32	HK-4008X	SDV 08X	SKRG	N	U	4	D	Approach	Undetermined	Collision W/Terrain
23	1/9/1997	E-120	N-265CA	COM 327	KDTW	D	I	29	D	Descent	Icing Stall	Uncontrolled Descent to Ground/Water
24	1/25/1997	Il-76	RA-76834	VSO 834	UHMA	U	U	0	D	Initial climb	Attempted TO W/Incorrect Config	Collision W/Terrain
25	2/1/1997	HS-748	6V-AEO	DS AEO	GOTT	U	U	23	D	Initial climb	Undetermined	Collision W/Terrain
26	3/2/1997	BE-200	N-117WM	N-117WM	KSLC	T	I	1	S	Final approach - prec	Stall	Uncontrolled Descent to Ground/Water
27	3/14/1997	F-27	D2-TFP	DTA TFP	FCBB	U	U	3	D	Initial climb	Undetermined	Collision W/Terrain
28	4/14/1997	An-24	RA-46516	RA-46516		D	U	50	D	Cruise	Structural Failure - Fatigue	Uncontrolled Descent to Ground/Water
29	4/19/1997	BAE-ATP	PK-MTX	MNA 106	WIOD	N	U	15	D	Approach	Undetermined	Uncontrolled Descent to Ground/Water
30	5/8/1997	B-737	B-2925	CSN 3456	ZGSZ	N	I	35	D	Landing	Atmospheric Disturbance	Hard Landing
31	5/12/1997	A-300	N-90070	AAL 903	KPBI	D	I	0	M	Level off from desce	Stall	Upset
32	5/20/1997	AC-1121	N-1121F	N-1121F		D	I	4	D	Cruise	Atmospheric Disturbance	Uncontrolled Descent to Ground/Water
33	6/8/1997	MD-11	JA-8580	JAL 706	RJNA	D	U	0	M	Descent	Pilot Induced Oscillation (PIO)	Upset
34	7/3/1997	F-27	VT-SSA	LBE SSA	VABB	N	I	2	D	Initial climb	Undetermined	Uncontrolled Descent to Ground/Water
35	7/12/1997	DC-9	N-9138	NWA 944	KMEM	D	V	0	M	Landing	Flight Controls	Upset
36	8/7/1997	DC-8	N-27UA	FBF 101	KMIA	D	V	4	D	Initial climb	Load - C/G Out Of Range	Uncontrolled Descent to Ground/Water
37	10/10/1997	DC-9	LV-WEG	AUT 2553		N	I	75	D	Descent	Structural Failure - Exceeded Limit	Uncontrolled Descent to Ground/Water
38	12/13/1997	SA-226	CP-1635	SAVE 635	SLVT	U	U	10	D	Initial climb	Undetermined	Collision W/Terrain
39	12/16/1997	CL-600	C-FSKI	ACA 646	CYFC	N	I	0	D	Go-around	Stall	Collision W/Terrain
40	2/16/1998	A-300	B-1814	CAL 676	RCTP	N	I	196	D	Missed approach	Stall	Uncontrolled Descent to Ground/Water

No	Date	Aircraft	Registr'n	Ident	Loc'n	Light	Wea	Fat	Dam	Phase	Occurrence	Result
41	3/18/1998	SF-340	B-12255	FOS 255	RCPO	N	I	13	D	Climb	Attempted TO W/Incorrect Config	Uncontrolled Descent to Ground/Water
42	5/21/1998	DC-10	N-68043	COA 75	KLAX	D	V	0	M	Climb	Autopilot	Uncommanded Pitch
43	6/18/1998	SA-226	C-GQAL	PRO 420	CYUL	D	U	11	D	Climb	Structural Failure - Fire/Explosion	Uncontrolled Descent to Ground/Water
44	7/23/1998	An-12	RA-11886	RA-11886	ULLP	D	U	0	D	Initial climb	Loss-of-Control (Vmc)	Collision W/Terrain
45	7/28/1998	SA-227	EC-FXD	SWT 704	LEBL	N	V	2	D	Approach	Loss-of-Control (Vmc)	Uncontrolled Descent to Ground/Water
46	7/30/1998	Do-228	VT-EJW	LLR EJW	VOCC	D	V	6	D	Initial climb	Flight Control Actuator	Uncontrolled Descent to Ground/Water
47	7/30/1998	BE-1900	F-GSJM	PRB 706		D	V	14	D	Approach	Structural Failure - Midair	Uncontrolled Descent to Ground/Water
48	8/24/1998	DC-3	ZS-NKK	SPZ NKK	FAWB	D	V	1	D	Initial climb	Attempted TO W/Mis-set Trim	Uncontrolled Descent to Ground/Water
49	9/2/1998	MD-11	HB-IWF	SWR 111	CYHZ	N	U	229	D	Cruise	Loss Of All Attitude Displays	Collision W/Terrain
50	10/17/1998	BE-99	N-299GL	TIMA 501	KMSO	N	V	0	S	Go-around	Failure To Maintain Airspeed	Collision W/Terrain
51	10/18/1998	A-320	EI-TLI	TRZ TLI	EIDW	U	U	0	M	Approach	Jammed Flight Controls	Upset
52	10/21/1998	E-120	PT-WKH	PT-WKH	SBFZ	D	U	3	D	Approach	Improper Control Operation	Uncontrolled Descent to Ground/Water
53	11/11/1998	SF-340	VH-LPI	KDA LPI	YMML	D	I	0	N	holding (IFR)	Icing Stall	Upset
54	12/2/1998	CE-501	N-501EZ	N-501EZ		D	V	1	D	Cruise	Undetermined	Uncontrolled Descent to Ground/Water
55	12/4/1998	An-12	LZ-SFG	LXR SFG	LPLA	N	U	7	D	Initial climb	Asymmetric Thrust/Drag	Uncontrolled Descent to Ground/Water
56	12/11/1998	A-310	HS-TIA	TIA 261	VSSB	N	I	101	D	Missed approach	Somatogravic Illusion	Uncontrolled Descent to Ground/Water
57	1/12/1999	F-27	G-CHNL	EXS HNL	EGJB	U	U	2	D	Approach	Stall	Uncontrolled Descent to Ground/Water
58	1/28/1999	LR-35	N-130F	USC 251	KMD	N	V	0	S	Landing	Unstabilized Approach	Hard Landing
59	2/2/1999	An-12	EY-ASS	FDN ASS	FNLU	N	U	11	D	Initial climb	Undetermined	Collision W/Obstacle
60	2/24/1999	Tu-154	B-2622	CSW 450	ZSWZ	U	U	61	D	Approach	Flight Control Disconnected	Uncontrolled Descent to Ground/Water
61	4/5/1999	DHC-6	N-838MA	DCC 8MA	KLNA	D	V	0	S	Approach	Loss-of-Control (Vmc)	Collision W/Terrain
62	4/7/1999	B-737	TC-JEP	THY 5904	LTAF	N	I	6	D	Climb	Instrument Failure	Uncontrolled Descent to Ground/Water
63	4/15/1999	MD-11	HL-7373	KAL 6316	ZSSS	D	U	3	D	Climb	Spatial Disorientation	Uncontrolled Descent to Ground/Water
64	8/31/1999	B-737	LV-WRZ	LPR 3142	SABE	N	U	63	D	Initial climb	Attempted TO W/Incorrect Config	Uncontrolled Descent to Ground/Water
65	9/2/1999	B-737	N-371UA	UAL 2036		D	V	0	M	Cruise	Wake Turbulence	Cabin Injuries
66	9/14/1999	DA-900	SX-ECH	OAL 3838	LROP	U	U	7	S	Descent	Attempt To Override Autopilot	Upset
67	9/24/1999	A-320	C-FKCO	ACA 630	CYSJ	N	V	0	M	Landing	Flight Controls Mode Change	Landed Short
68	10/9/1999	DA-900	N-523AC	N-523AC	KGRR	U	U	0	U	Descent	Attempt To Override Autopilot	Aircraft Pitch/Roll Oscillations
69	10/18/1999	SF-340	SE-LES	GAO 750	ENSN	N	I	0	M	Climb	Stall	Upset
70	10/25/1999	LR-35	N-47BA	SJ8 7BA		U	U	6	D	Climb	Incapacitation: Hypoxia	Spiral Dive Into Ground
71	11/9/1999	DC-9	XA-TKN	TEJ 725	MMPN	N	U	18	D	Climb	Spatial Disorientation	Collision W/Terrain
72	12/5/1999	Il-114	UK-91004	CTB 004	UUDD	U	U	5	D	Initial climb	Jammed Flight Controls	Collision W/Obstacle
73	12/12/1999	IAI-1124	N-50PL	N-50PL		D	V	3	D	Descent	Flight Control Disconnected	Uncontrolled Descent to Ground/Water
74	12/22/1999	B-747	HL-7451	KAL 8509	EGSS	N	U	4	D	Climb	Spatial Disorientation	Uncontrolled Descent to Ground/Water
75	1/5/2000	E-110	5N-AXL	EAN AXL	DNAA	U	U	1	D	Approach	Stall	Collision W/Terrain
76	1/10/2000	SF-340	HB-AKK	CRX 498	LSZH	N	I	10	D	Initial climb	Spatial Disorientation	Spiral Dive Into Ground
77	1/30/2000	A-310	5Y-BEN	KQA 431	DIAP	N	V	169	D	Initial climb	Stall	Collision W/Terrain
78	1/31/2000	MD-80	N-963AS	ASA 261		D	V	88	D	Cruise	Jammed Flight Controls	Uncontrolled Descent to Ground/Water
79	2/16/2000	DC-8	N-8079U	EWW 17	KMHR	N	V	3	D	Initial climb	Flight Control Disconnected	Uncontrolled Descent to Ground/Water
80	2/27/2000	B-747	G-BDXL	BAW 179		N	I	0	N	Descent	Uncommanded Pitch	Upset
81	3/9/2000	Yak-40	RA-88170	VGV 170	UUEE	D	U	9	D	Initial climb	Attempted TO W/Contaminated	Uncontrolled Descent to Ground/Water

No	Date	Aircraft	Registr'n	Ident	Loc'n	Light	Wea	Fat	Dam	Phase	Occurrence	Result
82	3/17/2000	DC-3	C-FNTF	PTSN NT	CYJC	U	U	2	D	Go-around	Load - C/G Out Of Range	Uncontrolled Descent to Ground/Water
83	3/30/2000	B-767	N-182DN	DAL 106	KJFK	N	I	0	N	Climb	Spatial Disorientation	Upset
84	5/2/2000	LR-35	G-MURI	NEX 4B	LFLL	U	U	2	D	Landing	Engine Failure	Uncontrolled Descent to Ground/Water
85	5/21/2000	JS-3101	N-16EJ	ORA 6EJ	KAVP	D	I	19	D	Approach	Directional Control Not Maintained	Uncontrolled Descent to Ground/Water
86	6/22/2000	Y-7	B-3479	CWU 343	ZHHH	D	I	42	D	Approach	Wind Shear	Collision W/Obstacle
87	6/23/2000	LR-55	N-220JC	UJT 0JC	KBCT	D	V	3	D	Climb	Structural Failure - Midair	Uncontrolled Descent to Ground/Water
88	6/27/2000	A-300	N-14065	AAL 065	EGLL	D	V	0	N	Climb	Wake Turbulence	Landed Without Further Incident
89	7/17/2000	B-737	VT-EGD	LLR 7412	VEPT	D	M	55	D	Approach	Stall	Uncontrolled Descent to Ground/Water
90	7/19/2000	G-159	C-GNAK	AWV 980		N	I	2	D	Cruise	Loss-of-Control (Vmc)	Uncontrolled Descent to Ground/Water
91	7/20/2000	DC-3	N-54AA	N-54AA	MYNN	D	V	2	D	Initial climb	Undetermined	Collision W/Terrain
92	7/25/2000	AS-100	F-BTSC	AFR 4590	LFPG	D	V	109	D	Initial climb	Structural Failure - Fire/Explosion	Uncontrolled Descent to Ground/Water
93	8/23/2000	A-320	A4-OEK	GFA 72	OBBI	N	V	143	D	Missed approach	Somatogravic Illusion	Collision W/Terrain
94	8/31/2000	An-26	D2-FDI	NCL FDI	FNSA	U	U	44	D	Cruise	Undetermined	Uncontrolled Descent to Ground/Water
95	10/2/2000	A-340	TC-JDN	THY JDN		U	U	0	N	Cruise	Flight Controls Mode Change	Altitude Deviation
96	10/26/2000	CL-600	N-958CA	COM 8CA		D	V	0	N	Cruise	Wake Turbulence	Upset
97	11/1/2000	DHC-6	C-GGAW	YWZ 151	CYHC	D	U	0	D	Initial climb	Loss-of-Control (Vmc)	Collision W/Terrain
98	11/9/2000	SA-226	N-731AC	ETA4 100	KFWA	N	I	1	D	Initial climb	Instrument Failure	Uncontrolled Descent to Ground/Water
99	11/15/2000	An-24	D2-FCG	API FCG	FNLU	D	U	57	D	Initial climb	Loss-of-Control (Vmc)	Collision W/Terrain
100	11/25/2000	MD-11	N-582FE	FDE 3015	KEWR	D	V	0	N	Climb	Flight Controls	Pilot Induced Oscillation (PIO)
101	12/2/2000	LR-35	C-GDJH	C-GDJH	CYVR	U	U	0	N	Climb	Jammed Flight Controls	Uncommanded Bank
102	12/27/2000	E-135	N-721HS	EGF 230	KORD	N	V	0	N	Initial climb	Jammed Flight Controls	Upset
103	1/25/2001	DC-3	YV-224C	RUC 225	SVCB	D	U	24	D	Approach	Unknown	Uncontrolled Descent to Ground/Water
104	1/27/2001	BE-200	N-81PF	JEK 1PF		T	I	10	D	Cruise	Instrument Failure	Uncontrolled Descent to Ground/Water
105	2/7/2001	A-320	EC-HKJ	IBE 1456	LEBB	N	V	0	D	Landing	Unexpected Control Gains	Hard Landing
106	2/8/2001	LR-35	I-MOCO	I-MOCO	EDDN	D	V	3	D	Approach	Stall	Uncontrolled Descent to Ground/Water
107	3/17/2001	A-320	N-357NW	NWA 985	KDTW	N	I	0	S	Initial climb	Pilot Induced Oscillation (PIO)	Collision W/Terrain
108	3/19/2001	E-120	N-266CA	COM 505	KPBA	D	I	0	S	Descent	Icing Stall	Upset
109	3/20/2001	A-320	D-AIPW	DLH IPW	EDFF	U	U	0	N	Initial climb	Reversed Controls	Uncommanded Bank
110	3/24/2001	DHC-6	F-OGES	ISB 1501	TFFJ	D	V	19	D	Final approach - non	Loss-of-Control (Vmc)	Uncontrolled Descent to Ground/Water
111	4/2/2001	CE-501	N-405PC	N-405PC	KGRB	D	I	1	D	Climb	Spatial Disorientation	Collision W/Obstacle
112	5/25/2001	A-340	F-GLZC	AFR 3682	SOCA	D	V	0	M	Landing	Atmospheric Disturbance	Landed Short
113	7/4/2001	Tu-154	RA-85845	VLK 352		N	I	145	D	Approach	Autopilot-Induced Stall	Uncontrolled Descent to Ground/Water
114	8/9/2001	BE-200	N-899RW	N-899RW	KOKZ	D	I	0	D	Approach	Stall	Collision W/Terrain
115	8/24/2001	LR-25	N-153TW	AJI 3TW	KITH	N	I	2	D	Initial climb	Somatogravic Illusion	Collision W/Terrain
116	9/12/2001	Let-410	XA-ACM	XA-ACM	MMCT	D	V	19	D	Initial climb	Failure To Maintain Control	Uncontrolled Descent to Ground/Water
117	9/14/2001	BE-1900	C-GSKC	SKK 621	CYYT	N	I	0	D	Initial climb	Uncommanded Pitch	Forced Landing
118	9/18/2001	Let-410	TG-CFE	TG-CFE	MGGT	U	U	8	D	Initial climb	Stall	Uncontrolled Descent to Ground/Water
119	10/4/2001	Tu-154	RA-85693	SBI 1812		D	U	78	D	Cruise	Hostile Action	Uncontrolled Descent to Ground/Water
120	10/10/2001	SA-226	EC-GDV	FTL 101		D	I	10	D	Cruise	Loss Of All Attitude Displays	Uncontrolled Descent to Ground/Water
121	10/16/2001	E-145	N-825MJ	ASH 5733	KROA	N	V	0	S	Landing	Stall	Hard Landing
122	11/12/2001	A-300	N-14053	AAL 587	KJFK	D	V	260	D	Climb	Wake Turbulence	In-flight Breakup

No	Date	Aircraft	Registr'n	Ident	Loc'n	Light	Wea	Fat	Dam	Phase	Occurrence	Result
123	11/19/2001	Il-18	RA-75840	LDF 840		U	U	27	D	Cruise	Flight Control System	Uncontrolled Descent to Ground/Water
124	11/22/2001	LR-25	N-5UJ	UJT 5UJ	KPIT	D	V	2	D	Initial climb	Overcontrol	Collision W/Terrain
125	12/10/2001	LR-24	N-997TD	X5CA 36		N	V	2	D	Descent	Undetermined	Uncontrolled Descent to Ground/Water
126	12/14/2001	DC-8	N-825BX	RTI 8101	PANC	N	V	0	N	Initial climb	Flight Control Hardover	Uncommanded Bank
127	12/20/2001	CE-560	HB-VLV	EGU 220	LSZH	N	I	2	D	Initial climb	Somatogravic Illusion	Uncontrolled Descent to Ground/Water
128	1/4/2002	CL-600	N-90AG	N-90AG	EGBB	D	V	5	D	Initial climb	Attempted TO W/Contaminated	Uncontrolled Descent to Ground/Water
129	1/22/2002	B-757	TF-FIO	ICE 315	ENGM	D	I	0	N	Go-around	Somatogravic Illusion	Upset
130	4/12/2002	SA-227	EC-GKR	TDC GKR	LEPA	N	U	2	D	Approach	Aggressive Maneuver	Collision W/Terrain
131	5/4/2002	BAC-111	5N-ESF	EXW 422	KNKN	D	U	71	D	Cruise	Stall	Uncontrolled Descent to Ground/Water
132	5/25/2002	B-747	B-18255	CAL 611		D	U	225	D	Cruise	Structural Failure - Fatigue	Uncontrolled Descent to Ground/Water
133	6/3/2002	MD-11	N-588FE	FEX 5181		N	I	0	S	Descent	Overcontrol	Structural Failure
134	6/4/2002	MD-80	N-823NK	NKS 970		D	V	0	N	Cruise	Autopilot-Induced Stall	Upset
135	6/14/2002	A-330	C-GHLM	ACA 875	EDDF	U	U	0	N	Approach	Flight Control Logic	Uncommanded Pitch
136	6/28/2002	SF-340	VH-OLM	HZL 185	YBTH	N	U	0	N	Approach	Icing Stall	Upset
137	7/1/2002	Tu-154	RA-85816	BTC 2937		N	U	69	D	Cruise	Structural Failure - Midair	Uncontrolled Descent to Ground/Water
138	7/1/2002	B-757	A9-CDHL	DHL 611		N	U	2	D	Cruise	Structural Failure - Midair	Uncontrolled Descent to Ground/Water
139	7/28/2002	Il-86	RA-86060	PLK 060	UUEE	D	U	14	D	Initial climb	Runaway Pitch Trim	Uncontrolled Descent to Ground/Water
140	8/14/2002	ATR-42	PT-MTS	TTL 5561		N	U	2	D	Cruise	Runaway Pitch Trim	Uncontrolled Descent to Ground/Water
141	10/9/2002	B-747	N-661US	NWA 85	PANC	N	V	0	M	Cruise	Flight Control Hardover	Uncommanded Bank
142	10/20/2002	B-757	TF-FII	ICE 662	KBWI	N	U	0	N	Climb	Spatial Disorientation	Upset
143	11/8/2002	IAI-1124	N-61RS	BQVA 1R	KSKX	D	V	2	D	Approach	Atmospheric Disturbance	Uncontrolled Descent to Ground/Water
144	12/3/2002	A-300	Unknown	Unknown	EDDM	D	U	0	N	Climb	Controls (Trim)	Design Airspeed Exceeded (Vne/Vmo)
145	12/7/2002	A-320	C-GIUF	ACA 1130	CYYZ	U	U	0	N	Final approach - prec	Pilot Induced Oscillation (PIO)	Go Around
146	12/7/2002	A-320	C-GJVX	ACA 457	CYYZ	U	U	0	N	Final approach - prec	Pilot Induced Oscillation (PIO)	Hard Landing
147	12/21/2002	ATR-72	B-22708	TNA 791		N	I	2	D	Descent	Icing Stall	Uncontrolled Descent to Ground/Water
148	12/27/2002	Let-410	9X-RRB	9X-RRB	FMCV	D	I	1	D	Missed approach	Spatial Disorientation	Uncontrolled Descent to Ground/Water
149	1/8/2003	BE-1900	N2-33YV	AMW 548	KCLT	D	V	21	D	Initial climb	Flight Control Integrity Lost	Uncontrolled Descent to Ground/Water
150	2/10/2003	An-28	ES-NOY	ENI 827	EETN	N	I	2	D	Initial climb	Attempted TO W/Contaminated	Collision W/Obstacle
151	3/6/2003	B-737	7T-VEZ	DAH 6289	DAAT	D	U	102	D	Initial climb	Stall	Uncontrolled Descent to Ground/Water
152	4/23/2003	BE-99	C-FDYF	ABS DYF	CYPA	D	U	0	D	Approach	Flight Control Actuator	Uncontrolled Descent to Ground/Water
153	5/1/2003	LR-45	I-ERJC	I-ERJC	ASN	U	U	2	D	Initial climb	Structural Failure - Birdstrike	Uncontrolled Descent to Ground/Water
154	6/16/2003	A-320	C-GTDK	SSV TDK	EGGD	U	U	0	S	Landing	Unexpected Control Gains	Hard Landing
155	7/8/2003	B-737	ST-AFK	SUD 139	HSSP	N	U	116	D	Missed approach	Failure To Maintain Control	Uncontrolled Descent to Ground/Water
156	8/4/2003	LR-35	N-135PT	RM6A 5P	KGON	D	V	2	D	Approach	Inadvertent Control Input	Collision W/Obstacle
157	8/24/2003	Let-410	HH-PRV	HH-PRV	MTCH	N	U	21	D	Circling approach	Failure To Maintain Control	Uncontrolled Descent to Ground/Water
158	8/26/2003	BE-1900	N-240CJ	CJC 9446	KHYA	D	V	2	D	Initial climb	Reversed Controls	Uncontrolled Descent to Ground/Water
159	10/3/2003	CV-580	ZK-KFU	AFN 642		N	I	2	D	Descent	Icing Stall	In-flight Breakup
160	10/26/2003	FH-227	LV-MGV	CTZ 760		N	U	5	D	Cruise	Loss-of-Control (Vmc)	Uncontrolled Descent to Ground/Water
161	11/22/2003	A-300	OO-DLL	BCS DLL	ORBS	D	V	0	S	Climb	Hostile Action	Runway Departure
162	12/23/2003	LR-24	N-600XJ	N-600XJ		D	V	2	D	Climb	Undetermined	Uncontrolled Descent to Ground/Water
163	1/3/2004	B-737	SU-ZCF	FLS 604	HESH	N	V	148	D	Climb	Spatial Disorientation	Spiral Dive Into Ground

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164	2/10/2004	FO-50	E-PLCA	IRK 7170	OMSI	D	U	43	D	Final approach - non	Undetermined	Uncontrolled Descent to Ground/Water
165	3/4/2004	Il-76	UR-ZVA	AZV ZVA	UBBB	U	U	3	D	Initial climb	Attempted TO W/Incorrect Config	Uncontrolled Descent to Ground/Water
166	3/19/2004	LR-35	N-800AW	BSYA 0A	KUCA	U	I	0	S	Go-around	Stall	Hard Landing
167	5/5/2004	SA-227	HK-4275X	HK-4275X	SKLC	D	V	5	D	VFR pattern-final	Stall	Uncontrolled Descent to Ground/Water
168	5/6/2004	Let-410	9X-REF	9X-REF		D	U	6	D	Initial climb	Stall	Uncontrolled Descent to Ground/Water
169	5/17/2004	DHC-6	8Q-TMC	TMW TM	VRMM	D	U	0	D	Initial climb	Attempted TO W/Incorrect Config	Collision W/Obstacle
170	5/18/2004	Il-76	4KAZ27	AHC Z27	ZWW	D	U	7	D	Initial climb	Undetermined	Collision W/Terrain
171	6/18/2004	SF-340	VH-KEQ	REX KEQ	YMML	D	I	0	U	Descent	Stall	Upset
172	7/2/2004	IAI-1124	N-280AT	N-280AT	MPTO	D	U	6	D	Initial climb	Undetermined	Uncontrolled Descent to Ground/Water
173	7/21/2004	DC-9	XA-BCS	SER 706	MMMX	U	U	0	D	Initial climb	Wind Shear	Collision W/Terrain
174	8/11/2004	B-737	3X-GCM	GIB GCM	GFLL	U	U	0	D	Initial climb	Attempted TO W/Incorrect Config	Collision W/Terrain
175	10/5/2004	An-12	ST-SAF	SRW SAF		D	U	4	D	Cruise	Failure To Maintain Control	Uncontrolled Descent to Ground/Water
176	10/14/2004	B-747	9G-MKJ	MKA 1602	CYHZ	N	U	7	D	Initial climb	Stall	Collision W/Terrain
177	10/14/2004	CL-600	N-8396A	FLG 3701	KJEF	N	V	2	D	Cruise	Autopilot-Induced Stall	Collision W/Terrain
178	11/21/2004	CL-600	B-3072	CES 5210	ZBOW	D	U	53	D	Initial climb	Attempted TO W/Contaminated	Uncontrolled Descent to Ground/Water
179	11/28/2004	CL-600	N-873G	YQCA 73	KMTJ	D	I	3	D	Initial climb	Attempted TO W/Contaminated	Uncontrolled Descent to Ground/Water
180	11/30/2004	HFB-320	N-604GA	GAE 4GA	KSUS	N	I	2	D	Initial climb	Controls (Trim)	Collision W/Terrain
181	12/10/2004	BE-200	N-648KA	YSDA 8K	TS94	D	V	0	D	Initial climb	Stall	Collision W/Obstacle
182	1/13/2005	E-110	N-49BA	RLR 2352	KEEN	N	I	1	D	Missed approach	Loss-of-Control (Vmc)	Uncontrolled Descent to Ground/Water
183	2/16/2005	CE-560	N-500AT	N-500AT	KPUB	D	I	8	D	Final approach - prec	Icing Stall	Uncontrolled Descent to Ground/Water
184	2/24/2005	IAI-1124	XC-COL	XC-COL		D	U	7	D	Approach	Undetermined	Collision W/Terrain
185	3/15/2005	An-26	OB-1778P	AMP 78P	SPIM	D	U	0	S	Initial climb	Attempted TO W/Incorrect Config	Collision W/Terrain
186	3/26/2005	Let-410	HK-4146	WCW 99	SKPV	D	U	9	D	Initial climb	Loss-of-Control (Vmc)	Uncontrolled Descent to Ground/Water
187	5/2/2005	SA-227	ZK-POA	AWK 23		N	I	2	D	Cruise	Load - C/G Out Of Range	Uncontrolled Descent to Ground/Water
188	5/12/2005	MD-90	N-10ME	MEP 490	KIRK	N	I	0	N	Cruise	Instrument Failure	Aircraft Pitch/Roll Oscillations
189	5/21/2005	CL-600	N-699CW	DGFA 9C	KAGS	N	V	0	N	Climb	Aggressive Maneuver	Cabin Injuries
190	5/27/2005	DHC-8	C-GZKH	C-GZKH	CYYT	D	I	0	N	Climb	Icing Stall	Upset
191	8/1/2005	B-777	9M-MRG	MAS 124	YPPH	U	U	0	N	Climb	Uncommanded Pitch	Upset
192	8/14/2005	B-737	5B-DBY	HCY 522	LGAV	U	U	121	D	Climb	Incapacitation: Hypoxia	Uncontrolled Descent to Ground/Water
193	8/16/2005	MD-80	HK-4374X	WCW 70		N	U	160	D	Cruise	Autopilot-Induced Stall	Uncontrolled Descent to Ground/Water
194	9/5/2005	B-737	PR-BRY	BRB 907		U	U	0	U	Cruise	Uncommanded Bank	Upset
195	9/5/2005	B-737	PK-RIM	MDL 91	WIMM	U	U	100	D	Initial climb	Attempted TO W/Incorrect Config	Collision W/Obstacle
196	9/30/2005	B-737	D-ABEA	DLH BEA	EDDF	U	U	0	N	Approach	Wake Turbulence	Landed Without Further Incident
197	10/3/2005	E-170	N-650RW	UHL 7621	KIAD	D	V	0	N	Approach	Aggressive Maneuver	Cabin Injuries
198	10/22/2005	B-737	5N-BFN	BVU 210		N	U	117	D	Climb	Undetermined	Collision W/Terrain
199	11/5/2005	A-320	OO-TCX	TCW TC	EDDF	U	V	0	N	Approach	Wake Turbulence	Landed Without Further Incident
200	11/8/2005	E-110	N-7801Q	BQTA 35	KMHT	D	V	0	D	Initial climb	Loss-of-Control (Vmc)	Collision W/Obstacle
201	12/19/2005	G-73	N-2969	CHK 101	KMPB	D	V	20	D	Initial climb	Structural Failure - Fatigue	Uncontrolled Descent to Ground/Water
202	12/23/2005	An-140	4K-AZ48	AHY 217		N	I	23	D	Cruise	Loss Of All Attitude Displays	Uncontrolled Descent to Ground/Water
203	12/28/2005	LR-35	N-781RS	S2KA 1R	KTRK	D	I	2	D	Approach	Stall	Uncontrolled Descent to Ground/Water
204	1/2/2006	SF-340	N-390AE	SIM 3008		D	I	0	N	Climb	Icing Stall	Upset

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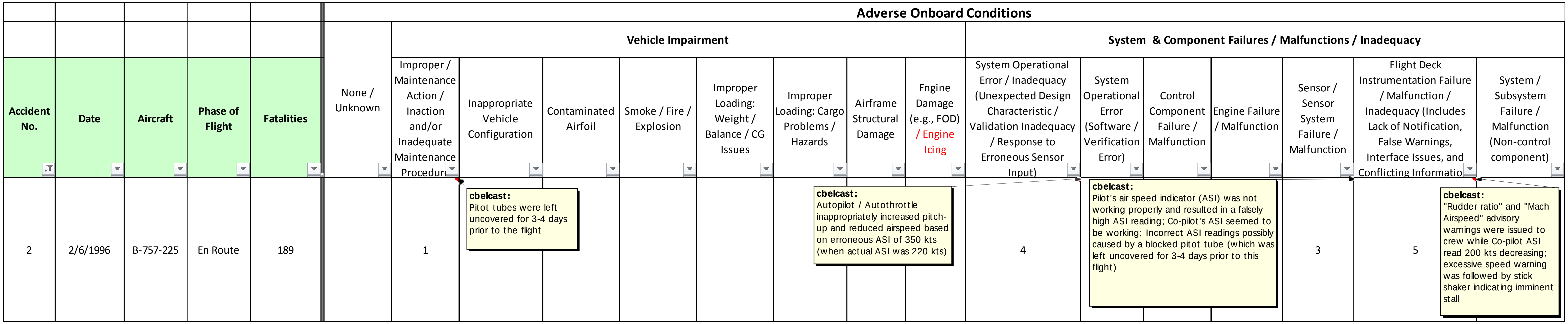
205	1/5/2006	CE-560	N-391QS	DXTA 1Q	KARV	D	V	0	S	Landing	Stall	Collision W/Obstacle
206	2/8/2006	SA-226	N-629EK	GAE 9EK		D	V	1	D	Cruise	Undetermined	Uncontrolled Descent to Ground/Water
207	2/9/2006	CL-600	N-900LG	N-900LG	KASE	D	V	0	S	Approach	Wake Turbulence	Hard Landing
208	5/3/2006	A-320	EK-32009	RNV 967	URSS	N	I	113	D	Missed approach	Spatial Disorientation	Uncontrolled Descent to Ground/Water
209	6/21/2006	DHC-6	9N-AEQ	NYT AEQ	VNJL	U	U	9	D	Go-around	Aggressive Maneuver	Collision W/Terrain
210	7/10/2006	F-27	AP-BAL	PIA 688	OPMT	D	U	45	D	Initial climb	Stall	Collision W/Terrain
211	8/13/2006	L-387	7T-VHG	DAH 2208		U	U	3	D	Cruise	Undetermined	Uncontrolled Descent to Ground/Water
212	8/22/2006	Tu-154	RA-85185	PLK 612		D	I	170	D	Cruise	Turbulence	Uncontrolled Descent to Ground/Water
213	9/29/2006	B-737	PR-GTD	GLO 1907		D	V	154	D	Cruise	Structural Failure - Midair	Uncontrolled Descent to Ground/Water
214	9/29/2006	E-135	N-600XL	N-600XL	SBCC	D	V	0	S	Cruise	Structural Failure - Midair	Forced Landing
215	10/23/2006	A-320	N-924FR	FFT 539	KDEN	D	V	0	N	Landing	Inadvertent Control Input	Uncommanded Pitch
216	10/29/2006	B-737	5N-BFK	ADK 53	DNAA	D	I	96	D	Initial climb	Wind Shear	Uncontrolled Descent to Ground/Water
217	10/31/2006	CL-600	N-322FX	N-322FX	KTEB	U	V	0	N	Approach	Aggressive Maneuver	Cabin Injuries
218	11/30/2006	NA-265	XA-TNP	FCS TNP	MMCL	U	U	2	D	Landing	Undetermined	Collision W/Obstacle
219	1/1/2007	B-737	PK-KKW	DHI 574		D	U	102	D	Cruise	Spatial Disorientation	Spiral Dive Into Ground
220	1/10/2007	LR-35	N-40AN	N-40AN	KCMH	N	V	0	S	Cruise	Intentional Acrobatics	Exceeded Design Loads
221	1/12/2007	CE-525	N-77215	SQ6R 215	KVNY	D	V	2	D	Initial climb	Stall	Uncontrolled Descent to Ground/Water
222	1/25/2007	FO-100	F-GMPG	RAE 7775	LFBP	D	V	0	S	Initial climb	Attempted TO W/Contaminated	Collision W/Obstacle
223	2/13/2007	CL-600	N-168CK	N-168CK	UUW	U	I	0	D	Initial climb	Undetermined	Uncontrolled Descent to Ground/Water
224	3/17/2007	CE-500	N-511AT	N-511AT	KBVY	D	I	0	S	Landing	Contaminated Airfoil	Collision W/Terrain
225	3/27/2007	E-170	HZ-AEN	SVA 1866	OERK	U	U	0	U	Descent	Undetermined	Uncommanded Pitch
226	5/5/2007	B-737	5Y-KYA	KQA 507	FKKD	N	U	114	D	Initial climb	Spatial Disorientation	Spiral Dive Into Ground
227	5/17/2007	Let-410	TN-AHE	SAFE AH		U	U	3	D	Initial climb	Undetermined	Collision W/Obstacle
228	6/4/2007	CE-550	N-550BP	DJQ 0BP	KMKE	D	V	6	D	Climb	Spatial Disorientation	Spiral Dive Into Ground
229	7/29/2007	An-12	RA-93912	VAS 9655	UUDD	N	U	7	D	Initial climb	Loss-of-Control (Vmc)	Uncontrolled Descent to Ground/Water
230	8/9/2007	DHC-6	F-OIQI	TAH 1121	NTTM	D	V	20	D	Initial climb	Flight Control Integrity Lost	Uncontrolled Descent to Ground/Water
231	9/23/2007	B-737	G-THOF	TOM HOF	EGHH	N	I	0	N	Final approach - prec	Stall	Uncommanded Pitch
232	10/17/2007	LR-35	N-31MC	N-31MC	KGLD	D	I	0	S	Landing	Aircraft Pitch/Roll Oscillations	Collision W/Terrain
233	11/4/2007	LR-35	PT-OVC	PT-OVC	SBMT	U	U	2	D	Initial climb	Undetermined	Uncontrolled Descent to Ground/Water
234	12/10/2007	BE-200	N-925TT	N-925TT	KSMN	W	I	2	D	Initial climb	Attempted TO W/Contaminated	Collision W/Obstacle
235	12/16/2007	CL-600	N-470ZW	AWI 3758	KPVD	D	I	0	S	Landing	Stall	Hard Landing
236	1/10/2008	A-320	C-GBHZ	ACA 190	KOMK	N	V	0	M	Climb	Wake Turbulence	Upset
237	2/14/2008	CL-600	EW-101PJ	BRU 1834	UDYZ	U	U	0	D	Initial climb	Attempted TO W/Contaminated	Collision W/Terrain
238	3/4/2008	CE-500	N-113SH	N-113SH	KPWA	D	U	5	D	Climb	Structural Failure - Birdstrike	Collision W/Terrain
239	4/9/2008	SA-227	VH-OZA	VH-OZA	YSSY	N	V	1	D	Climb	Spatial Disorientation	Spiral Dive Into Ground
240	5/23/2008	BE-1900	N-195GA	TIM 5008	KBIL	N	I	1	D	Initial climb	Undetermined	Uncontrolled Descent to Ground/Water
241	5/26/2008	An-12	RA12957	GAI 2063	USCC	U	U	9	D	Climb	Flight Control Integrity Lost	Uncontrolled Descent to Ground/Water
242	6/14/2008	MD-10	N-554FE	FDE 764		U	V	0	S	holding (IFR)	Stall	Exceeded Design Loads
243	6/18/2008	DHC-6	N-656WA	WIG 6601	KHYA	D	V	1	D	Initial climb	Attempted TO W/Gust Locks Eng	Uncontrolled Descent to Ground/Water
244	6/30/2008	Il-76	ST-WTB	BBE 700	HSSS	D	U	4	D	Initial climb	Attempted TO W/Incorrect Config	Collision W/Terrain
245	7/10/2008	BE-99	CC-CFM	CC-CFM	SCPF	U	U	9	D	Initial climb	Stall	Uncontrolled Descent to Ground/Water

No	Date	Aircraft	Registr'n	Ident	Loc'n	Light	Wea	Fat	Dam	Phase	Occurrence	Result
246	7/16/2008	DHC-6	C-GBEB	NWI BEB		D	V	0	S	VFR pattern-base tur	Stall	Collision W/Obstacle
247	8/20/2008	MD-80	EC-HFP	JKK 5022	LEMD	U	U	154	D	Initial climb	Attempted TO W/Incorrect Config	Collision W/Terrain
248	9/14/2008	B-737	VP-BKO	AFL BKO	USPP	N	I	88	D	Approach	Spatial Disorientation	Spiral Dive Into Ground
249	10/7/2008	A-330	VH-QPA	QFA 72	YPLM	U	U	0	M	Cruise	Flight Control Logic	Upset
250	11/1/2008	CASA-212	N-437RA	ATS 7RA		T	V	0	S	Go-around	Asymmetric Thrust/Drag	Collision W/Terrain
251	11/4/2008	LR-45	XC-VMC	XC-VMC	MMMX	U	U	9	U	Approach	Wake Turbulence	Uncontrolled Descent to Ground/Water
252	12/7/2008	LR-23	XC-LGD	XC-LGD		U	U	2	D	Go-around	Undetermined	Uncontrolled Descent to Ground/Water
253	1/27/2009	ATR-42	N-902FX	CFS 8284	KLLB	N	I	0	S	Final approach - prec	Stall	Uncontrolled Descent to Ground/Water
254	1/28/2009	B-757	G-STRZ	AEU TRZ	DGAA	N	I	0	N	Cruise	Instrument Failure	Landed Without Further Incident
255	2/7/2009	CE-650	I-FEEV	AOE 301		U	U	2	D	Climb	Undetermined	Spiral Dive Into Ground
256	2/7/2009	E-110	PT-SEA	PT-SEA	SWK	D	U	24	D	Climb	Undetermined	Collision W/Terrain
257	2/12/2009	DHC-8	N-200WQ	CJC 3407	KBUF	N	V	49	D	Approach	Stall	Uncontrolled Descent to Ground/Water
258	2/25/2009	B-737	TC-JGE	THY 1951	EHAM	D	U	9	D	Approach	Stall	Collision W/Terrain
259	5/11/2009	B-747	G-BYGA	BAW YG	FAJS	N	V	0	N	Initial climb	Uncommanded Configuration Cha	Stall Buffet
260	6/1/2009	A-330	F-GZCP	AFR 447	TASIL	N	I	228	D	Cruise	Spatial Disorientation	Uncontrolled Descent to Ground/Water
261	6/30/2009	A-310	7O-ADJ	IYE 626	FMCH	N	V	152	D	Circling approach	Failure To Maintain Airspeed	Collision W/Terrain
262	7/15/2009	Tu-154	EP-CPG	CMP 790		U	U	168	D	Cruise	Undetermined	Collision W/Terrain
263	10/21/2009	B-707	ST-AKW	SUD 2241	OMSJ	U	U	6	D	Initial climb	Failure To Maintain Control	Uncontrolled Descent to Ground/Water
264	11/1/2009	Il-76	RF-76801	RF-76801	UERR	U	U	11	D	Initial climb	Undetermined	Collision W/Terrain
265	11/28/2009	MD-11	Z-BAV	SMJ 324	ZSPD	U	U	3	D	Initial climb	Undetermined	Uncontrolled Descent to Ground/Water
266	1/5/2010	LR-35	N-720RA	RAX 988	KPWK	D	V	2	D	Circling approach	Undetermined	Uncontrolled Descent to Ground/Water
267	1/6/2010	BE-99	N-206AV	JIKA 6AV	KEAR	W	I	0	S	Landing	Icing Stall	Hard Landing
268	1/21/2010	BE-1900	N-112AX	AER 22	PASD	N	V	2	D	Initial climb	Undetermined	Uncontrolled Descent to Ground/Water
269	1/25/2010	B-737	ET-ANB	ETH 409	OLBA	N	I	90	D	Climb	Spatial Disorientation	Spiral Dive Into Ground
270	2/13/2010	B-737	N-221WN	SWA 253	KBUR	D	V	0	N	Approach	Aggressive Maneuver	Cabin Injuries
271	2/14/2010	CE-550	OK-ACH	TIE 039C		N	V	2	D	Cruise	Intentional Acrobatics	Uncontrolled Descent to Ground/Water
272	5/12/2010	A-330	5A-ONG	AAW 771	HLLT	D	I	103	D	Go-around	Somatogravic Illusion	Collision W/Terrain
273	8/25/2010	Let-410	9Q-CCN	9Q-CCN	ZFBO	U	U	20	D	Approach	Load - C/G Out Of Range	Collision W/Terrain
274	9/3/2010	B-747	N-571UP	UPS 006	OMDB	N	U	2	D	Climb	Structural Failure - Fire/Explosion	Uncontrolled Descent to Ground/Water
275	10/11/2010	A-380	F-HPJA	AFR 006	KJFK	D	U	0	N	Go-around	Flap/Slat Extension Speed Exceed	Altitude Deviation
276	11/4/2010	ATR-72	CUT1549	CRN 883		U	I	68	D	Cruise	Contaminated Airfoil	Uncontrolled Descent to Ground/Water
277	11/5/2010	BE-1900	AP-BJD	JSJ BJD	OPKC	U	U	21	D	Initial climb	Loss-of-Control (Vmc)	Collision W/Terrain
278	11/28/2010	Il-76	4L-GNI	4L-GNI	OPKC	U	U	8	D	Initial climb	Loss-of-Control (Vmc)	Collision W/Obstacle

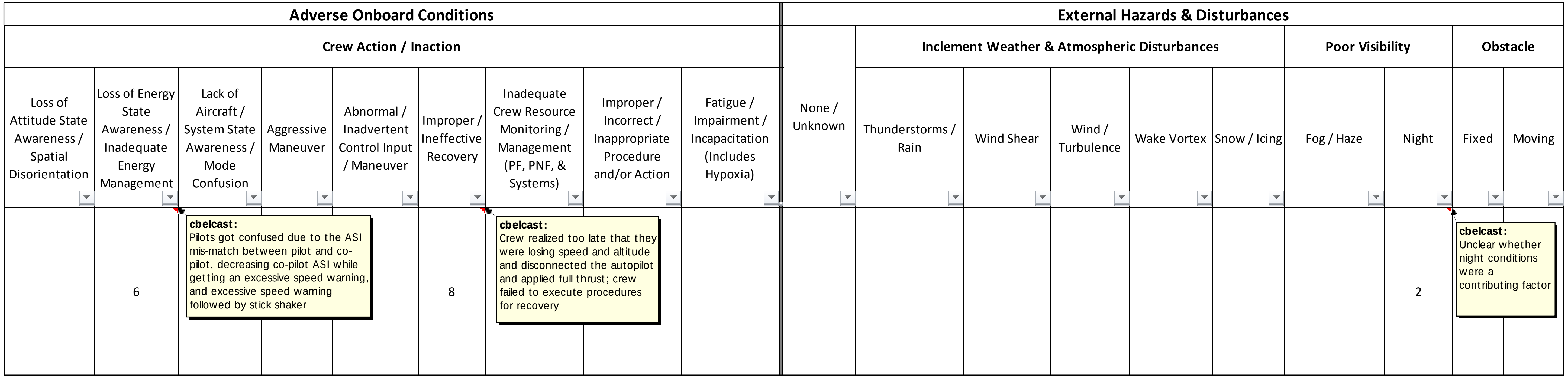
Appendix B: LOC Accident Analysis Spreadsheet Illustration

Example LOC Analysis Spreadsheet Entry: Birgenair 301 (2/6/1996)

The spreadsheet entries below illustrate the precursor analysis, comments, and potential for mitigation through research for Birgenair 301.



					Adverse Onboard Conditions																
						Vehicle Impairment									System & Component Failures / Malfunctions / Inadequacy						
Accident No.	Date	Aircraft	Phase of Flight	Fatalities	None / Unknown	Improper / Maintenance Action / Inaction and/or Inadequate Maintenance Procedur	Inappropriate Vehicle Configuration	Contaminated Airfoil	Smoke / Fire / Explosion	Improper Loading: Weight / Balance / CG Issues	Improper Loading: Cargo Problems / Hazards	Airframe Structural Damage	Engine Damage (e.g., FOD) / Engine Icing	System Operational Error / Inadequacy (Unexpected Design Characteristic / Validation Inadequacy / Response to Erroneous Sensor Input)	System Operational Error (Software / Verification Error)	Control Component Failure / Malfunction	Engine Failure / Malfunction	Sensor / Sensor System Failure / Malfunction	Flight Deck Instrumentation Failure / Malfunction / Inadequacy (Includes Lack of Notification, False Warnings, Interface Issues, and Conflicting Informatio	System / Subsystem Failure / Malfunction (Non-control component)
2	2/6/1996	B-757-225	En Route	189		1 **cbelcast:** Pitot tubes were left uncovered for 3-4 days prior to the flight								4 **cbelcast:** Autopilot / Autothrottle inappropriately increased pitch-up and reduced airspeed based on erroneous ASI of 350 kts (when actual ASI was 220 kts)				3 **cbelcast:** Pilot's air speed indicator (ASI) was not working properly and resulted in a falsely high ASI reading; Co-pilot's ASI seemed to be working; Incorrect ASI readings possibly caused by a blocked pitot tube (which was left uncovered for 3-4 days prior to this flight)	5 **cbelcast:** "Rudder ratio" and "Mach Airspeed" advisory warnings were issued to crew while Co-pilot ASI read 200 kts decreasing; excessive speed warning was followed by stick shaker indicating imminent stall	



Adverse Onboard Conditions									External Hazards & Disturbances									
Crew Action / Inaction										Inclement Weather & Atmospheric Disturbances					Poor Visibility		Obstacle	
Loss of Attitude State Awareness / Spatial Disorientation	Loss of Energy State Awareness / Inadequate Energy Management	Lack of Aircraft / System State Awareness / Mode Confusion	Aggressive Maneuver	Abnormal / Inadvertent Control Input / Maneuver	Improper / Ineffective Recovery	Inadequate Crew Resource Monitoring / Management (PF, PNF, & Systems)	Improper / Incorrect / Inappropriate Procedure and/or Action	Fatigue / Impairment / Incapacitation (Includes Hypoxia)	None / Unknown	Thunderstorms / Rain	Wind Shear	Wind / Turbulence	Wake Vortex	Snow / Icing	Fog / Haze	Night	Fixed	Moving
	6 **cbelcast:** Pilots got confused due to the ASI mis-match between pilot and co-pilot, decreasing co-pilot ASI while getting an excessive speed warning, and excessive speed warning followed by stick shaker				8 **cbelcast:** Crew realized too late that they were losing speed and altitude and disconnected the autopilot and applied full thrust; crew failed to execute procedures for recovery											2 **cbelcast:** Unclear whether night conditions were a contributing factor		

Abnormal Dynamics & Vehicle Upset Conditions													
	Abnormal Vehicle Dynamics				Vehicle Upset Conditions								Comments
None / Unknown	Uncommanded Motions	Oscillatory Vehicle Response (Includes PIO)	Abnormal Control for Trim / Flight and/or Control Asymmetry	Abnormal / Counterintuitive Control Responses	Abnormal Attitude	Abnormal Airspeed (Includes Low Energy)	Abnormal Angular Rates	Undesired Abrupt Dynamic Response	Abnormal Flight Trajectory	Uncontrolled Descent (Includes Spiral Dive)	Vmc / Departure	Stall / Departure (Includes Falling Leaf, Spin)	
												7	

cbelcast:
Stick shaker activated

Crew Distraction / Preoccupation / Mis-aligned Focus Flag		Potential Human-Machine Interface Issue Flag (Includes Displays, Controls, Flight Management, Envelope Protection, & Warning Systems that Influence Flight Control)		Potential to Mitigate through Research (Technologies, Training, Procedures, etc.)		
Yes / No / Not Enough Information (NEI)	Comment	Yes / No / Not Enough Information (NEI)	Comment	Yes / No / Not Enough Information (NEI)	Mitigation Description	References
No		Yes	Faulty ASI to Autopilot/Autothrottle caused aircraft to pitch up and lower airspeed, which led to stall; Conflicting warnings in flight deck (overspeed and stick shaker)	Yes	1. Improved pilot training 2. NASA NRA with UIUC includes sensor failure detection and isolation (FDI) 3. NASA SBIRs on Sensor Integrity Management with Scientific Systems and Barron Associates (Awarded 2014) 4. NASA SBIR with Barron Associates on Upset Recovery Guidance System 5. Resilient flight control	1. 2. Felemban, Che, Cao, Hovakimyan, and Gregory, "Estimation of Airspeed Using Continuous Polynomial Adaptive Estimator," 2014 SciTech Conference, National Harbor MD. 3. None yet 4. Gandhi, Neha, Richards, Nathan D., and Bateman, Alec J., "Simulator Evaluation of an In-Cockpit Cueing Systems for Upset Recovery," 2014 SciTech Conference, National Harbor, MD. 5.

Appendix C: Worst Case Precursor Analysis Examples

Worst case precursor combinations are illustrated in Figures C.1 and C.2 at the sub-category and precursor levels, respectively. Note that sphere size is directly proportional to number of accidents, and sphere color relates to number of fatalities.

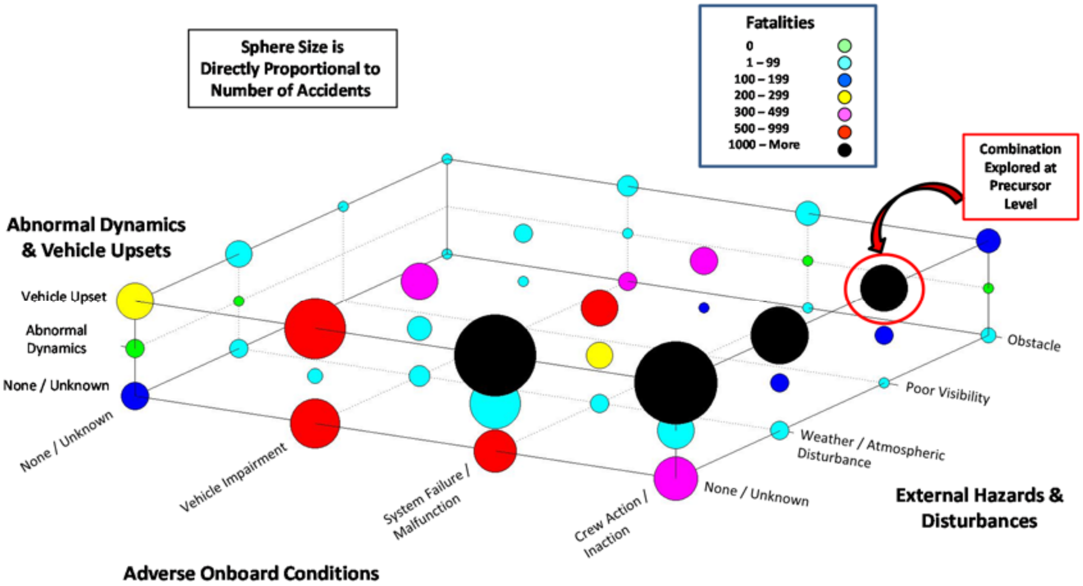


Figure C.1. Example of Worst Case Precursor Combinations Analysis at the Sub-Category Level, with one Combination Indicated for Analysis at Precursor Level (see Figure A.2).

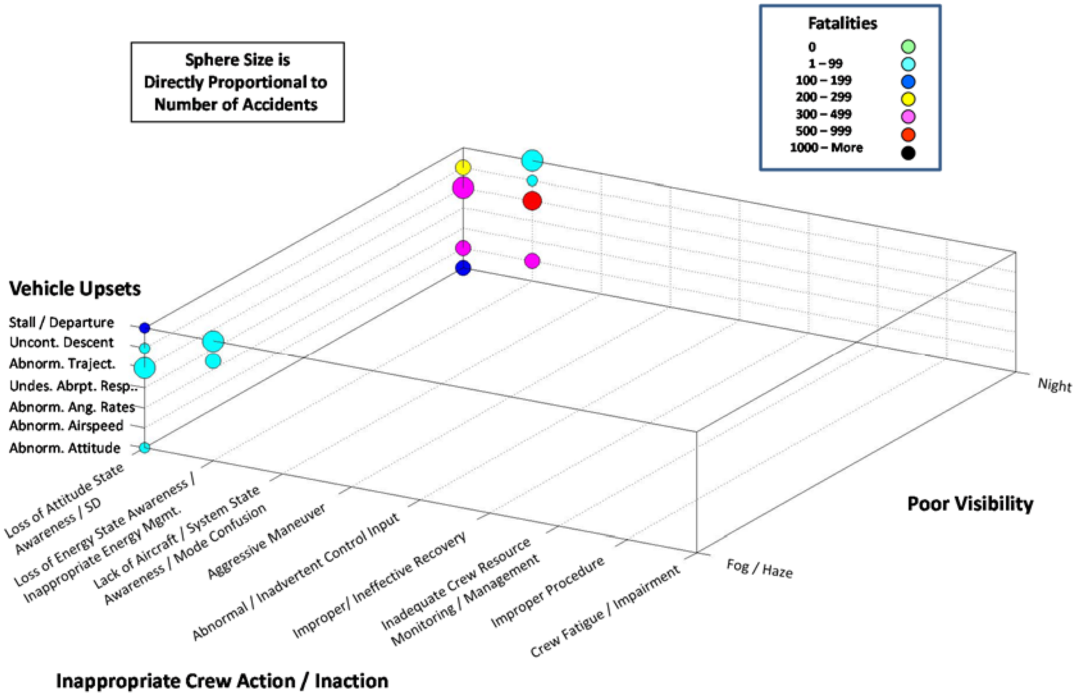


Figure C.2. Precursor Combinations within Sub-Category Combination of Figure A.1.

Worst case precursor sequences are illustrated in Figure C.3 for events initiated by system and component failures, and in Figure C.4 for events initiated by inappropriate crew action (or inaction).

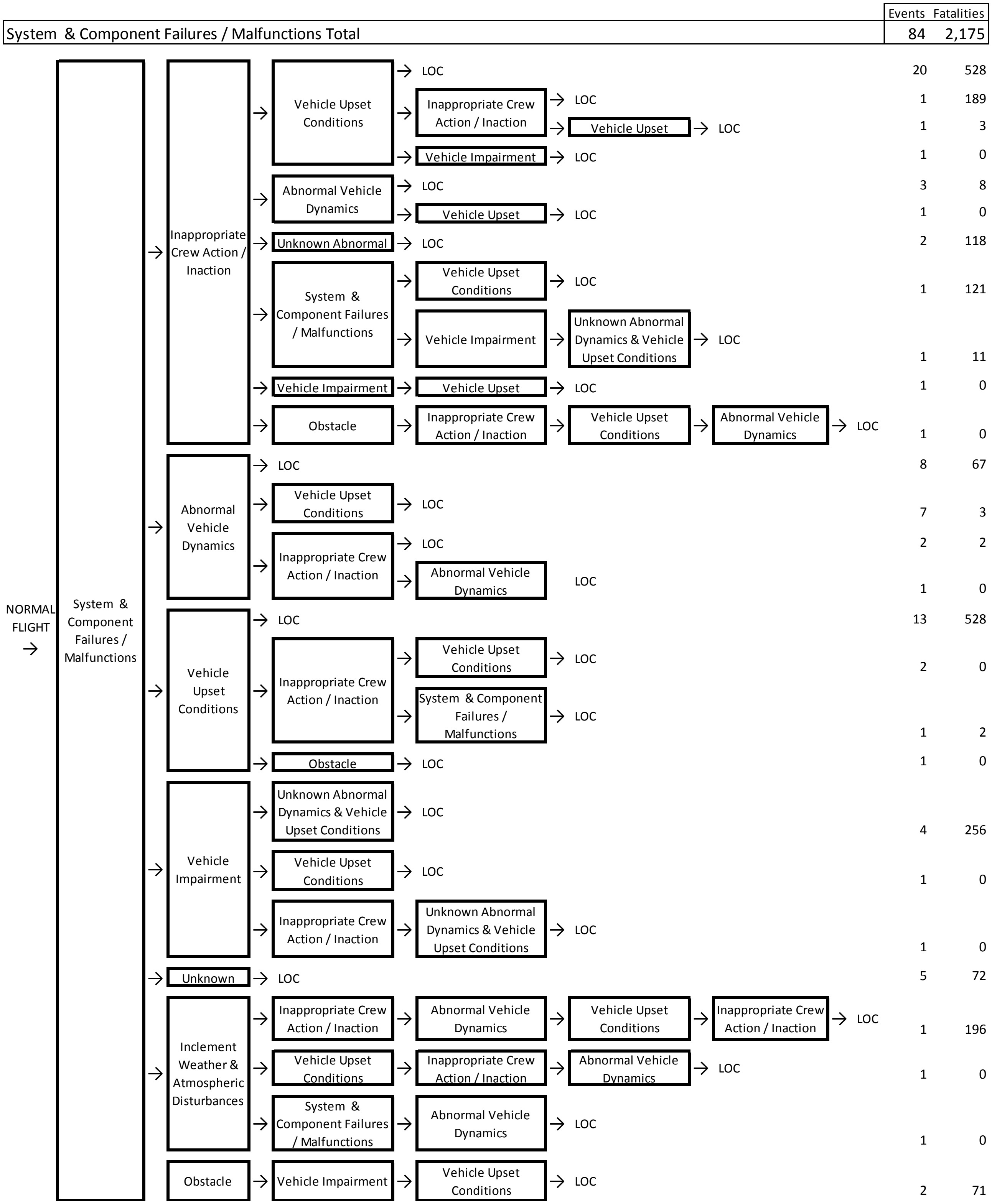


Figure C.3. LOC Sequences Initiated by System & Component Failures / Malfunctions.

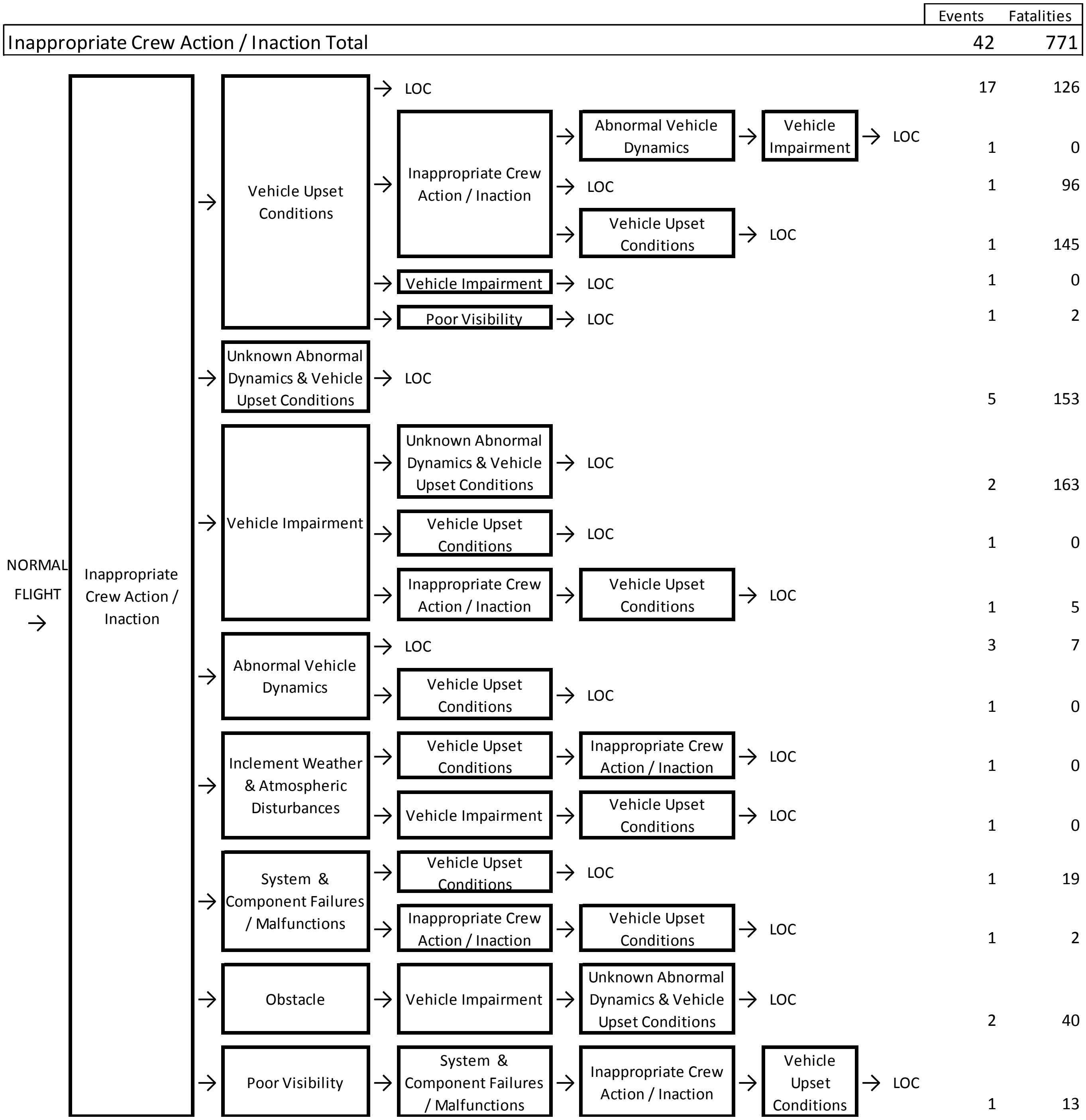


Figure C.4. LOC Sequences Initiated by Inappropriate Crew Action / Inaction.

Note that the example results illustrated in Figures C.1 – C.4 are taken from Ref. 10.

Appendix D. Precursor Sequences for Mishaps Involving Blocked Pitot Tubes or Static Ports

The precursor sequences for the blocked pitot tube or static ports mishaps presented in Section III-C are provided below in Figures D.1 – D.8. The comments and flags associated with these mishaps are presented in Tables D.2 – D.3. The information in Table 3 from Section III-C is repeated here as Table D.1 with the fatal accidents nonfatal incidents grouped together.

Table D.1. LOC Accidents and Incidents from the Data Set Involving Blocked Pitot Tubes or Static Ports, Grouped by Fatal and Nonfatal Events

Accident No.	Date	Location	Airline	Flight No.	Aircraft	Phase of Flight	Fatalities
2	2/6/1996	Dominican Republic	Birgenair	301	B-757-225	En Route	189
14	10/2/1996	Peru	AeroPeru	603	B-757	Climb	70
37	10/10/1997	Uruguay	Austral Lineas Aereas	2553	DC-9	En Route	74
62	4/7/1999	Ceyhan, Turkey	THY Turkish Airlines	5904	B-737	En Route	6
260	6/1/2009	Atlantic Ocean (Near Sao Paulo Archipelago)	Air France	447	A-330	En Route	228
142	10/20/2002	Baltimore, Maryland	Icelandair	662	B-757	En Route	0
188	5/12/2005	Missouri	Midwest Airlines		MD-90	Initial Climb	0
254	1/28/2009	Ghana	Astraeus for Ghana Airways		B-757	Cruise	0

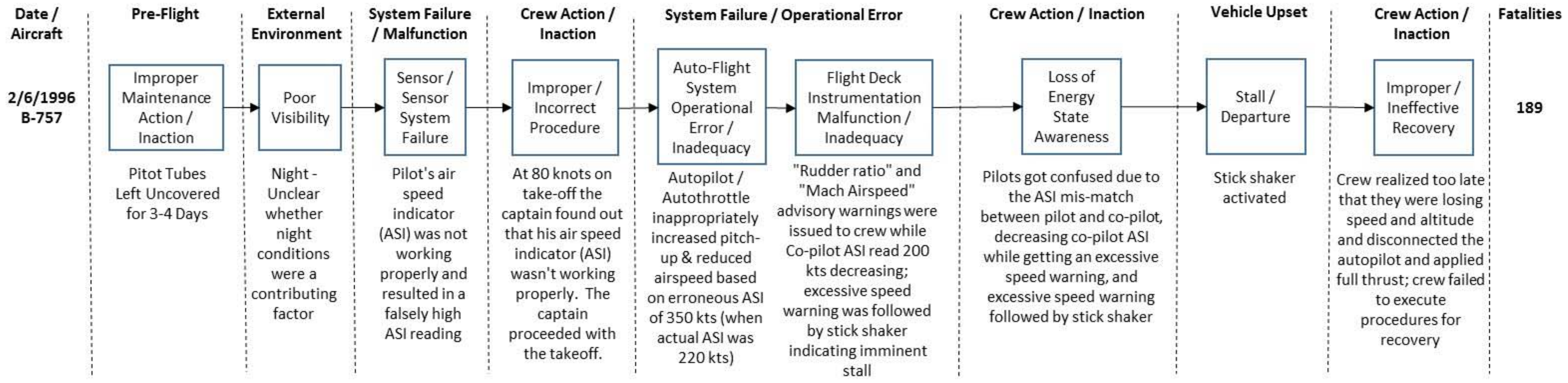
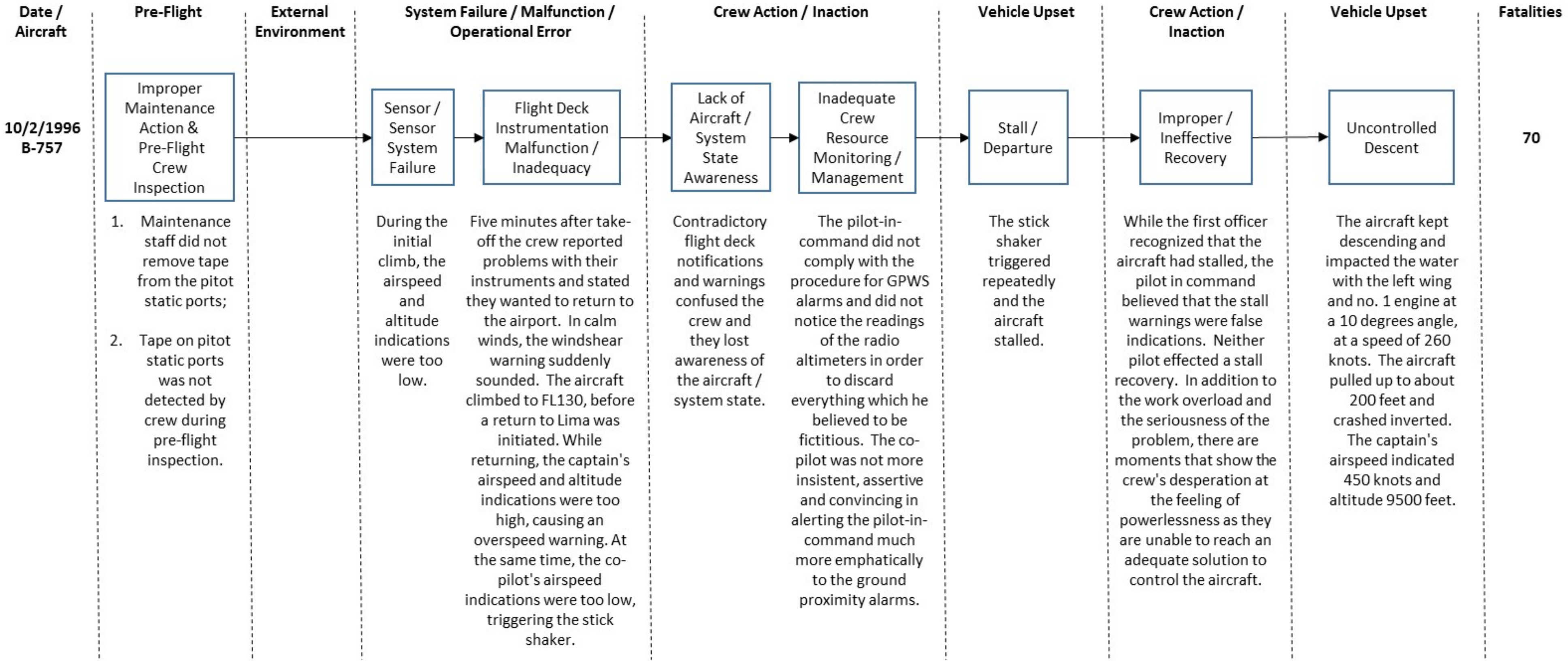


Figure D.1. Precursor Sequence for Fatal Accident No.2 of Table D.1



1. Maintenance staff did not remove tape from the pitot static ports;
2. Tape on pitot static ports was not detected by crew during pre-flight inspection.

During the initial climb, the airspeed and altitude indications were too low.

Five minutes after take-off the crew reported problems with their instruments and stated they wanted to return to the airport. In calm winds, the windshear warning suddenly sounded. The aircraft climbed to FL130, before a return to Lima was initiated. While returning, the captain's airspeed and altitude indications were too high, causing an overspeed warning. At the same time, the co-pilot's airspeed indications were too low, triggering the stick shaker.

Contradictory flight deck notifications and warnings confused the crew and they lost awareness of the aircraft / system state.

The pilot-in-command did not comply with the procedure for GPWS alarms and did not notice the readings of the radio altimeters in order to discard everything which he believed to be fictitious. The co-pilot was not more insistent, assertive and convincing in alerting the pilot-in-command much more emphatically to the ground proximity alarms.

The stick shaker triggered repeatedly and the aircraft stalled.

While the first officer recognized that the aircraft had stalled, the pilot in command believed that the stall warnings were false indications. Neither pilot effected a stall recovery. In addition to the work overload and the seriousness of the problem, there are moments that show the crew's desperation at the feeling of powerlessness as they are unable to reach an adequate solution to control the aircraft.

The aircraft kept descending and impacted the water with the left wing and no. 1 engine at a 10 degrees angle, at a speed of 260 knots. The aircraft pulled up to about 200 feet and crashed inverted. The captain's airspeed indicated 450 knots and altitude 9500 feet.

Figure D.2. Precursor Sequence for Fatal Accident No. 14 of Table D.1

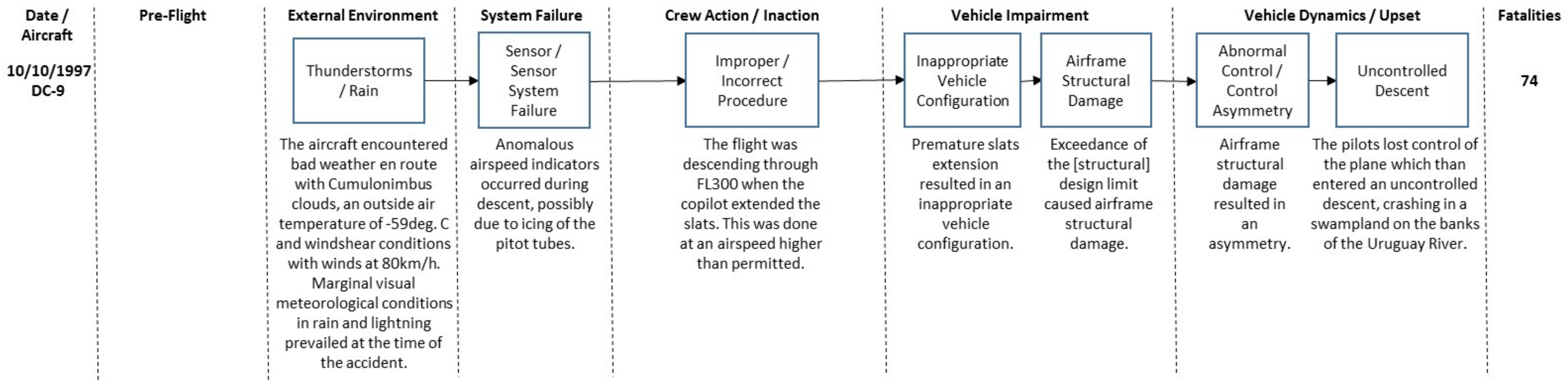


Figure D.3. Precursor Sequence for Accident No. 37 of Table D.1

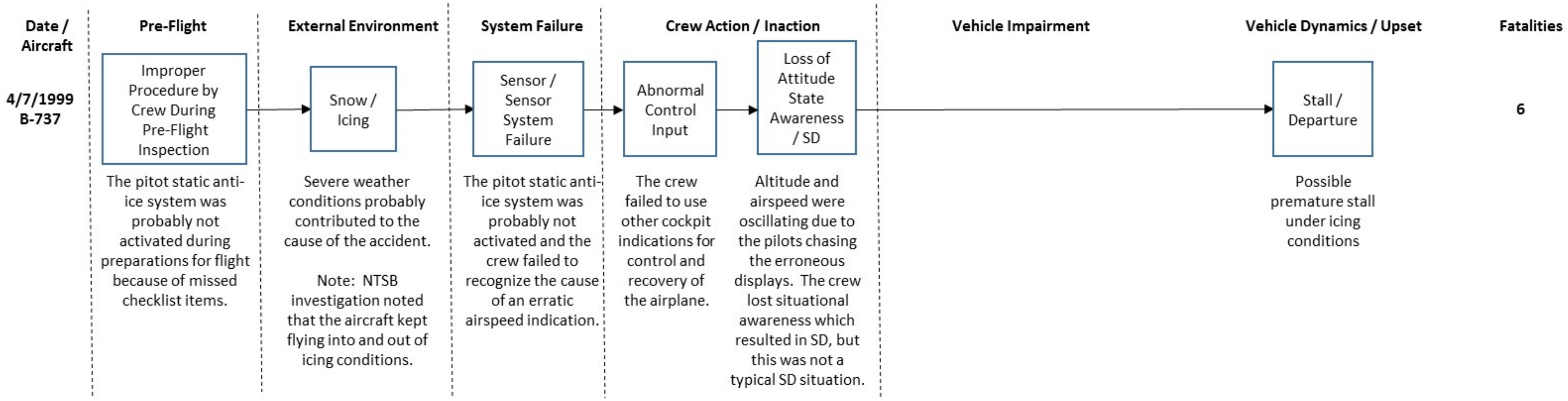
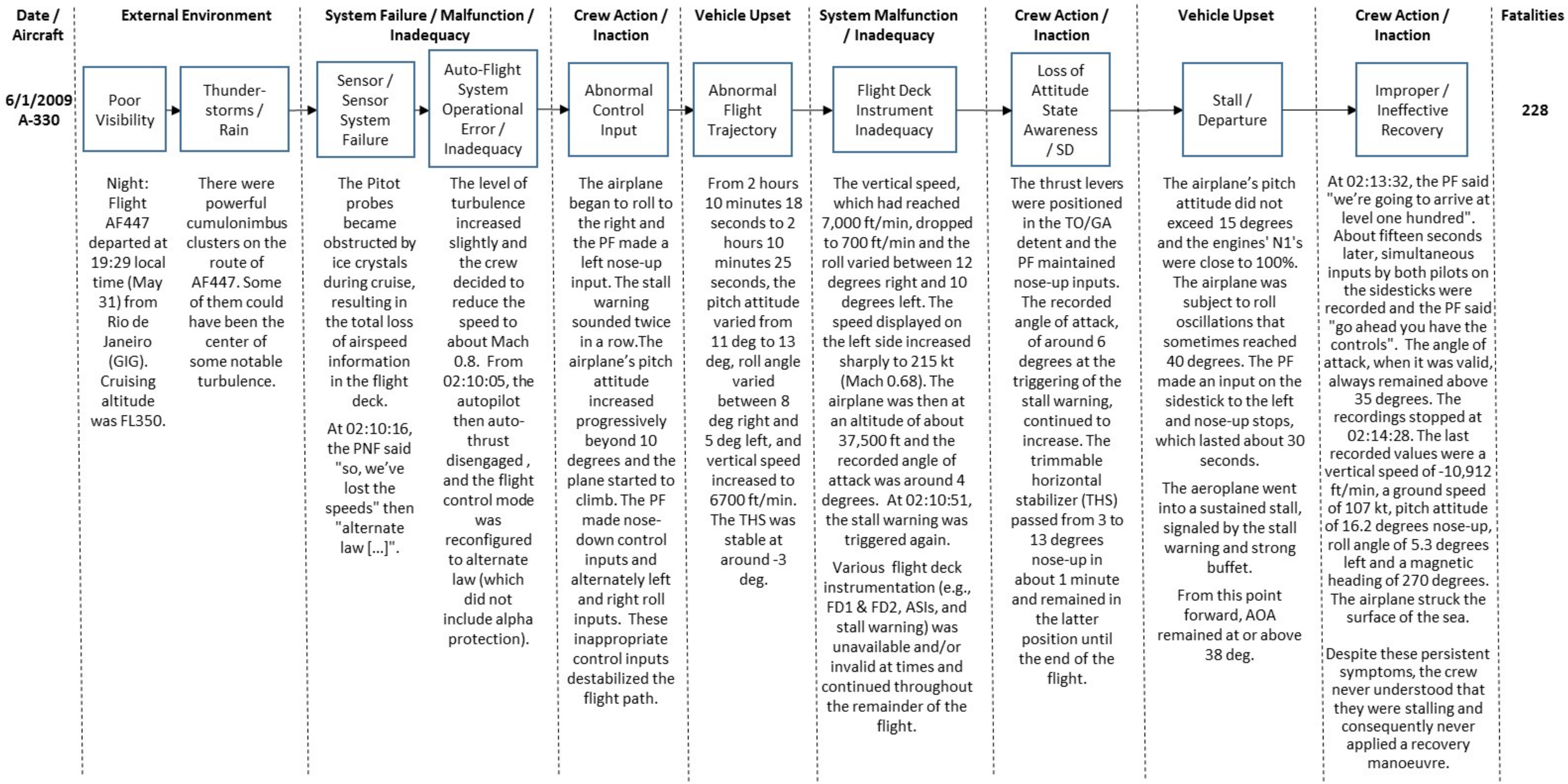
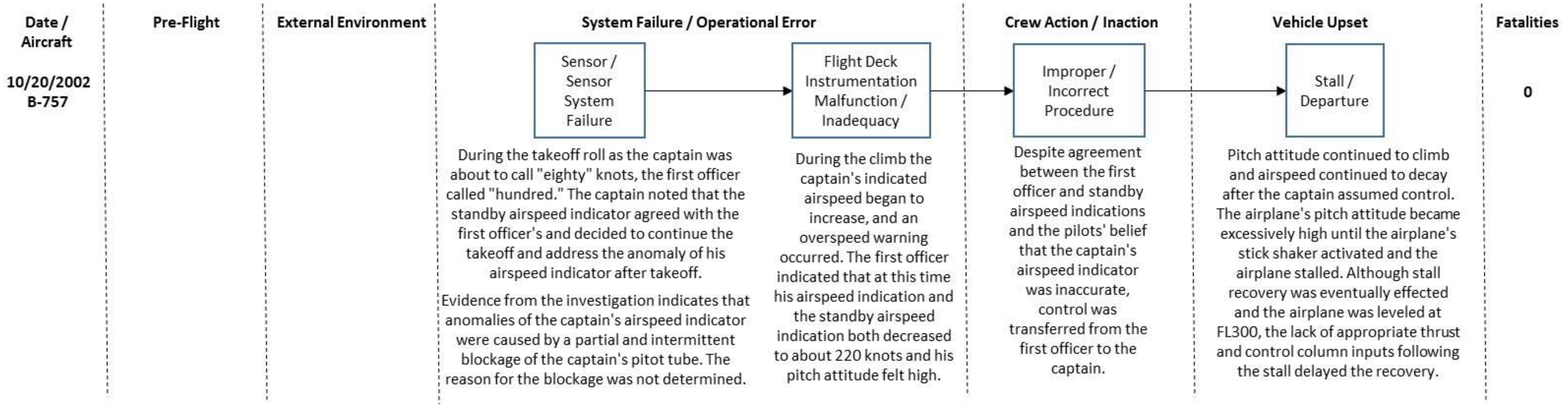


Figure D.4. Precursor Sequence for Accident No. 62 of Table D.1



Date / Aircraft	External Environment		System Failure / Malfunction / Inadequacy		Crew Action / Inaction	Vehicle Upset	System Malfunction / Inadequacy	Crew Action / Inaction	Vehicle Upset	Crew Action / Inaction	Fatalities
6/1/2009 **A-330**	Poor Visibility	Thunder-storms / Rain	Sensor / Sensor System Failure	Auto-Flight System Operational Error / Inadequacy	Abnormal Control Input	Abnormal Flight Trajectory	Flight Deck Instrument Inadequacy	Loss of Attitude State Awareness / SD	Stall / Departure	Improper / Ineffective Recovery	**228**
	Night: Flight AF447 departed at 19:29 local time (May 31) from Rio de Janeiro (GIG). Cruising altitude was FL350.	There were powerful cumulonimbus clusters on the route of AF447. Some of them could have been the center of some notable turbulence.	The Pitot probes became obstructed by ice crystals during cruise, resulting in the total loss of airspeed information in the flight deck. At 02:10:16, the PNF said "so, we've lost the speeds" then "alternate law [...]".	The level of turbulence increased slightly and the crew decided to reduce the speed to about Mach 0.8. From 02:10:05, the autopilot then auto-thrust disengaged , and the flight control mode was reconfigured to alternate law (which did not include alpha protection).	The airplane began to roll to the right and the PF made a left nose-up input. The stall warning sounded twice in a row.The airplane's pitch attitude increased progressively beyond 10 degrees and the plane started to climb. The PF made nose-down control inputs and alternately left and right roll inputs. These inappropriate control inputs destabilized the flight path.	From 2 hours 10 minutes 18 seconds to 2 hours 10 minutes 25 seconds, the pitch attitude varied from 11 deg to 13 deg, roll angle varied between 8 deg right and 5 deg left, and vertical speed increased to 6700 ft/min. The THS was stable at around -3 deg.	The vertical speed, which had reached 7,000 ft/min, dropped to 700 ft/min and the roll varied between 12 degrees right and 10 degrees left. The speed displayed on the left side increased sharply to 215 kt (Mach 0.68). The airplane was then at an altitude of about 37,500 ft and the recorded angle of attack was around 4 degrees. At 02:10:51, the stall warning was triggered again. Various flight deck instrumentation (e.g., FD1 & FD2, ASIs, and stall warning) was unavailable and/or invalid at times and continued throughout the remainder of the flight.	The thrust levers were positioned in the TO/GA detent and the PF maintained nose-up inputs. The recorded angle of attack, of around 6 degrees at the triggering of the stall warning, continued to increase. The trimmable horizontal stabilizer (THS) passed from 3 to 13 degrees nose-up in about 1 minute and remained in the latter position until the end of the flight.	The airplane's pitch attitude did not exceed 15 degrees and the engines' N1's were close to 100%. The airplane was subject to roll oscillations that sometimes reached 40 degrees. The PF made an input on the sidestick to the left and nose-up stops, which lasted about 30 seconds. The aeroplane went into a sustained stall, signaled by the stall warning and strong buffet. From this point forward, AOA remained at or above 38 deg.	At 02:13:32, the PF said "we're going to arrive at level one hundred". About fifteen seconds later, simultaneous inputs by both pilots on the sidesticks were recorded and the PF said "go ahead you have the controls". The angle of attack, when it was valid, always remained above 35 degrees. The recordings stopped at 02:14:28. The last recorded values were a vertical speed of -10,912 ft/min, a ground speed of 107 kt, pitch attitude of 16.2 degrees nose-up, roll angle of 5.3 degrees left and a magnetic heading of 270 degrees. The airplane struck the surface of the sea. Despite these persistent symptoms, the crew never understood that they were stalling and consequently never applied a recovery manoeuvre.	

Figure D.5. Precursor Sequence for Accident No. 260 of Table D.1



During the takeoff roll as the captain was about to call "eighty" knots, the first officer called "hundred." The captain noted that the standby airspeed indicator agreed with the first officer's and decided to continue the takeoff and address the anomaly of his airspeed indicator after takeoff.

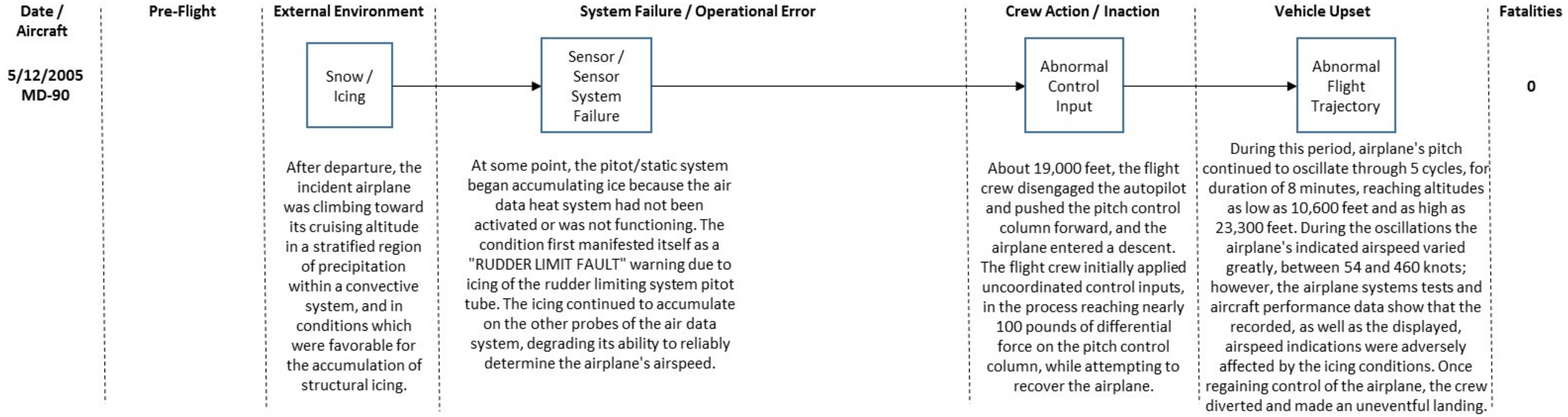
Evidence from the investigation indicates that anomalies of the captain's airspeed indicator were caused by a partial and intermittent blockage of the captain's pitot tube. The reason for the blockage was not determined.

During the climb the captain's indicated airspeed began to increase, and an overspeed warning occurred. The first officer indicated that at this time his airspeed indication and the standby airspeed indication both decreased to about 220 knots and his pitch attitude felt high.

Despite agreement between the first officer and standby airspeed indications and the pilots' belief that the captain's airspeed indicator was inaccurate, control was transferred from the first officer to the captain.

Pitch attitude continued to climb and airspeed continued to decay after the captain assumed control. The airplane's pitch attitude became excessively high until the airplane's stick shaker activated and the airplane stalled. Although stall recovery was eventually effected and the airplane was leveled at FL300, the lack of appropriate thrust and control column inputs following the stall delayed the recovery.

Figure D.6. Precursor Sequence for Nonfatal Incident No. 142 of Table D.1



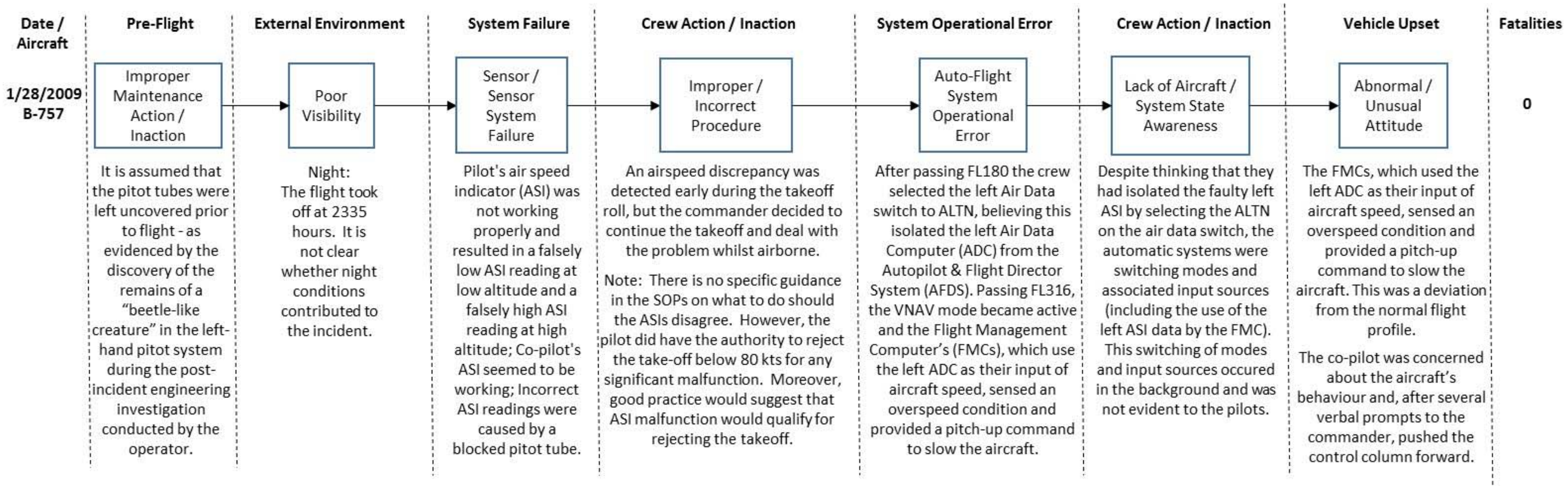
After departure, the incident airplane was climbing toward its cruising altitude in a stratified region of precipitation within a convective system, and in conditions which were favorable for the accumulation of structural icing.

At some point, the pitot/static system began accumulating ice because the air data heat system had not been activated or was not functioning. The condition first manifested itself as a "RUDDER LIMIT FAULT" warning due to icing of the rudder limiting system pitot tube. The icing continued to accumulate on the other probes of the air data system, degrading its ability to reliably determine the airplane's airspeed.

About 19,000 feet, the flight crew disengaged the autopilot and pushed the pitch control column forward, and the airplane entered a descent. The flight crew initially applied uncoordinated control inputs, in the process reaching nearly 100 pounds of differential force on the pitch control column, while attempting to recover the airplane.

During this period, airplane's pitch continued to oscillate through 5 cycles, for duration of 8 minutes, reaching altitudes as low as 10,600 feet and as high as 23,300 feet. During the oscillations the airplane's indicated airspeed varied greatly, between 54 and 460 knots; however, the airplane systems tests and aircraft performance data show that the recorded, as well as the displayed, airspeed indications were adversely affected by the icing conditions. Once regaining control of the airplane, the crew diverted and made an uneventful landing.

Figure D.7. Precursor Sequence for Nonfatal Incident No. 188 of Table D.1



Date / Aircraft	Pre-Flight	External Environment	System Failure	Crew Action / Inaction	System Operational Error	Crew Action / Inaction	Vehicle Upset	Fatalities
1/28/2009 B-757	Improper Maintenance Action / Inaction	Poor Visibility	Sensor / Sensor System Failure	Improper / Incorrect Procedure	Auto-Flight System Operational Error	Lack of Aircraft / System State Awareness	Abnormal / Unusual Attitude	0
	It is assumed that the pitot tubes were left uncovered prior to flight - as evidenced by the discovery of the remains of a “beetle-like creature” in the left-hand pitot system during the post-incident engineering investigation conducted by the operator.	Night: The flight took off at 2335 hours. It is not clear whether night conditions contributed to the incident.	Pilot's air speed indicator (ASI) was not working properly and resulted in a falsely low ASI reading at low altitude and a falsely high ASI reading at high altitude; Co-pilot's ASI seemed to be working; Incorrect ASI readings were caused by a blocked pitot tube.	An airspeed discrepancy was detected early during the takeoff roll, but the commander decided to continue the takeoff and deal with the problem whilst airborne. Note: There is no specific guidance in the SOPs on what to do should the ASIs disagree. However, the pilot did have the authority to reject the take-off below 80 kts for any significant malfunction. Moreover, good practice would suggest that ASI malfunction would qualify for rejecting the takeoff.	After passing FL180 the crew selected the left Air Data switch to ALTN, believing this isolated the left Air Data Computer (ADC) from the Autopilot & Flight Director System (AFDS). Passing FL316, the VNAV mode became active and the Flight Management Computer’s (FMCs), which use the left ADC as their input of aircraft speed, sensed an overspeed condition and provided a pitch-up command to slow the aircraft.	Despite thinking that they had isolated the faulty left ASI by selecting the ALTN on the air data switch, the automatic systems were switching modes and associated input sources (including the use of the left ASI data by the FMC). This switching of modes and input sources occured in the background and was not evident to the pilots.	The FMCs, which used the left ADC as their input of aircraft speed, sensed an overspeed condition and provided a pitch-up command to slow the aircraft. This was a deviation from the normal flight profile. The co-pilot was concerned about the aircraft’s behaviour and, after several verbal prompts to the commander, pushed the control column forward.	

Figure D.8. Precursor Sequence for Nonfatal Incident No. 254 of Table D.1

Table D.2. Comments and Flags for Fatal Mishaps #2, #14, #37, #62, #260

Date Aircraft (Fatalities)	Comments	Crew Distraction / Preoccupation / Misaligned Focus		Potential Human-Machine Interface Issue		Potential to Mitigate through Research	
2/6/1996 B757 (189)		No		Yes	Faulty ASI to Autopilot/Autothrottle caused aircraft to pitch up and lower airspeed, which led to stall; Conflicting warnings in flight deck (overspeed and stick shaker)	Yes	1. Improved pilot training on diagnosing and mitigating onboard system failures (including sensor system failures and the use of alternate instrumentation) 2. Improved sensor failure detection and isolation (FDI) systems 3. Sensor Integrity Management systems 4. Resilient Upset Recovery Guidance and/or Automatic Recovery System 5. Resilient flight control system
10/2/1996 B-757 (70)		Yes	Crew was distracted by erroneous sensor readings and flight deck warning systems	Yes	Numerous conflicting warning and alerts were sounding simultaneously	Yes	1. Sensor integrity management system capable of detecting and mitigating sensor failures (including common mode failures) 2. Resilient flight control system capable of ensuring safety of flight under system failures 3. Automatic ground collision avoidance system
10/10/1997 DC-9 (74)	Sequence details obtained from ASN	NEI		Yes	Lack of situational awareness or mitigation of anomalous airspeed indications, which led to premature extension of slats	Yes	1. Improved crew training on diagnosing and mitigating onboard system failures (including sensor systems and the use of alternate instrumentation) 2. Sensor integrity management system capable of detecting and mitigating sensor failures (including blocked pitot tubes and common mode failures) 3. Resilient flight control system capable of ensuring safety of flight under system failures (including sensor system failures) 4. Resilient upset recovery system capable of providing guidance and/or automatically effecting upset recovery under vehicle system failures
4/7/1999 B-737 (6)	Very little accident information available.	Yes	The presence of cabin crew in the cockpit probably distracted the attention of the cockpit crew.	NEI	Lack of reliable sensor information under icing conditions; lack of notification of sensor system problem	Yes	1. Improved pilot training relative to use of alternate instrumentation 2. Improved anti-icing methodologies 3. Sensor integrity management system

6/1/2009 A-330 (228)	The obstruction of the Pitot probes by ice crystals during cruise was a phenomenon that was known but misunderstood by the aviation community at the time of the accident. From an operational perspective, the total loss of airspeed information that resulted from this was a failure that was classified in the safety model. After initial reactions that depend upon basic airmanship, it was expected that it would be rapidly diagnosed by pilots and managed where necessary by precautionary measures on the pitch attitude and the thrust, as indicated in the associated procedure. The occurrence of the failure in the context of flight in cruise completely surprised the pilots of flight AF 447. The apparent difficulties with aeroplane handling at high altitude in turbulence led to excessive handling inputs in roll and a sharp nose-up input by the PF. The destabilization that resulted from the climbing flight path and the evolution in the pitch attitude and vertical speed was added to the erroneous airspeed indications and ECAM messages, which did not help with the diagnosis. The combination of the ergonomics of the stall	Yes	Crew was overwhelmed by the multiple hazards conditions involving external disturbances (turbulence), an onboard common-mode sensor system failure (blockage of all pitot tubes due to ice crystal formation), lack of external sensory information (due to night low visibility conditions over the ocean), and stall warning system triggers at high altitude during cruise	Yes	Inability of the system to detect and mitigate sensor failures associated with blocked pitot tubes; the ergonomics of the stall warning design; the lack of displays providing situation awareness under multiple hazards and guidance for upset recovery; flight director indications that may led the crew to believe that their actions were appropriate, even though they were not; difficulty in recognizing and understanding the implications of a reconfiguration in alternate law with no angle of attack protection	Yes	1. Improved crew training under unexpected and abnormal conditions (including multiple hazards events) and in the implications of existing protections associated with system operational modes 2. Sensor integrity management system capable of detecting and mitigating sensor failures (including blocked pitot tubes and common mode sensor failures) 3. Improved algorithms and displays that provide improved situational awareness to the systems and crew under multiple hazards conditions 4. Resilient flight control system capable of ensuring flight safety under multiple hazards (including system failures, external disturbances, and inappropriate control inputs by the crew and/or autoflight systems) 5. Resilient upset recovery system capable of providing guidance for and/or automatically recovery from upset conditions (including stall) under multiple hazards conditions

	warning design, the conditions in which airline pilots are trained and exposed to stalls during their professional training and the process of recurrent training does not generate the expected behavior in any acceptable reliable way. In its current form, recognizing the stall warning, even associated with buffet, supposes that the crew accords a minimum level of “legitimacy” to it. This then supposes sufficient previous experience of stalls, a minimum of cognitive availability and understanding of the situation, knowledge of the aeroplane (and its protection modes) and its flight physics. An examination of the current training for airline pilots does not, in general, provide convincing indications of the building and maintenance of the associated skills. More generally, the double failure of the planned procedural responses shows the limits of the current safety model. When crew action is expected, it is always supposed that they will be capable of initial control of the flight path and of a rapid diagnosis that will allow them to identify the correct entry in the						

	dictionary of procedures. A crew can be faced with an unexpected situation leading to a momentary but profound loss of comprehension. If, in this case, the supposed capacity for initial mastery and then diagnosis is lost, the safety model is then in “common failure mode”. During this event, the initial inability to master the flight path also made it impossible to understand the situation and to access the planned solution.						

Table D.3. Comments and Flags for Nonfatal Mishaps #142, #188, #254

Date Aircraft (Fatalities)	**Comments**	**Crew Distraction / Preoccupation / Misaligned Focus**		**Potential Human-Machine Interface Issue**		**Potential to Mitigate through Research**	
10/20/2002 B-757 (0)	The pilots indicated that EICAS messages appeared and disappeared several times after takeoff and during the climb, including the messages MACH/SPD TRIM and RUDDER RATIO. Checklists for MACH/SPD TRIM and RUDDER RATIO messages did not mention an unreliable airspeed as a possible condition. The modifications associated with Boeing Alert Service Bulletin 757-34A0222 (and mandated by FAA Airworthiness Directive 2004-10-15 after the incident), which had not been incorporated on the incident airplane, would have provided a more direct indication of the airspeed anomaly. According to information in the Icelandair Operations Manual, these EICAS messages (in conjunction with disagreements between the captain and first officer airspeed indicators) may indicate an unreliable airspeed. Overspeed indications and simultaneous overspeed and stall warnings (both of which occurred during the airplane's climb from FL330 to FL370) are also cited as further indications of a possible unreliable airspeed. The crew did take actions in an attempt to isolate the anomalies (such as switching from the center autopilot to the right autopilot at one point during the flight). However, this did not affect the flight management computer's use of data from the left (captain's) air data system, and the erroneous high airspeeds subsequently contributed to airplane-nose-up autopilot commands during and after the airplane's climb to FL370.	No		Yes	Lack of a failure detection and notification system capable of detecting and identifying blocked pitot tubes; indistinct alerts generated by the airplane's crew alerting system, which added to the flight crew's confusion during the flight.	Yes	1. Improved pilot training relative to diagnosing and mitigating onboard system failures (including sensor system failures and use of alternate instrumentation) 2. Sensor integrity management systems capable of detecting, identifying and mitigating sensor system failures (including blocked pitot tubes) 3. Resilient flight control and guidance system capable of mitigating system failures and providing situational awareness & guidance to the crew 4. Resilient upset recovery system capable of providing guidance and/or automatically effecting upset recovery under vehicle system failures

5/12/2005 MD-90 (0)	Post-incident testing of the airplane's mechanical and electronic systems revealed no abnormalities that would have accounted for the unreliable airspeed indications or the loss of control reported by the flight crew. Post-incident computer modeling also confirmed that the airplane performed in a manner consistent with all deviations from normal flight having been initiated or exacerbated by the control inputs of the flight crew. Review of flight data recorder, cockpit voice recorder, and flight crew interviews revealed that the flight crew's actions during the event were in part contradictory with operator's training and operational procedures. Specifically, the crew initially failed to properly identify and respond to the erroneous airspeed indications that were presented and failed to coordinate their recovery of the airplane to controlled flight.	No		Yes	Lack of system failure detection capability for a blocked pitot tube	Yes	1. Improved crew training on diagnosing and mitigating onboard system failures (including sensor systems and the use of alternate instrumentation) 2. Sensor integrity management system capable of detecting and mitigating sensor failures (including blocked pitot tubes and common mode failures) 3. Resilient flight control system capable of ensuring safety of flight under system failures (including sensor system failures) 4. Resilient upset recovery system capable of providing guidance and/or automatically effecting upset recovery under vehicle system failures
1/28/2009 B-757 (0)	The commander, uncertain as to what was failing, believed that a stick-pusher had activated*. He disengaged the automatics and lowered the aircraft's nose, then handed over control to the co-pilot when he became aware that the co-pilot was on the controls. The FD's were disengaged and the aircraft returned to Accra with the co-pilot flying. The company has amended their engineering procedures to include the fitting of pitot covers and blanks when the aircraft is on the ground during long turnarounds. There were times during this flight where the flight crew were confused as to what was happening. In this incident, the commander recognized a failure of his ASI before 80 kt and the takeoff could have been safely rejected. Instead, he continued the takeoff using the co-pilot's and standby ASIs and encountered a number of related emergencies. These eventually led to the declaration of a mayday and return to the departure airfield. Although the commander considered that conditions were suitable for resolving the problem when airborne, a low	No		Yes	Lack of system failure detection capability for a blocked pitot tube; Numerous opportunities for mode confusion in existing FCS and FMS design and operation as well as warning and annunciations; Purposeful settings by the crew to isolate malfunctioning equipment are overridden by the automatic systems without notification to the crew	Yes	1. Improved crew training on diagnosing and mitigating onboard system failures (including sensor systems and the use of alternate instrumentation) 2. Sensor integrity management system capable of detecting and mitigating sensor failures (including blocked pitot tubes and common mode failures) 3. Resilient flight control system capable of ensuring safety of flight under system failures (including sensor system failures) 4. Resilient upset recovery system capable of providing guidance and/or automatically effecting upset recovery under vehicle system failures

	speed rejected takeoff would have been more appropriate in these circumstances. As a result of this incident, the company has implemented refresher training for its pilots on the AFDS, its modes, and operation. A blocked pitot tube event is also included as a part of their simulator recurrent training. The company now advise their crews to reject the takeoff if the problem is recognized at speeds below 80 kt. *Note: The Boeing 757 aircraft is not fitted with a stick pusher but the commander had previously flown an aircraft which had been fitted with a stick pusher						

Appendix E. Resilient Autonomous Systems Technology Requirements

This Appendix will provide a preliminary roadmap for the development and validation of resilient autonomous and semi-autonomous aircraft systems, as illustrated in Figures E.1 and E.2.

Figure E.1. Preliminary Technology Requirements for Resilient Autonomous Safety-Critical Systems.

Technology Impediments

Certification of Safety-Assured Autonomy Systems for Reliable Operation under Uncertainties & Hazards

Far-Term

Validation of Safety-Critical Autonomous Systems

Enable the validation of complex integrated safety-assured autonomous and semi-autonomous systems with deterministic & non-deterministic components

Mid-Term

Validation of Integrated Resilient Systems

Enable validation of complex integrated systems at the functional / algorithm level (including error propagation and containment between subsystems)

Near-Term

Validation of Resilient Systems

Develop analytical, simulation, and experimental test methods that enable validation of resilient systems technologies (including LOC hazards coverage and technology level of effectiveness and limitations)

Baseline: Standard V&V Techniques to Support Current Certification Requirements

Enabling Technologies / Research Needs

Validation Technologies for Resilient & Autonomous Systems

- Integrated Validation Process (Analysis, Simulation, and Experimental Methods) for Complex Integrated Deterministic & Non-Deterministic Systems
- Level of Confidence Assessment Methods

- Analysis Methods for Non-Deterministic / Reasoning Systems
- Analysis Methods for Complex Integrated Systems
- Integrated Validation Process for Resilient Systems
- Experimental Test Methods for Integrated Multidisciplinary Systems under Uncertain / Hazardous Conditions

- Nonlinear Analysis Methods & Tools (e.g., Bifurcation)
- Robustness Analysis Methods & Tools for Nonlinear Systems
- Uncertainty Quantification Methods & Tools
- Stability Analysis Methods for Stochastic Filters and Sensor Fusion Systems
- Multidisciplinary Vehicle Dynamics Simulation Modeling Methods for Characterizing Hazards Effects
- Hazards Analysis & Test Scenarios for Resilience Testing
- Experimental Test Methods for High-Risk Operational Conditions

Baseline: Linear Analysis Methods, Gain & Phase Margins for SISO Systems, Monte Carlo Simulations, Structured Singular Value Robustness Analysis for MIMO Linear Systems

Figure E.2. Preliminary Technology Validation Requirements for Resilient Autonomous Safety-Critical Systems.

Dedication

This work is dedicated to the memory and careers of the following researchers who substantially contributed to aviation safety through their tireless and dedicated research, and who were taken from the research community in the prime of their lives and careers.

Dr. Celeste M. Belcastro
NASA Langley Research Center

Dr. Gary J. Balas
University of Minnesota

Mr. David G. Ward
Barron Associates, Inc.

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