# ISASI Proceedings

INTERNATIONAL SOCIETY OF AIR SAFETY INVESTIGATORS

# 36th Annual International Seminar

## 'Investigating New Frontiers of Safety'

**Sept. 12–15, 2005**
**Fort Worth, Texas, U.S.A.**

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*Air Safety Through Investigation*

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WestJet ◆

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**Panel participants did not submit written text of their discussions. Also, Joseph Rakow's presentation "Thermal Failure in Aviation Accidents" is not available in text form.*

# PREFACE
# Investigating New Frontiers Of Safety

By Frank Del Gandio, President

*(ISASI President Frank Del Gandio's opening address to ISASI 2005, Sept. 23, 2005, Fort Worth, Texas.)*

Good morning, and welcome to Texas.

I'll start this morning by thanking our hosts, the DFW Chapter, for all the hard work its members have put into this seminar. I also will try to correct a misunderstanding. Texas does *not* get its name from an ancient word that means "hot and humid."

In fact, Texas has always had a special place in American folklore. To most Americans and to many people in other lands, Texas symbolizes open space, self-reliance, and, perhaps most of all, size—everything associated with Texas is BIG.

Let me give you a sense of scale about just how big Texas is. From Beaumont in the east to El Paso in the west is 840 miles, or 1,375 kilometers. Brownsville in the south is 915 miles or 1,500 kilometers from the Oklahoma Panhandle in the north. The state is nearly twice the size of Japan, or 1,000 square miles bigger than France, Belgium, the Netherlands, Luxembourg, and Denmark, combined.

I hope all the delegates and companions will take the time to experience at least some of the Dallas-Fort Worth area plus other parts of this great state. Go to San Antonio, Austin, or anywhere else. I guarantee you will enjoy it.

It's fitting that we should meet in Dallas-Fort Worth because this area is rooted in transportation. As an early cattle town, Forth Worth had links to the Chisholm Trail and later became an early railroad center.

Transportation remains part of the region's economic foundation, with two of the world's four largest air carrier fleets in American and Southwest, and the world's largest regional airline in American Eagle. The region also is home to DFW, one of the world's largest airports, and to Love Field. The region also has an important history in aircraft manufacturing: General Dynamics and Bell Helicopters and other aerospace firms. If aviation is your thing, you have come to the right city.

Our thing in ISASI is aviation safety. Once again, the past year reminds us that we who work in accident investigation and aviation safety are not at risk of going out of business. I must tell you that I first drafted my comments in mid-July, when I was preparing to talk about the wonderfully safe year that we had. At that time, just 7 weeks ago, we had four jet accidents of note, worldwide, with 185 fatalities, the majority of which occurred in a single event.

My short list of noteworthy jet accidents at that time included a Kam Air CFIT accident in Afghanistan that killed 104 people; a China Eastern RJ that crashed on takeoff, killing 53 people; a high-speed overrun by Lion Air of Indonesia, killing 25; and an Iranian 707 that landed long and overran at high speed into a river, drowning 3 of 176 occupants. Then I planned to add a fairly short list of five significant turboprop accidents, with 99 fatalities.

Overall, I was prepared to argue that the past year had been a good year and a continuation of long-term improvements in air safety, particularly at the air carrier level.

**All the major accidents of the past year remind us that when major accidents occur, the basic scenarios are all too familiar. For example, of the major accidents I mentioned, we had five CFITs, four undershoots, one windshear, and one fuel exhaustion. In short, when things go wrong, we continue to see the usual suspects. Yet, the long-term story remains a good one.**

However, as I was working on that draft, an AN-24 crashed on climbout in Equatorial Guinea, killing all 62 occupants. At that point I thought, "Okay, I need to make a slight change in my comments." Then came August and early September!

On August 2, an Air France A340 overran at high speed in Toronto, with no fatalities but a badly burnt-out airplane. Just four days later, a Tunisian ATR 72 ditched off the coast of Sicily, killing 16 of 39 occupants. This was followed quickly by the Helios Airways 737-300 in Greece (121 fatal), the Colombian MD-80 that crashed in Venezuela (160 fatal), then a 737-200 operated by TANS of Peru, killing 40 people. Finally, a 737-200 crashed on climbout in Indonesia, killing 111 on board and up to 50 people on the ground.

Five short weeks had turned a good story into a bad story, with six major accidents and some 500 fatalities. This brought the total to eight major jet accidents, seven major turboprop accidents, and close to 800 fatalities in air carrier passenger operations since we last met. In the end, the past year or so has not been all that good a story.

All the major accidents of the past year remind us that when major accidents occur, the basic scenarios are all too familiar. For example, of the major accidents I mentioned, we had five CFITs, four undershoots, one windshear, and one fuel exhaustion. In short, when things go wrong, we continue to see the usual suspects.

Yet, the long-term story remains a good one. Just a few short years ago, we would have been thrilled with "only" eight major jet accidents. In fact, we can expect the long-term improvement in accident rates to continue and even to accelerate. We will continue to see more application of satellite navigation, such as RNP and Local Area Augmentative System (LAAS) or WAAS.

On the design side, manufacturers continue to make major advances in their ability to test new designs and materials, complete with lifecycle testing, before an actual aircraft is ever built. The cockpit, too, will continue to advance with synthetic and enhanced vision, vertical situation display, energy-state displays, electronic flight bags, fault isolation, etc. These are just some of the improvements that are under way or very close at hand in the airline world.

Think of where we were just 10 years ago. Many of us thought accident rates had already reached such low levels that they would stubbornly resist major improvement. Yet, accident rates have fallen by half since then, and we are likely to see them cut in half again in the next decade.

As promising as the future is for air carriers, the real revolution in aviation safety is coming in general aviation. Except perhaps for large corporate jets at the very top of the general aviation market and some improvement in engine reliability, technology in general aviation had stagnated for years. That state of affairs is finally changing, and fast!

Almost while we were not watching, general aviation has incorporated satellite technology into the cockpit with precision navigation, much better displays, datalink, air-to-air monitoring, on-board diagnostics—the whole package. Suddenly the term "glass cockpit" is part of the general aviation vocabulary. Every established manufacturer now offers a glass cockpit of one degree or another. New aircraft like the Cirrus SR-20 and SR-22 and the Diamond DA-40 already show 2,000 aircraft on the U.S. Registry. These will soon be followed by micro-jets, such as the Adam-700, the Citation Mustang, the Diamond D-Jet, and the Eclipse, some of which will have capabilities for real-time FOQA analysis. All indications are that the new micro-jets will enter the fleet at least as rapidly.

In short, the air carrier industry, particularly among the richer countries of the world, already has achieved accident rates that we thought were beyond reach just a few years ago, and those rates will continue to improve over the next decade or more. Yet, the really exciting news for safety is likely to come from the world of general aviation.

If things keep going this way, folks like us might be out of a job some day. Meanwhile, however, we still have some work to do, and our annual seminars offer a chance to improve our skills and understanding of a broad range of issues in accident investigation and aviation safety in general. I must tell that each year I think the presentations improve so much that they cannot get better next year. At the same time, with venues like Barcelona, Boston, Ireland, Taipei, Washington, and Australia, I think the social activities and the local attractions cannot get any better. Once again, after last year's seminar in Australia's Gold Coast, I found myself thinking that we will never beat the social or professional quality of that seminar. Improving on Australia is a challenge, but Curt Lewis and the DFW chapter probably will do it, and then our Mexican hosts probably will improve on this yet again next year in Cancun.

I will close by strongly encouraging you to participate actively in the seminar. Every year this seminar brings together the largest group of very knowledgeable aviation safety professionals. Look around you. Chances are very good that you are seated close to someone who knows everything there is to know about some topic that interests you. Get involved in this seminar and take advantage of all the expertise that is in this hall. Enjoy the seminar. Thank you. ◆

**Every year this seminar brings together the largest group of very knowledgeable aviation safety professionals. Look around you. Chances are very good that you are seated close to someone who knows everything there is to know about some topic that interests you. Get involved in this seminar and take advantage of all the expertise that is in this hall.**

# Rawson Earns 2005 Lederer Award

By Esperison Martinez, Editor

John D. Rawson, a Fellow member of the Society, was an almost-absent recipient of the Jerome F. Lederer Award for 2005 at the ISASI annual awards banquet. Unaware of his selection for the prestigious award, his original plans to attend the annual seminar were abruptly altered when Hurricane Katrina changed some of the landscape of his property in Meridian, Miss. This change of plans caused a dilemma for President Frank Del Gandio, who secrets away the name of the selectee until the opening day of the seminar. Finally reaching Rawson by phone, Del Gandio inquired, “John, have you decided if you are coming to Texas?” The reply was quick and positive, “Can’t make it.” With no recourse, Del Gandio had to share the secret: “John, you are receiving the Lederer Award!” Stunned silence was the reply, until, again, a quick and positive: “I’ll be there.”

So while the pleasure of surprise was absent when

PHOTOS: E. MARTINEZ

***President Del Gandio, right, presents the 2005 Lederer Award to John Rawson.***

President Del Gandio introduced award winner Rawson to the near 400 attendees who filled the cavernous room, he appeared humbled at the thundering applause that filled the air. The early announcement allowed many delegates to offer private congratulations to the 29th recipient of the award, who would be more fully honored on the last evening of the seminar program.

The Jerome F. Lederer Award is conferred for outstanding lifetime contributions in the field of aircraft accident investigation and prevention and was created by the Society to honor its namesake for his leadership role in the world of aviation safety since its infancy. Jerry Lederer “flew west” on Feb. 6, 2004, at age 101. Awarded annually by ISASI, the Lederer Award also recognizes achievement of the Society’s objectives and technical excellence of the recipient.

The presentation of the award always takes place on the last evening of the seminar, and it is the highlight of the award banquet. In introducing the winner to the audience, President Del Gandio commented, “The Jerry Lederer Award is the most prestigious award that the Society can confer, and John Rawson’s 45 years of experience in aircraft accident investigation and aviation safety has proven spectacularly worthy of the highest accolades.” He went on to relate highlights of Rawson’s contributions:

“John started his career in accident investigation in 1960, when he accepted employment with the engineering division of the Civil Aeronautics Board (CAB), predecessor of the NTSB.

“As a system specialist, he became one of only two original flight data recorder readout specialist for the CAB. He also was involved with investigating and analyzing electrical/electronics instrument systems and hydraulics and communications problems in dozens of major accidents.

“In 1962, he transferred to the CAB’s Miami field office where he was an investigator-in charge (IIC) for 8 years and investigated a great many general aviation and air carrier accidents. In 1968, John left the government and joined HydroAire as a flight data recorder technical representative. In 1970, he returned to the NTSB as an CVR/FDR specialist in the Washington, D.C., headquarters, subsequently becoming chief of the CVR laboratory.

“John transferred to the FAA in 1974 and served as the FAA IIC on more than 70 major catastrophic accidents worldwide. In 1976 he became a branch manager and in 1982 was promoted to manager of the Accident Investigation Division in the Office of Accident Investigation, a position he held until retiring in 1994.

“During his career in both agencies, John authored more than a 100 safety recommendations, which have had a tremen-

***Recent Lederer Award winners strike a pose. Left to right, Ronald L. Schleede (2002), Caj Frostell (2003), Rawson, Ron Chippindale (2004), and John Purvis (2001).***

dous positive impact on aviation safety. He established and was responsible for the curriculum and training activities of the FAA's Accident Investigation School in Oklahoma City and lectured at the basic investigation class for many years. He was also instrumental in organizing and implementing the helicopter accident investigation course that is taught at the Bell Helicopter facility in Fort Worth, Tex.

"John's involvement with ISASI is as impressive as his government career. He joined in 1965 and held member number CH59, marking him as one of the founders of our Society. He has served as membership chairman, secretary, and as treasurer. In that position, he established an accounting system that served ISASI for many years. He has presented laudable papers at numerous ISASI seminars and at ICAO meetings worldwide.

"His government career and his involvement in ISASI indicate a total dedication and concern for aircraft accident investigation and aviation safety. His contribution to the aviation industry and this Society are monumental and worthy of making him the 2005 Jerome F. Lederer Award recipient. John, I present to you the Jerry Lederer Award for 2005. Congratulations."

As the applause of the full room quieted, the unassuming, straight-backed, and soft-spoken award winner moved to the microphone. The room was now still, all eyes front, ears primed to hear: "Thank you," he whispered. And with a stronger voice continued, "It is a great honor to receive this award and to be included with those people who have come before me as recipients of the same award. As Frank said, I have been doing this a long time. I have worked with a lot of you in this room and certainly with your organizations. I can say with all honestly that my experience totally shows that ISASI has made a big difference in safety, worldwide.

"One of the reasons is, of course, that we exchange information here, meet each other, go back to our organizations and inform about what is going on. Fortunately, a lot of the people here work for rule-making agencies and accident investigation groups. That's a good thing, and I want people to keep up the good work.

"A thought I want to pass along is something I've always practiced in my investigations and urged all the people I have worked with to practice: When you are investigating an accident, tell the person or the group that 'I appreciate all you have explained to me, but I would rather have you show me.'" ◆

## Past Lederer Award winners

1977—Samuel M. Phillips
1978—Allen R. McMahan
1979—Gerard M. Bruggink
1980—John Gilbert Boulding
1981—Dr. S. Harry Robertson
1982—C.H. Prater Houge
1983—C.O. Miller
1984—George B. Parker
1985—Dr. John Kenyon Mason
1986—Geoffrey C. Wilkinson
1987—Dr. Carol A. Roberts
1988—H. Vincent LaChapelle
1989—Aage A. Roed
1990—Olof Fritsch
1991—Eddie J. Trimble
1992—Paul R. Powers
1993—Capt. Victor Hewes
1994—U.K. Aircraft Accidents Investigation Branch
1995—Dr. John K. Lauber
1996—Burt Chesterfield
1997—Gus Economy
1998—A. Frank Taylor
1999—Capt. James McIntyre
2000—Nora Marshal
2001—John Purvis and the Transportation Safety Board of Canada
2002—Ronald L. Schleede
2003—Caj Frostell
2004—Ron Chippindale

# Kam Air Flight 904—Investigation Challenges in Kabul And on Chaperi Ghar

By Robert Benzon, U.S. NTSB

*__Robert Benzon__ began his aviation career in the United States Air Force flying EC-47s from Da Nang Air Base, Republic of Vietnam. He later transitioned into KC-135 Stratotankers for two further stateside assignments. Upon leaving active military duty in 1984, he joined the United States National Transportation Safety Board. He has been the Investigator-in-Charge of 29 major aircraft accident investigations within the United States and has been the U.S. accredited representative on numerous major overseas accident investigations. Among his assignments as Investigator-in-Charge or U.S. accredited representative were the loss of Pan Am 103 over Lockerbie, Scotland, and the loss of American Airlines Flight 587 in New York City, the second-worse aircraft accident in U.S. history.*

Experienced accident investigators probably feel that after a while, there is a certain "sameness" to major accident investigation protocols, even though, as we all know, each accident itself is distinctly different. We investigators fly to a location near the accident site, find hotels, rent automobiles, drive to a central meeting point to join counterparts from industry, other government officials, the press, and the like. Then we hold some sort of organizational meeting, and, finally, we proceed to examine wreckage. The investigation then progresses in an orderly manner, familiar to us all. Accident after accident, these basic steps, with minor variations, seem to always take place.

Not so, my small team and I discovered when we assisted in an aircraft accident investigation in an active war zone.

On Feb. 3, 2005, Kam Air Flight 904 was reported missing during a flight from Herat to Kabul, Afghanistan, during conditions of extremely low visibility in the area surrounding Kabul International Airport. It was subsequently located on the top of Chaperi Ghar, an 11,000-foot mountain about 20 miles east southeast of the airport, 2 days after its disappearance. None of the 104 people on board survived. The aircraft was a 23-year-old Boeing 737, which meant that under the auspices of ICAO Annex 13, the NTSB was obliged to assist the government of Afghanistan in its investigation of this tragedy. Kam Air is a company in Kyrgyzstan serving Afghanistan air travel, and the airplane was registered in Kyrgyzstan. It was operated by Phoenix Aviation, headquartered in Dubai, United Arab Emirates, and there were citizens from Afghanistan, Italy, Turkey, Canada, Iran, and the United States on board. Many of the victims were associated with various humanitarian aid missions helping to rebuild Afghanistan.

My agency was nominally aware of the difficult political and security situation in Afghanistan, and became acutely aware of it after lengthy telephone conversations and e-mail exchanges with U.S. Embassy personnel in Kabul following the initial accident notification. We were told that the Embassy compound, where we would be staying, was an armed, walled camp, replete with guard towers, sandbagged revetments, armored vehicles, and the like. We were also told that we would always be accompanied by heavily armed escorts when we left the compound to do our work and that climactic conditions on top of the mountain were very severe. Conditions in Afghanistan did not appear to be conducive to an orderly accident investigation. Because of these difficulties, participation by NTSB investigators became voluntary. It quickly became apparent that this would not be a normal overseas assignment for us.

Although usually eager to do so, the U.S. airframe and engine manufacturers declined to accompany us on this overseas trip. Personal safety concerns were uppermost in their minds, of course. Their expertise would certainly have been put to use, but the reluctance to travel to Afghanistan was understandable. So, our team consisted of representatives of the governments of Afghanistan, Kyrgyzstan, Italy, Turkey, the United States, and Kam Air and Phoenix Aviation.

The very task of getting to Kabul proved to be quite difficult. The non-stop flight on Emirates Air to Dubai was the last routine portion of our trip. Once we arrived in Dubai, we not exactly sure of how we were actually going to get into Afghanistan. We need not have worried. While checking in at the reception desk at the hotel, I was handed a telephone. On the other end of the line was a U.S. Army colonel who told us to be at a small terminal at 6 o'clock the next morning to board a U.S. Air Force C-130 that would take us to Kabul. Under the mistaken belief that this would be some kind of an interesting clandestine VIP flight, we soon discovered otherwise and found ourselves crammed into the aircraft with about 60 quiet soldiers on their way to the war zone. Several hours into the flight, we were told that the aircraft was refused clearance to overfly Pakistan and would have to return to Dubai. To the credit of the flight crew, they set up an orbit off the Pakistani border and finally secured overflight clearance some time later.

Because the delay that occurred would have caused us to arrive at Kabul after sunset (something no airplanes were allowed to do…Kabul was day VFR only), we were forced to land at Bagram Air Base and spend the night. We went from a 5-star hotel in Dubai to a large uninsulated plywood box at Bagram. The box contained six folding cots, each complete with its own army blanket (no sheets, no mattress, no pillow…just a blanket), a space heater, and a single 40-watt light bulb hanging from the ceiling. After dumping our gear in the box by our "beds," we borrowed a military computer and contacted the Embassy in Kabul via e-mail. We were instructed to be ready to depart in a small, armed convoy at 7 o'clock the next morning for the drive down to Kabul. We found the convoy, were issued flak jackets, and after an hour-long, very speedy ride on a rough road, replete with bomb craters and tanks and trucks destroyed in previous conflicts, we rolled into the U.S. Embassy compound at Kabul.

Our Embassy contacts did not exaggerate the austerity of conditions there, although it immediately looked better than Bagram to us. The once-beautiful Embassy building was now surrounded by sandbags, festooned with radio antennas, and topped off by four machine gun nests. All available space around the building, once a park-like setting, we were told, now contained dozens of white 20-foot-long steel overseas shipping containers. These containers had been converted into comfortable but somewhat claustrophobic living quarters for the burgeoning Embassy staff, the large U.S. Marine security unit, and now us. The U.S. Ambassador, because of his high rank, lived in several containers hooked together, complete with potted plants by the door.

Our host and handler at the Embassy was a competent young political/economic officer, Robert, whose hobby during his Kabul tour was leading a pick-up rock band of sorts that performed in the mess hall every Friday, the one day off allowed by the Embassy's heavy work schedule. He would change the name of the band every couple of weeks to make Embassy staffers think they would be hearing something new once in a while. The ruse only really worked once, he said. Upon our arrival, Robert smiled and handed us an Embassy procedural guide with this interesting item in it:

"Outside the [Embassy] compound, red rocks indicate uncleared mine areas while white rocks are considered mine-free areas. Be advised, however, there remains a 10% chance that unexploded mines remain in the mine-cleared areas. For this reason, during all travel in Kabul or out of the city, travelers should remain on hard-surface roads at all times."

We never saw any painted rocks anywhere, and as one might imagine, staying on hard surface roads did not turn out to be a viable option during our visit.

Our next order of business was to meet our Afghan counterparts in the Ministry of Transport (MOT). This proved to be a sad introduction to the effects of the long period of armed strife in that part of the world. The MOT, and virtually the entire Afghan government, is in the process of reconstituting itself after 20 years of warfare and difficulty in Afghanistan associated with the Soviet occupation, an internal civil war, the times of the Taliban, and our military activity after 9/11. Much of this current governmental reconstitution has to be prioritized, and government agencies such as the Ministry of Defense, logically, are ahead of agencies such as the MOT in this regard. At the time of the accident, the MOD was being advised by many, many, U.S. military personnel and military contingents from other nations. The MOT, on the other hand, was receiving advice from one aviation expert assigned to the U.S. Embassy and perhaps a small handful of transportation advisors from other countries. There were no U.S. Federal Aviation Administration personnel in Afghanistan at the time of the accident. Now, one FAA advisor is stationed in Kabul for an extended amount of time. This is good.

At the time of the accident, there was no established intra-governmental agency plan in Afghanistan to deal with a major aircraft crash. Initially, it was proposed that the Ministry of Transportation be responsible for not only the investigation but also human remains identification and recovery and wreckage recovery. When the logic of this concept fell apart because of the small size of the MOT and its almost total lack of resources, these duties were divided among the Ministry of Defense and Ministry of Health (human remains), the Ministry of the Interior (wreckage recovery), and the MOT (the actual accident investigation).

The MOT headquarters building, a two-block, daytime-only, flak-jacketed walk from the Embassy, was very poorly equipped—one or two old photocopiers, no e-mail capability for the staff, intermittent lighting, many manual typewriters in use, old Soviet maps with Cyrillic captions on the walls, and so on. The three gentlemen who served as Afghan investigators for this accident were extremely dedicated, and I admire them. But, they lacked any kind of formal investigative training. To their credit, they were quite familiar with ICAO Annex 13 and are using that document (as general as it is) as their basic investigation guide. Several of them have air traffic control backgrounds. They mentioned ATC training they received in the United States as young men in the late 1960s. Because of these difficulties, the Afghan investigators were extremely receptive to our suggestions on where to begin and how to proceed through the on scene phase of their investigation. We all then for-

***Photo 1***

Photo 2

me, many of the helicopter door gunners were very capable female soldiers. Besides serving their machine guns, they also made sure we did not fall out of the helicopters.

The landing zone was only big enough for one helicopter at a time. This meant that the helicopters could not shut down and stay with us. If one could not be restarted, for instance, there would be no rapid, practical way to get parts up the mountain to repair it. Our first trip up the mountain was on one of the Blackhawks. During the "landing" on the only flat spot available, about 200 meters from the main wreckage, the pilot had to maintain a near hover RPM with his main landing gear just touching the surface—otherwise the machine would sink into the snow and possibly strike a rotor blade on nearby rock outcroppings. This, of course, meant that we were immediately exposed to hurricane-force winds and blowing snow and landing zone debris the instant we flopped out the door. The downdraft from the rotor blades on this and subsequent Blackhawk landings bowled us over on a routine basis and we all lost stocking caps, sunglasses, and other equipment down the mountainside during these operations. This, in my mind, was possibly the most dangerous part of our time in Afghanistan. The Cougars, on the other hand, were equipped with skis and could bring rotor speed down to idle during debarkation and embarkation. This made

mulated a basic investigation plan, received word that the immediate impact area had been cleared of mines, and would fly to the site the next morning.

Getting to Kabul was a bit of an adventure, and getting to the accident site from Kabul proved to be equally interesting. Air operations around Kabul are the responsibility of a large NATO peacekeeping subgroup called the International Security Assistance Force (ISAF). ISAF helicopters had discovered the wreckage earlier and had made two previous reconnaissance landings on the mountaintop. They would carry us up to the Chaperi Ghar crash site. This, of course, entailed yet other armed convoys to get us from the Embassy compound to the military side of Kabul International Airport. Once there, we would either board Turkish Army Blackhawks or Spanish Air Force Eurocopter Cougars. The helicopters always flew in two-ship cells, in case one of them became disabled enroute. They also always flew with both doors open and with heavy automatic weapons at the ready. In a sense, these precautions were comforting, but they were yet further indications that this was not a normal investigation.

The flight crews of both nations were very professional, as was the entire ISAF air staff. Full safety briefings led off every preflight, and all the pilots were extremely weather conscious. In that part of the world, at that time of year, flight visibility in the mountains can drop to an unsafe level in mere minutes. On two occasions, we launched, and although everyone knew how important getting to the wreckage was we turned back because of low visibility. Interestingly to

Photo 3

helicopter loading and unloading much easier.

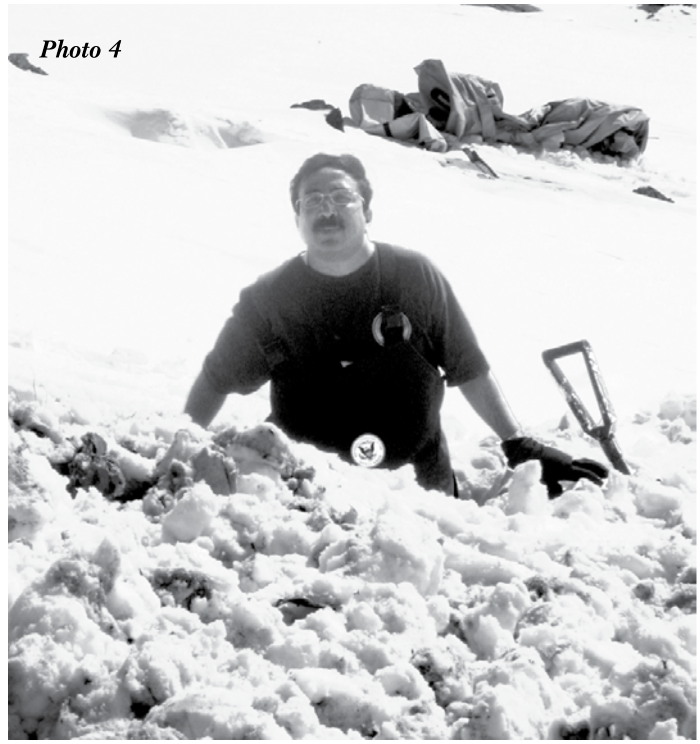
Scheduling of the helicopters soon fell into a routine. This was made simpler for me because the commander of the Turkish ISAF helicopter unit had attended the NTSB accident investigation school several years earlier. He claimed to actually have stayed awake during my lecture, but I believe he was just being polite. In the evening we would relay a list of investigators and volunteer snow diggers to the ISAF helicopter operations office via cell phone or e-mail and would then be told which nation's helicopter ramp to report to the next morning. The most difficult part of this operation turned out to be the actual assembly of the team at the ramp. The U.S. personnel were housed either at the Embassy or in various military installations in the city. Those from other countries were widely scattered around Kabul, and communication among all contingents was extremely difficult. In addition, as mentioned, each group had to always be escorted to and from the airfield by armed military or civilian security personnel. Seemingly small problems like these took up an inordinate amount of time and energy.

Because of the remote and hostile location of the accident site, we had limited time on scene to document the wreckage. The team spent perhaps a total of about 30 hours on top of Chaperi Ghar, broken down into five visits. No investigators stayed overnight on the mountain because of the cold nighttime temperatures, the possibility of being weathered in, and the fact that the wreckage was attracting wild animals at night. Mountain wolves were mentioned and their tracks in the snow were noted in the mornings. The only people who actually remained on the mountain overnight were a squad of very hardy and, I imagine, wide-awake Afghan National Army troops.

The accident site itself was compact in a horizontal sense, but not so vertically. See Photograph 1 (page 9), looking east (along the flightpath), and photograph, looking west. The Kabul runway can be seen in the central right portion of Photograph 2. The aircraft struck a ridgeline on an easterly heading near the crest of the mountain about 50 feet down from the very top. The final flightpath probably had some amount of upward vector to it, because the fuselage forward of the wing box was propelled, in fragments, over the crest and fell over the cliff side into the valley below. The actual wreckage documentation during five site visits was difficult because most of the parts were either buried under several feet of snow and inaccessible, outside the mine-free cordon and inaccessible, or down the cliffside and, therefore, also inaccessible to all without mountain climbing training. Fortunately, the Italian investigator brought two Italian Army officers with him with such training, and some photographic documentation of the cockpit area was done by these individuals. The most prominent and recognizable piece of wreckage present was the vertical stabilizer and a small portion of the rear fuselage. (See photograph 3.)

Most of the visible wreckage was located between two stacked-stone, roofless structures that were observation posts used by Mujahadeen fighters to monitor Soviet troop movements in the Kabul valley during the 1980s. Within a 200-foot circle, after a lot of arduous snow removal, we identified portions of both engines, both wings, the left main landing gear assembly, many aft galley components, the horizontal stabilizer, human remains and personal effects, and much miscellaneous debris. Some material, such as an escape slide and some right engine components, were located outside the landmine-free area. These items were "documented" with binoculars and digital camera zoom features.

*Photo 4*



The flight data recorder was found almost immediately, although as of this writing, the cockpit voice recorder has not been located. We did locate the mounting bracket for the CVR. It was very frustrating to locate this item and not the CVR itself. We spent a good deal of time digging blind holes in the snow in the immediate vicinity of where this bracket was found, and also forward of that location, to no avail. (See Photograph 4.) Unfortunately also, the FDR eventually yielded no useful data. As near as could be determined, the external flight data acquisition unit had not been providing valid signals to this device for a long time.

Our physical well-being during the wreckage documentation was of concern to me. Except for the Afghans, I was the oldest person on the team and I used my age (55) and my lack of any formal physical exercise regimen as a benchmark of sorts for onsite strenuous activity. In other words, when I got tired, that would seem to be a conservative time to wind down activity on the mountain for the day. This canary-in-a-coal mine approach probably was not the best way to deal with this issue. To wit the Afghan investigators were all in their late 50s and early 60s, one of our Embassy volunteers was overweight, and even some of the U.S. military personnel who volunteered to assist us were not in the best physical condition. The 11,000-foot altitude, the strenuous debarkation from the helicopter, and the snow caused the Embassy employee to spend his single session with us on the mountain sitting down. One U.S. officer became quite winded during the early part of her site visit but acclimated quickly. Ironically, the Afghan investigators, my main worry, faired the best of all. They are very tough individuals. Fortunately, the information about severe weather on the mountaintop turned out to not be true. It was quite cold when the sun was not shining and the wind was blowing. However, on one occasion, during sunny weather, we were working in shirtsleeves.

I was less worried about landmines on Chaperi Ghar, but should have been more worried, in hindsight. We had been warned in a


*Photo 5*

general way about the dangers of mines in Afghanistan, as noted earlier. In spite of this, we felt confident in our safety because we had been assured by one U.S. government source and two Afghan military officers that the area where the wreckage was located was clear of mines. We were still wary, though. On the second trip to the site, one of the Turkish investigators found what he thought was a mine, or at least something very suspicious with wires coming out of it, wedged between two of the flat stones that made up one of the old Mujahadeen observation posts. He called several of us over to take a look, and like fools, we did so. We at least had the presence of mind not to touch the object. A moment later an Afghan National Army sergeant arrived, and after several minutes of peering at the device and a short conversation with several other soldiers, he cleared the area of people and then gently removed it. The "mine" turned out to be an electrical connector assembly from Kam Air 904, jammed into the rocks by the force of the aircraft impact. Frowns turned to looks of relief and we went about our business.

An important point must be made here. Landmines, with all their varied colors, shapes, and sizes, often resemble aircraft parts. Unlike other places where mines may be found in war zones, crash sites force investigators and rescuers to stay in a mined area for a very long time. An investigator's job is to examine everything at a site, turn over every piece of wreckage, look under every rock, and so on. This could be a recipe for disaster, as one might imagine. Mines and aircraft crash sites mix only too well. My advice on this subject would be to trust what your mine advisors tell you, but verify, verify, verify to the best of your ability. Sadly, a week after we returned to the United States, an Afghan National Army soldier helping with the human remains recovery operation at Chaperi Ghar stepped on a landmine at the site and was killed. Another soldier was seriously injured in the same explosion. The accident site had supposedly been cleared of mines, but the experts missed at least one.

Having said that, we had been told that the site was completely inaccessible via land routes in the winter because of the heavy snowfall, no roads, and, again, the ever-present landmines. However, on our third visit to the site, an ANA soldier with binoculars spotted a party of five individuals making their way slowly on foot up the western slope of the mountain. They arrived at the site about an hour-and-a-half later. Although everyone was initially suspicious of these people, it turned out that they were representatives from the nearest local village, located many miles away, and had climbed the mountain simply to see what was going on and to extend greetings. They heard about the accident on a transistor radio. After meeting them, we somehow did not feel quite so heroic. (See Photograph 5.)

As the investigation work progressed both on the mountain and down below in Kabul, it became apparent to all that there was room for improvement concerning certain aspects of civilian air operations in Afghanistan. Recommendations, of course, are the most important aspect of any aircraft accident investigation. The Afghan MOT had no formal mechanism for forwarding specific safety recommendations to entities within the country (both domestic and foreign), so our solution was to distribute a simple informal "white paper" of safety suggestions to several government ministries, the U.S. Embassy aviation advisor, the ISAF military air staff, and others—a shotgun approach, so to speak. We handed a copy of the white paper to anyone in authority who seemed even remotely interested. These suggestions ranged from the acquisition of mobile radar for then-radarless Kabul International Airport to the importance of rebuilding a previously blown up ILS array to the consolidation and tightening up of visual flight rules operations in Kabul airspace. I believe the white paper, although unofficial and a bit unorthodox, proved effective and many of the suggestions are being acted upon at this time. In addition, the Afghan Investigator-in-Charge asked us to compose a letter for his internal use containing ideas about how the safety staff of the Ministry of Transportation itself could increase its effectiveness.

The U.S. members of the team traveled back to the United States in three groups. The FAA representative and our operations specialist went back after 1 week on a convoluted, difficult routing with the flight data recorder. Our systems and structure specialists left a week later via a United Nations contract flight to Dubai. I remained one further week to finalize our on-scene assistance to the Afghans.

The Afghan investigation into the tragic loss of Kam Air Flight 904 is still open, and may remain so for some time. The Investigator-in-Charge hopes to be able to recover the cockpit voice recorder in the near future, but in a nation with many other priorities, this may take a while, or, in fact, prove to be impossible. A final report following ICAO Annex 13 guidelines is the goal. I believe that the effort put forth so far on this investigation is an excellent example of cooperation between many groups—the government investigators from Afghanistan, Italy, Turkey, and Kyrgyzstan, the military flight crews and flight planners in ISAF, the NTSB, the U.S. Armed Forces, the U.S. State Department, and the Kam Air and Phoenix Aviation participants.

From tragedy we draw knowledge to improve the safety of us all. ◆

# Accident, Serious Incident, And Incident Investigations: Different Approaches, the Same Objective

By Stéphane Corcos and Pierre Jouniaux, BEA, France

***Stéphane Corcos,*** *41, is the Head of the BEA Investigations Department. He joined the BEA as Head of Safety Analysis Division in 1996. Prior to joining the BEA, he worked for the DGAC (French Civil Aviation Authority) for 8 years, including 4 years as Deputy Head of the Flight Training Organization Supervision. Stéphane graduated from the French National Civil Aviation School (ENAC) with a masters degree in aeronautical engineering in 1987 including an internship at the Flight Safety Foundation, in Arlington, Va. He is the current holder of a commercial pilot's license and a multiengine instrument rating. He also has a Beech 200 type rating.*

***Pierre Jouniaux,*** *36, received a masters degree in aerospace engineering and aviation operations from the French National Civil Aviation School (ENAC). He received a post-graduate degree in human factors from Paris University. After an appointment as operations inspector with the French Civil Aviation Authority, he joined the BEA in 1997. He has acted as Investigator-in-Charge, accredited representative, or group leader on many investigations and is now a senior investigator. Since 2003 he has been coordinator for public transport incident investigations. Pierre holds a commercial pilot's license and helicopter private pilot's license.*

## Introduction

This paper will comment on some of the most recent reports issued by the BEA. Our attention has been drawn to the fact that many accidents have precursors in incidents. In addition, investigations can now be conducted in a variety of ways. Depending on the seriousness of the event, the number of parties involved, the difficulty of carrying out examinations, an investigation can be a long and costly process. However, at an early stage it is often possible to identify the major safety issues raised by an event. What usually takes much longer is the validation process, through examinations, testing, and the highly sensitive discussions between all the parties needed to produce the final report. It is also noteworthy that nowadays 80% of causal factors are related to human factors. Thus, what is important is to have an insight into safety issues and to make an early determination of the potential of an event. This enables us to put the appropriate weight on particular investigations. This approach has two prerequisites: being informed of the majority of events in time and having an organization that allows us to choose selectively. To address the first issue, the European Union recently made a regulation asking all operators (as well as ATC, manufacturers, and repair stations) to report significant events to investigative bodies. These operators should also, in the future, participate in event identification. For the second requirement, the problem is to be able to identify the relevant type of event. This can be a bit like panning for gold, so the investigator needs a sharp eye. The best way to do this is to have a group of dedicated specialists working together to draw out the relevant data from the different events.

## Conduct of approaches

Non-stabilized approaches have claimed many lives over the years, and they keep occurring all around the world. Many of them have the following in common: IMC conditions, at least a partial loss of situational awareness, lack of crew coordination, deviation from SOPs, insufficient or nonexistent consideration given to safety warnings (GPWS in the cockpit, MSAW in the tower). They also often highlight the basics of instrument flight, and they can be studied in a variety of ways. European airlines have long conducted mandatory analysis of flight parameters, known in North America as FOQA, and have identified many safety deficiencies, including non-stabilized approaches. In addition, while investigative bodies have insights into accidents, we do not want to miss an opportunity to study near-ALARs, near-CFITs or near-mid-air collisions. These studies are complementary. Here are two examples of different ways to deal with them.

A CRJ was flying the Brest-Nantes route with the captain at the controls. The meteorological conditions were deteriorating at Brest a short time before the takeoff from Nantes. The crew was informed in flight of the deteriorating visibility on arrival. A NOTAM indicated that Category II and III approaches were not available at Brest Guipavas from June 2 to July 31, 2003. The crew was aware of this. The pilots communicated little with each other during the approach and some callouts were omitted. The airplane was number two on arrival. The approach controller asked the crew to descend to four thousand, then to three thousand feet, and to enter a holding pattern. He then cleared them to descend to two thousand feet.

When the previous airplane had landed, the controller, seeing the CRJ on the localizer track and thinking that they were established, asked them to continue the approach, before they had joined the holding pattern. The crew started the approach after this clearance. The APPR mode on the autopilot system was never activated. The start of the approach was performed in HDG and VS modes.

The wind, which was turning progressively to the northwest, then the north during the descent, made the airplane drift toward the left. This drift was not detected by the crew. The airplane exited the automatic localizer capture beam. The airplane descended below the glidepath, and the pilot selected VS to get back onto the path. The crew's attention was focused on managing the airplane's vertical track. The airplane intercepted the path from above and the crew's attention was then focused on the horizontal track. The

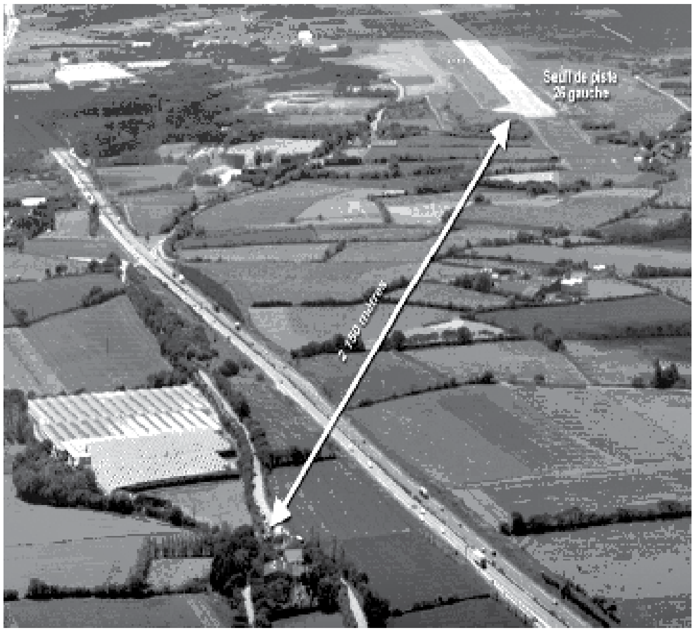



*Photo 1*

airplane then descended through the glidepath and remained below it until contact with the ground. (See photo 1.)

The captain started a turn to the right and disconnected the autopilot. Several GPWS "glide slope" and "sink rate" warnings were issued without the crew reacting in any significant way. The captain started the go-around at decision altitude. The airplane, offset to the left of the extended centerline, was then at about a hundred feet from the ground and its speed was low (between 115 and 120 kt). The first significant pitch-up input on the elevators was then recorded 4 seconds after the thrust increase. The airplane continued to descend, touched down softly, ran along the ground, and then struck several obstacles that severely damaged the cockpit. It came to a stop after about 150 meters. The airplane was totally destroyed by impact and post-impact fire. (See photo 2.)

The causes were identified as

• Failure to select APPR mode at the initiation of the approach, which led to a failure to capture the localizer, then the glideslope;
• Incomplete detection of flightpath deviations due to the crew focusing on vertical navigation, then on lateral navigation;
• The continuation of a non-stabilized approach until decision altitude;
• Lack of communication and coordination in the cockpit and a strategy change in the controller's handling of the airplane were contributory factors.

*Photo 2*

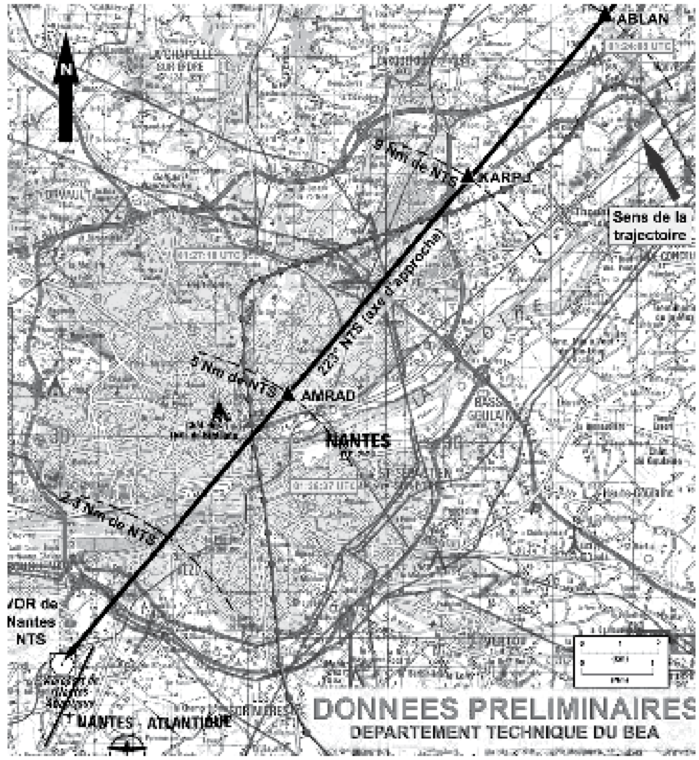



*Photo 3*

Detailed examinations of many airplane components had to be undertaken: flaps, all the pitch-axis channel components, ELT, electronic components with non-volatile memories, as well as use of flight simulator, MSAW simulator, flight deck and instrument ergonomics, etc. Due to the condition of the various components after the accident, this used up a considerable amount of human and financial resources over an 18-month period. Despite the extensive technical work carried out, the report's conclusions determined that the main causes were related to human factors.

Less than a year later, in the same region of France, at night, a foreign-operated MD-83 was flying a VOR-DME approach into Nantes (LFRS). It was 02 h 20 local time and the weather was marginal with drizzle, poor visibility and low ceilings. The airplane was deliberately flown with 30° offset from the approach course due to suspected storm cells on the way to the runway (these were actually no more than ground clutter on the weather radar). The descent was initiated near the FAP, at a much higher rate than that published. The airplane overflew the city of Nantes and broke through the clouds at about 400 ft, then veered sharply to the left as a go-around was initiated. The crew's situational awareness was affected, with reference to the weather information, the position of the city, and a lack of knowledge of the characteristics of non-precision approaches. (See Figure 1.)

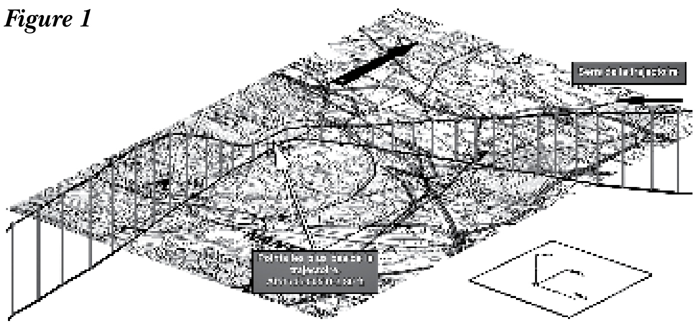
The causes were determined as

• an erroneous interpretation of weather radar display, a lack of knowledge concerning protection envelopes, and more generally a lack of accuracy concerning VOR DME approach techniques;
• improvisation of an action (offset from approach procedure course) without any defined or shared action plan.

Several factors contributed to the event:

• lack of CRM training by the operator,
• the operator's inadequate feedback system,
• discomfort and stress due to adverse weather,

*Figure 1*



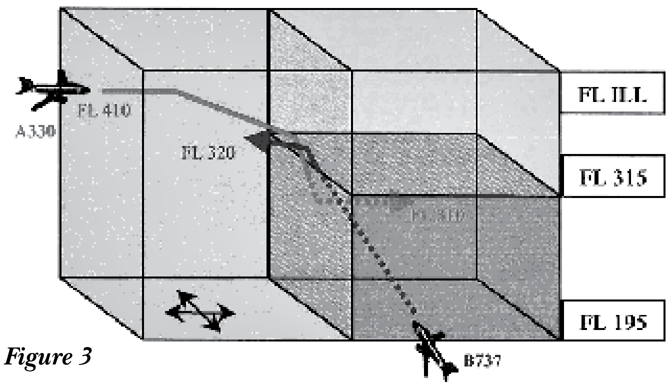



*Figure 3*

- deviation from SOPs, and
- a lack of air-ground synergy.

Two investigators worked on this for 3 months, and safety lessons were learned because it became clear that the root cause of the incident was related to human factors. Those concerned were willing to share information because they understood this would be in the interest of safety. The investigators were able to establish the facts rapidly, despite the lack of any flight recorder information using radar plots and by interviewing all those involved, including those who were abroad by the time the investigation took place.

### TCAS procedure training and TCAS ergonomics

The integration of TCAS in the aviation system has generated new challenges. In order for it to be able to mature, the use of TCAS has to be adapted to the aviation environment. One aviation disaster and a number of incidents highlighted the need for improved feedback. Pilots have had to get used to a new device (procedures, training, knowledge, etc.). Controllers have had to find a new way of interacting in order to make the system safe. A serious incident that occurred in March 2003 illustrates this.

An Airbus A3191 was climbing to FL260 following the controller's clearance. The TCAS triggered a Traffic Advisory for a target located above and on an opposing route. Eight seconds later an "Adjust Vertical Speed" Resolution Advisory was generated, asking the crew to reduce the vertical speed. The pilot responded with a pitch up input. The conflicting traffic was an Airbus A320, in level flight at FL270. Nine seconds after the initial Resolution Advisory in the A319, a "Climb" Resolution Advisory was triggered in the A320. The crew acted on this. During the crossing, the crews of both aircraft made visual contact. The pilot flying the A319 turned smoothly to the left. QAR recordings enabled us to compute the minimum lateral and vertical separations as 0.8 nm and 300 ft. (See Figure 2.)

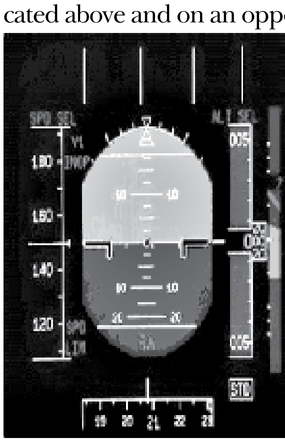


*Figure 2*

Two investigators were involved intensively in this investigation. Many tests were performed and extensive research was carried out, working with a number of different organizations: Airbus (system issues, ergonomics), Air France (event analysis, training), ATC (procedures, testimony), TCAS specialists (systems and events review), human factors specialists (ergonomics, fatigue, stress). This was a complex investigation, and the report was issued within 2 years. The major findings concerned the ergonomics of the TCAS interface, pilot and controller training, and TCAS versus autopilot logic. The report contained eight safety recommendations.

While this investigation was under way, TCAS events were becoming more and more frequent, all such events being reportable. There were a number that had similar origins to the one just mentioned, but other events emerged of a type that had previously been considered to have been covered by the investigation into the Überlingen accident. One of these events led to a long investigation, though a full report was not subsequently deemed necessary as most of the issues had already come to light and been studied. The BEA issued a simplified form of report on this incident to raise awareness and remind the aviation community of some important principles concerning TCAS

In the upper airspace of a French control area, a B-737 was in climb, an A330 in descent, on two converging routes. The controller incorrectly gave a level to the climbing aircraft above the descending one. A Short Term Conflict Alert was presented to the controller that was not considered valid by him, and the aircraft continued toward each other. The controller realized there was a conflict and issued a descent order to the climbing aircraft, which the pilot acted on. As the controller had ordered the other aircraft to climb, the TCAS triggered in both aircraft. The TCAS gave an opposite order to the controller's emergency instruction. In the end, as the B-737 pilot saw the other aircraft, he decided to follow the controller's instruction and not the TCAS. The A330 pilot followed the TCAS. The two aircraft crossed with a lateral separation of less than 1 nm. (See Figure 3.)

The seriousness of the event was initially underestimated as the local investigation performed by the ATC service did not bring to light all of the issues, especially those related to visual separation and to the conflict between a Short Term Conflict Alert and TCAS. The investigation was reopened 6 months later by the BEA, and investigators worked on it for 4 months. The scope of the investigation was quite extensive though the report writing process was deliberately simplified. As the aircraft were operated by foreign airlines, two accredited representatives were associated with the investigation, along with ATC personnel and radar specialists. One year after the incident, the simplified report was issued.

This type of simplified report does not include safety recommendations but is aimed at contributing to the feedback system. Thus, safety issues presented in this document dealt with ATC methods, the coexistence of backup systems based on radar and TCAS, as well as visual separation at high speed and high altitude. ◆

### Footnote

1 A short summary of the event is given here, but please refer to the BEA website www.bea.aero to read the report for a more complete understanding.

# Removing Pilot Errors Beyond Reason! Turning Probable Causes Into Plausible Solutions

By Dr. Robert O. Besco (Capt., American Airlines, Ret.), President, PPI

***Dr. Bob Besco** has more than 45 years of experience as a USAF fighter pilot, a Manager of Human Factors Engineering Groups at North American Aviation and Hughes Aircraft, a captain for American Airlines, an Adjunct Associate Professor in the Institute of Systems Safety and Management at USC, an aircraft accident investigator, and as a independent consultant in aviation safety and flight crew performance. (Photo not available.)*

Aircraft accident investigators have become relatively proficient at determining "what" happened in human performance breakdowns. Currently, most accident reports find that pilots and other highly skilled professionals make unbelievable blunders, omissions, errors, and choices, The questions regarding what caused the defective performance are seldom adequately addressed.

When the probable cause statement is a description of the flawed human performance, there is very little benefit to improving flight safety margins if you simply recommend, "Tell everyone not to do that!" Asking why the performance was flawed is even more important than the descriptions of what happened. Aircraft designers, industry leaders, operating technicians, and flight crews are often left with the conclusion that the errors were made by unreasonable and/or irrational behavior on the part of the involved individuals.

Professional aviators are left with the conclusion that the flawed performance described in accident investigation reports is the result of the poor performance by the "dumb other guys." Most of us conclude that "it couldn't happen here." We convince ourselves that we would not do something as reckless, unprofessional, or irresponsible as the accident-involved individuals. As a result, we do not acknowledge that we as individuals, crews, or organizations are at risk to commit the same blunders. The syndromes of "It won't happen here," "It couldn't happen to me," and "our organization is better that that" (Besco, 1991b) are all reinforced by probable cause findings that describe the errors without searching for and finding the "why" behind the errors.

I challenge ISASI members, in particular, and all aviation safety professionals, in general, to adopt a system of human performance analysis that analyzes and reports all of the factors causing dedicated professionals to make destructive choices. Aviation needs an effective analysis system that attributes the errors to the fundamental reasons the errors were made. Removing these reasons will improve the margins of safety and reduce accident rates.

Most human performance analysis models, theories, and systems are merely descriptions and semantic definitions of human performance breakdowns that point to

1. classifications or taxonomies of errors or
2. categorizations of unreasonable attitudes or
3. conceptual/theoretical models such as the chain of errors or the "Swiss cheese" models or the SHEL model.

Descriptive models by Reason (1997) and Shappell and Weigmann (2000) may be useful in conceptual descriptions of accident events. However, they do not identify the changes that can be made to eliminate or reduce the risks of the same human errors occurring in the future. Other authors, Faith (1996), Rimson and Benner (2005), Miller (1988 and 1991), Shorrock et al (2004), Weir (1999), Wittingham (2004), Woods and Sarter (1995), and Young et al (2005) all join in criticizing these models as being primarily descriptive and not predictive—and certainly not effective in improving the margins of safety.

There are reasons why the errant individuals involved in accidents thought they were doing the right thing (Besco, 2004). Accident investigators need tools to determine all of the plausible causes and reasons that the participants

1. filed to recognize the anomalies and dangers or
2. filed to detect the reduced margins of safety or
3. decided that the errors or deviations wouldn't matter this time or
4. chose strategies and mission options that increased risks or
5. decided that the deviations resulted in acceptable safety margins reductions.

The accident investigation process needs to go beyond "breaking the chain" or "moving the Swiss cheese." The main goal of the accident investigation process is to determine "what to do" to remove the factors that enable or sometimes even encourage the breakdowns to occur. We need to find the factors that can be attributed as direct causation factors in human performance breakdowns and remove them.

### Turning probable causes in to plausible solutions

The landing gear warning horn is an example of such a system. When the causes of gear-up accidents were being described as "The probable cause was the crew failed to lower the landing gear," the recommended remedies were usually to give the pilots better training in the pre-landing checklist procedures. The gear-up landings continued. The cause of the gear-up landings was gradually evolved from "crew failed to lower the gear' to "crew was unaware that the gear was not down and locked."

This shifted the emphasis from "crew error" to defining the required information for the crew to have before landing. The rate of gear-up landings was drastically reduced. The focus on preventing gear-up landings shifted from the ineffectual "train them to put the gear down" to providing an alerting system to warn the pilots the gears were not down and locked. The recommendations evolved to making the pilots aware that the gear was still up during the final approach phase. This causal definition led to

1. an improved mnemonic checklist (GUMP),
2. alerting systems (gear-up warning horn), and

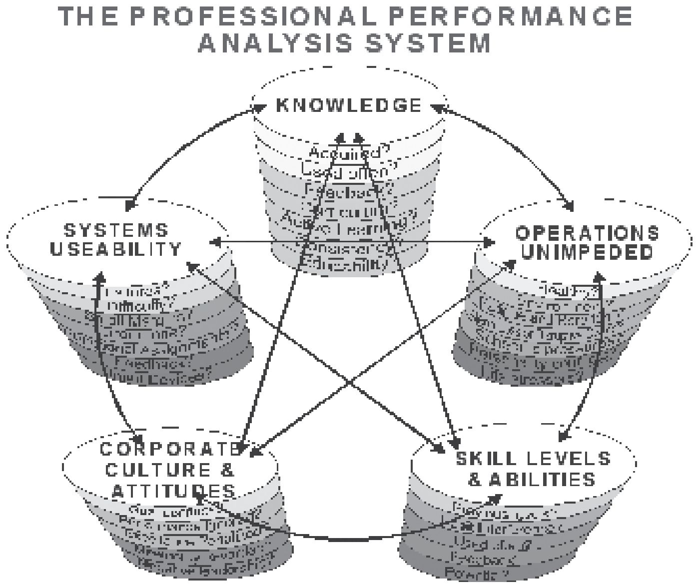



***Figure 1: A diagnostic model to analyze and understand what happened, why it happened, and what to do to improve performance.***

3. elimination of false and nuisance warnings.

The gear-up warning horn has now further evolved to provide warning horns with enhanced logic systems that do not give false gear-up warnings at high speeds, high altitudes and/or high power settings. Gear-up landings in modern aircraft have all but disappeared. This gear-up warning scenario is an excellent example of the utility of turning the search for probable causes into finding plausible solutions.

A similar evolution of causation in controlled flight into terrain (CFIT) investigations has led to the Enhanced Ground Proximity Warning Systems. These new systems have had a dramatic effect on reducing the CFIT accidents.

What is needed are accident investigation systems, processes, or algorithms that identify the reasons why the operators made the errors and what can be done to improve the future performance within the system. Martinko (1995) has edited a collection of articles into a book titled *Attribution Theory: An Organizational Perspective*. Maritnko's main theme is that professional behavior is purposeful and can be attributed to antecedent conditions. It would be very beneficial to apply an analysis system that is focused on attributing the performance breakdowns to definable events and elements that can be modified or removed to prevent the performance failures from reoccurring. When the antecedent conditions are removed, they cannot feed the resulting performance errors and breakdowns. The performance breakdowns will starve, dry up, and blow away when they are no longer being fed (Chaney, 1996).

Many authors have observed that human errors are usually the result of several breakdowns in the safety culture that was developed to protect the system from catastrophic errors, omissions, or inappropriate strategies. Bennett (2001), Bruggink (1975a and b), Chaney (1996), Chiles (2001), Drucker (1992), Faith (1996), Last (1995), Miller (1988 and 1991), Perrow (1999), Rimson and Brenner (2005), Senders and Moray (1991), Vaughn (1996), Weir (1999), Wiener, (1995), Wittingham (2004), Woods and Sarter (1995), and Young et al (2005) have all called for a system of analysis that goes beyond mere descriptions of errors or beyond categorizations or classifications of errors or even beyond error taxonomies. They all call for error analysis and descriptions that deal with the plausible causes of the errors

Mager and Pipe (1970) developed a performance analysis system that applies simple binary logic in a process flow analysis to identify the antecedent causation factors that could be attributed to performance discrepancies. Their system has been widely used successfully in high tech manufacturing and process industries. Accident and incident investigators who are also experienced subject-matter experts have been very successful at utilizing their Performance Analysis System (PAS) to identify the factors causative to the performance breakdowns. The direct simplicity of their process flow diagram leads to basic definitions and easily definable elements. Their PAS can be understood and successfully applied by subject-matter experts without post-doctoral experience as a behavioral scientist. Their basic reference book is now in its third edition (Mager and Pipe, 1999).

Their system analyzes the basic reasons behind poor choices, errant performance, and human errors. Even more importantly, their Performance Analysis System isolates the reasons why the mistakes, errors, and poor choices were judged to be reasonable before the accident. By removing these reasons, we can starve our human performance error problems and reduce our accident rates. Mager and Pipe point out three things that must happen to ensure that maximum safety margins result from professional performance.

1. Performance must be monitored. It must not be ignored.
2. Good performance must be recognized and positive feedback provided.
3. Poor performance must be consequential and steps taken to improve performance.

These simple steps of effective management and leadership will establish a corporate culture that ensures the widest possible safety margins are provided in daily operations.

## Professional Performance Analysis System

The Professional Performance Analysis System (PPAS) was tailored to pilot error accidents and was first presented publicly to the Joint Meeting of the Association of Aviation Psychologists and the Human Factors Society in San Francisco in 1977 (Besco, 1977). More than 50 major aircraft accidents have been analyzed with the PPAS. The basic process flow analysis of Mager and Pipe was expanded to cover five attributes that are causative to human performance in aviation, illustrated in Figure 1. The Eastern Airlines L-1011 accident in the Florida Everglades in 1972 was the first accident analyzed with the PPAS applied to the analysis of the crew errors (Besco 1990, 1991). The results were very encouraging and validated the thoroughness of the process to resolve some very thorny liability issues. (See Figure 1.)

The full, complete version of the PPAS was first presented to the International Society of Air Safety Investigators meeting in Vancouver in 1988 (Besco, 1989). Figures 2A and 2B contain the process flow chart of the PPAS (see page 19). USAF aviation safety classes at the University of Southern California were first taught the PPAS process starting in 1975. A complete description of the application of the knowledge dimension was published in Besco (1989 and 1992). The systems usability dimension was presented at the SAE Human Error Avoidance Techniques Conference (Besco, 1988). The skill levels and abilities dimension was first presented to the Lawyer-Pilots Bar Association (Besco, 1990). The environmental obstacle dimension was first introduced to the Seventh Aerospace Behavioral Technology Conference of the SAE (Besco, 1989). The Attitude Dimension was introduced in the *Flight Safety Foundation Accident Prevention Bulletin,* Volumes 47 and 48 (Besco, 1990 and 1991).

**PPAS applied to Flight 1420**

Why would a very senior flight department manager, with decades of successful professional flying experience, while flying with a very experienced professional copilot, make serious and lethal blunders that would result in a tragedy with loss of life? It would seem that the several layers of defenses, which have successfully operated for decades, would guide the crew to make choices that would not put their aircraft, their passengers, and themselves in harm's way.

What then, did happen on American Airlines Flight 1420 (NTSB, 2001) from DFW into Little Rock on the evening of June 1, 1999? The flight crew pressed on into intolerable weather conditions resulting in an overrun accident that killed 10 passengers and the captain. The aircraft was destroyed by impact and subsequent fire.

The probable cause findings of the NTSB will be reviewed with the PPAS to define all of the plausible causes that need to be removed to lower the risks of the 1420 accident being repeated. The NTSB determined that the majority of the malperformance occurred in the PPAS dimension defined as productive attitudes?. The illustrations in this presentation will be drawn exclusively from factors contained with the productive attitudes dimension. The procedures, techniques, and analysis of the breakdowns that could occur in the other four dimensions are identical.

The National Transportation Safety Board (NTSB Report Number: AAR-01-02) determined that the probable causes of this accident were

1. "the flight crew's failure to discontinue the approach when severe thunderstorms had moved into the airport area," and
2. "the crew's failure to ensure that the spoilers had extended after touchdown."

The NTSB concluded that contributing to the accident was the flight crew's

1. "impaired performance resulting from fatigue and the situational stress associated with the intent to land under the circumstances,
2. "continuation of the approach to a landing when the company's maximum crosswind component was exceeded, and
3. "use of reverse thrust greater than 1.3 engine pressure ratio after landing."

Theses statements of probable causes are typical of the level of detail found in aircraft accident reports. Although factual, the statements are primarily descriptions of what happened. They shed very little light on why it happened and even less on what can be done to minimize the future reoccurrence of the fatal errors. These definitions do not explain why these normally routine events, which had been successfully managed hundreds of times by flight crews with even less-experienced aviators, on this occasion were allowed to deteriorate into serious lethal blunders.

The members of this flight crew were well-intentioned, well-trained, and currently proficient. They were operating in relatively familiar environmental and operational conditions with fully functioning system components. However, a subtle combination of lowered performance margins, deteriorating weather conditions, and an overly committed sense of "damn the torpedoes" led them to make choices that in retrospect they would never have repeated. At every point in the approach and landing, it is virtually a certainty that the crew felt that they were maintaining adequate margins of safety and that they perceived that they were fully committed to the welfare of their passengers.

**PPAS analysis of the NTSB probable causes of Flight 1420**

Figures 2a and b contain a process flow chart for the PPAS. This illustration is focused exclusively on the productive attitudes dimension of the organizational culture and flight crew as it pertains to Flight 1420 (NTSB, AAR-01-02, 2001), The identical process would be applied to the other four first level dimensions.

The productive attitudes dimension of inquiry contains five 2nd tier factors. Each of these five factors has a third level of analysis. The 2nd and 3rd levels of analysis serve as a checklist to ensure that all plausible causes are explored by the investigation team. The third level elements should be tailored to the organization and type of operation being reviewed. Safety investigators will develop a supplemented list of the second and third level elements tailored to organizational and situational characteristics of the accident. This will ensure that the analysis is exhaustive of the type of operations and missions for the specific organizational structure and for the types of equipment being reviewed. Each probable cause uncovered by the investigators is reviewed with the PPAS process.

**NTSB Probable Cause 1.** ***"The flight crew's failure to discontinue the approach when severe thunderstorms and their associated hazards to flight operations had moved into the airport area."***

**A. Is performance ignored? NOT COMPLETELY; HOWEVER, PERFORMANCE WAS NOT ADEQUATELY MONITORED**

The flight crews all had received intensive instruction and simulator training on avoidance of thunderstorms and windshear on landing. However, compliance with the operational restrictions was not closely monitored. If Flight 1420 had made it to the gate uneventfully, it is unlikely that the violation of the SOPs and the flight crew's disregard for maintaining adequate margins of safety would have been recorded as a negative and/or reportable event. **Recommendations to improve margins of safety—**arrange monitoring and consequences with flight following by Systems Operational Control. Review FOQA recordings correlated with weather service records for marginal weather landings.

**B. Is excellence penalized? NO**

There is no criticism of aircrews for lengthy holds to allow weather to improve. There is no criticism if they fly to an alternate landing airport.

**Recommendations to improve margins of safety—**provide a no-fault appeal or performance review process. If a flight crew is subjected to professional second-guessing for diverting or delaying or if a copilot is criticized for suggesting delays or diversions, a no-fault review of the circumstances will remove any organizational pressure to "damn the torpedoes" and press on into unsuitable conditions.

**C. Is poor performance encouraged? NO**

The SOC or flight supervisor does not have the option of second-guessing or criticizing a crew decision on being conservative. The captain does not have a silencer to keep the copilot from making suggestions that maintain a margin of safety.

**Recommendations to improve margins of safety—**provide an appeal or objective performance review process in the event there is a disagreement within the cockpit on a prudent plan or if the

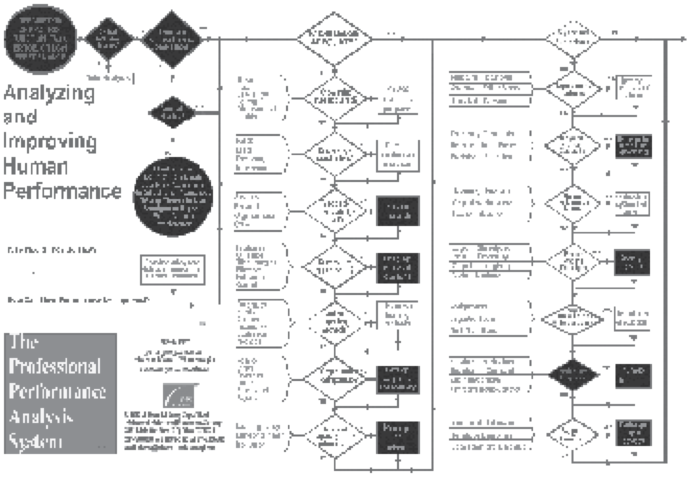



***Figure 2A: The Professional Performance Analysis System. The Knowledge Adequate? and The Systems Functional? analysis steps of the process flow chart to identify the plausible causes and potential strategies to improve the margins of safety.***

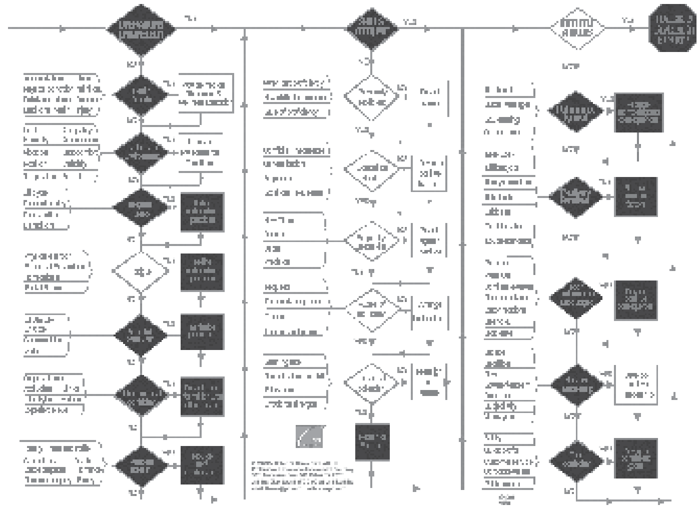


***Figure 2B: The Operations Unimpeded? and Skills Adequate and Productive Attitudes dimension of the PPAS.***

captain is challenged or questioned by supervisors when conservative decisions are made.

**D. Are leadership practices negative? YES**
The captain used his authority as a flight department manager to diminish the copilot's concerns for the proximity of unsuitable thunderstorm activity and excessive crosswinds.
**Recommendations to improve margins of safety—**have an appeal and adjudication process in place that is non-threatening to both flight crews and supervisors if conservative recommendations and decisions made by flight crews are questioned or overridden by managers or captains.

**E. Are goal conflicts present? YES**
Are the priorities of safety, comfort, schedule and economy universally applied?
**Recommendations to improve margins of safety—**continuously have the CEO, board members, and senior managers communicate the importance of these priorities to everyone involved with flight operations.

**NTSB Probable Cause 2.** "***The crew's failure to ensure that the spoilers had extended after touchdown.***"

**A. Is performance ignored? YES**
In normal operations, the spoilers are armed manually by the flight crew in the pre-landing checklist. The spoilers deploy automatically after touchdown without further interaction by the pilots. The system and the procedures are so routine and reliable that the crews are not immediately wary of a rare fault in the spoiler deployment procedure. The crews will not recognize the non-deployment of the spoilers until lack of deceleration becomes a significant danger. By then, it may be too late to safely stop the aircraft.
**Recommendations to improve margins of safety—**provide an alerting sensor on the spoiler armed function similar to the landing gear up warning system.

**B. Is excellence penalized? NO**
There is no cost or workload penalty to arm the spoilers.

**C. Is poor performance encouraged? NO**
There is no benefit to not arming the spoilers.

**D. Are leadership practices negative? NO**
There is no benefit to not arming the spoilers.

**E. Are goal conflicts present? NO**
There is no benefit to not arming the spoilers.

**Analysis of the NTSB contributing probable causes on Flight 1420**

**NTSB Contributing Probable Cause 1.** "***Impaired performance resulting from fatigue and the situational stress associated with the intent to land under the circumstances.***"

**A. Is performance ignored? YES**
If there had not been a reportable event, the crew would have been thanked for "damning the torpedoes" and getting the passengers on to Little Rock. The reduced margins of safety would have been ignored. The deviance would have been "normalized" (Perrow, 1999).
**Recommendations to improve margins of safety—**arrange monitoring and consequences with flight following by Systems Operational Control and by Flight Crew Scheduling. Before the crew runs out of duty time, implement a no-challenge, no-fault, and no-blame policy when crews take themselves off schedule for fatigue.

**B. Is excellence penalized? YES**
If a flight crew determines that the duty period has resulted in unusual stresses and that it would be imprudent to press on for the final leg, the minimum feedback that they would get is the requirement to file a report on why they could not complete the final leg. Second-guessing the crew on fatigue calls is analogous to second-guessing the crew's call on a landing go-around. It will influence the crew to press on in marginal conditions.
**Recommendations to improve margins of safety—**remove all organizational policies and practices that challenge "crew fatigue" calls even before the running delays force a cancellation due to an illegal over-duty-time event.

**C. Is poor performance encouraged? YES**

The copilot was still on probation as a new hire at the airline. He was flying with the highest ranking, senior management captain at his domicile. Although the copilot was very experienced as an aviator in high-performance aircraft and missions, there was a lot of organizational culture pressuring the copilot to not challenge or to not make waves about the questionable decisions of the captain.

The airline did not have any non-threatening protocols to support the copilot in breaking through the captain's fixation and tunnel vision that was causing him to disregard fatigue limits, convective weather limits, and aircraft performance limits. The copilot was not provided with the operational tools, such as the PACE process (Besco, 1994), to influence the captain to abandon his aggressive risk taking behavior.

**Recommendations to improve margins of safety—**establish and follow through on a policy for inflight mission changes and diversion options. Establish that the crew reach a consensus before there is a commitment to a revised mission plan.

**D. Are leadership practices negative? UNDETERMINED**

The question was not explored or even asked by the NTSB investigation team.

**Recommendations to improve margins of safety—**establish an organizational climate that attracts the best pilot/leaders into supervisory roles. Promote a leadership climate that actively builds a sense of contribution for the first line supervisors by making the organization the best place in the world to be an aviator. (Besco, 1989a)

**E. Are goal conflicts present? YES**

The airline was in the throes of a labor relations dispute and upper management viewed a flight safety campaign as being a bargaining ploy. The airline also was in a marginal profitability period, and there was significant high-level pressure to reduce costs or "fold the tent."

**Recommendations to improve margins of safety—**define the flight department goals that are consistent with goals, policies and practices of the parent corporation, the FAA, and the pilots' employment agreement.

**NTSB Contributing Probable Cause *2. "Continuation of the approach to a landing when the company's maximum crosswind component was exceeded."***

**A. Is performance ignored? YES**

The only condition on which performance is monitored is when there is a reportable event as a result of an exceedance or deviation from SOP.

**Recommendations to improve margins of safety—**arrange monitoring and consequences with flight following by Systems Operational Control. Before descent, have SOC alert the crew to the possibility of unacceptable crosswinds or other marginal conditions.

**B. Is excellence penalized? NO**

If the approach is abandoned and the alternate airport was selected, there would have been no penalty or even an inquiry concerning the choice.

**C. Is poor performance encouraged? NO**

There were no informal or formal "attaboys" for successfully exceeding limitations and beating the system.

**D. Are leadership practices negative? YES**

The captain as the chief MD-80 pilot in Chicago set a negative example by "pressing on" into unacceptable thunderstorm and crosswind conditions.

**Recommendations to improve margins of safety—**install a non-threatening crew conflict resolution system, such PACE (Besco, 1994).

**E. Are goal conflicts present? YES**

The captain had gone to considerable lengths to rearrange and adapt the crew and aircraft assignment to Flight 1420. The "mission completion goal" and "we can do it goal" were placed well ahead of the goal to stay within proven operational limits.

**Recommendations to improve margins of safety—**set up the corporate culture so that "management pilots" are scheduled and paired as if they are low-time pilots. The pairing of a probationary copilot with a marginally current management pilot is putting the passengers at an unnecessary risk. Schedule crew pairings and weather minimums for supervisory "desk jockeys" as if they are in their first 100 hours in type.

**Contributing Probable Cause 3. *"Use of reverse thrust greater than 1.3 engine pressure ratio after landing."***

**A. Is performance ignored? YES**

The only condition on which performance is monitored is when there is a reportable event as a result of an exceedance or deviation from SOP.

**Recommendations to improve margins of safety—**use FOQA to detect and track exceedances.

**B. Is excellence penalized? NO**

**C. Is poor performance encouraged? NO**

**D. Are leadership practices negative? NO**

**E. Are goal conflicts present? YES**

When the EPR restriction is set solely for engine health and longevity, the dangers of overshooting the runway on rollout would be in conflict with the dangers of engine damage

**Recommendations to improve margins of safety—**establish thrust reverser limits for both maximum deceleration in an emergency and for maximum engine economic life in normal operations.

## PPAS applied to other aircraft accidents

The PPAS has been applied to several dozen aircraft accidents to define causation sequences and remedial changes that could have prevented the accident. Just as vital are the changes that could be implemented to reduce the risks of the errors being repeated. Two reports on the results of applying the PPAS to accidents have been published and are available to the public. The L-1011 in the Florida Everglades in 1972 (Besco, 1990 and 1991a) and the A320 CFIT at Strasbourg, France, in 1992 (Besco, 1997).

In the 1972 Florida Everglades L-1011 crash, the PPAS identified 15 plausible solutions that could have prevented the accident. In the 1992 Strasbourg A320 CFIT crash, the PPAS isolated 40 plausible solutions that when implemented would greatly reduce, if not eliminate, the possibility that the accident would be repeated.

## Recommendations

The Professional Performance Analysis System is a simple, powerful, and proven tool. It is easy to use, learn, and teach for identifying the multiple causes behind human performance breakdowns. The PPAS is economical and requires no sophisticated equipment or high level of education. The PPAS is easily learned by flight crews and accident investigators. The PPAS can serve as a checklist for reasonably experienced aviation safety professionals to identify an exhaustive set of plausible causes for errors.

The PPAS provides a thorough, detailed checklist of the plausible causes of errors. The PPAS contains five independent attributes of human error at the first level of analysis. Each of the five first-level factors contains five to seven second-level categories of error causation. For each of the 31 items on the second level of detail, there are five to seven subfactors. The third level of detail contains more than 200 potential checklist items to be considered by the investigators to ensure that no stone will be unturned. This set of causation factors should be tailored to each organization and its specific goals and to the type of equipment operated. The PPAS and its hundreds of checklist items are easily updated and revised as the state of the art requires changes.

I challenge ISASI members and all safety professionals to apply the PPAS as a powerful and proven tool in identifying the reasons human performance breaks down. The PPAS helps the investigator both in pre-mishap and post-accident analyses to improve margins of safety. The PPAS is simple to use and objectively focuses on the causes of human errors. The PPAS is an open-ended system that is not limited or bounded by any current theories of the significant dimensions of human performance. The safety professional can bring very powerful tools from the quantitative behavioral sciences to bear on the question of improving human performance in aviation. A special support team of academic researchers is not required to realize the cost-effective benefits of the PPAS.

I urge everyone to apply the PPAS to the most difficult human performance problems they encounter. It the PPAS does not help identify preventive measures or performance improvement measures, I will come to anywhere in the U.S.A. and take you and your significant other out to dinner to discuss the issues over a good bottle of wine. If you are overseas, we need to work out an equal value alternative. ◆

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# Performance and Flight Dynamic Analysis of the Flight in Ice Accretion

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## Abstract

The purpose of this paper is to discuss the performance and flight dynamic of a turboprop aircraft flying in ice accretion conditions. Aircraft that encounter inflight severe icing will have degraded lift, declined climb rate, increased drag and stall speed, which can lead to uncommanded roll and/or pitch and loss control that may result in a crash into terrain. On Dec. 21, 2002, an ATR 72-200 freighter scheduled from Taipei to Macau, light number GE791, departed from Taipei at 01:05 local time (UTC+8). During cruising at FL180 with the autopilot engaged and airspeed around 200 knots, it encountered a prolonged exposure to severe icing conditions that caused the flight crew to keep the airframe deicing activated.

Performance analysis based on the GE791 flight data recorder (FDR) indicates a drag increase of 100 counts. This drag increase induced airspeed decay by 10 knots in the first 25 minutes after initial ice accretion. The amount of drag increase 4 minutes prior to the autopilot being disengaged was 500 counts, and the airspeed decayed to 158 knots. Ten seconds before the roll upset, the longitudinal and lateral stabilities were largely affected by the severe ice that accumulated on the wings, which produced the flow separation. Prior to autopilot disengagement, the aerodynamic behavior of the aircraft (lift/drag) was degraded about 40%.

Based on FDR data, performance analysis, and the cockpit voice recorder (CVR), the Aviation Safety Council believes that GE791 most likely encountered a severe icing condition worse than icing certification requirements of FAR/JAR 25 Appendix C.


**Keywords:** CVR, FDR, aerodynamic, ice accretion, severe icing, turboprop aircraft

## I. Introduction

*1.1. History of flight*

On Dec. 21, 2002, an ATR 72-200 cargo flight (flight number GE791) departed from Taipei at 01:05 local time (UTC+8). During cruising at FL180 with autopilot engaged and airspeed around 200 knots, it encountered a prolonged exposure to severe icing conditions that imposed the flight crew to keep the airframe deicing activated. The ice accretion, together with the flight crew's operation eventually caused the aircraft to stall then crash into the Taiwan Strait near Penghu Islands. Both pilots were missing.

After takeoff, GE791 selected the route as follows: CANDY 1 departure, reached the assigned Flight Level 180 (FL180) at 0125 and joined A-1 when passing MKG VOR/DME. The meteorological conditions data depict that the ground temperature was 20 degrees Celsius when GE791 departed from CKS International Airport, and the estimated temperature at an altitude of 18,000 ft of the accident area was minus 9 degrees C. Furthermore, the FDR recorded "total air temperature (TAT)" at FL180 of between minus 2 and minus 4 degrees C.

The FDR recorded data revealed that when GE791 reached FL180, the autopilot was engaged with indicated airspeed (IAS) of 202 knots, both propellers speed were 86%, torque was degraded from 72.8% to 70.8%, estimated weight 20,800 Kg. During the cruising phase, the airframe de-icing system was activated during the periods of 0134 to 0137 and 0141 to 0152 (when FDR stopped recording).

A highlight of the CVR recording together with the respective airspeed is shown in the following (0132-0152):

| UTC | | CVR transcript | IAS (kts) |
|---|---|---|---|
| 0132:35 | CM-2 | Looks like it's iced up….Look at my side. Your side is also iced up, right. | 201 |
| 0134:29 | CM-1 | Oh, it is icing up.**1st airframe deicing ON** | 198 |
| 0137:24 | CM-1 | It's gone again. **(airframe deicing OFF** | 197 |
| 0141:25 | CAM | (-4 s: sound of single chime.) **(2nd airframe deicing ON** | 196 |
| 0144:47 | CM-1 | it's iced up quite a huge chunk. | 188 |
| 0150:29 | CM-1 | Wow, it's a huge chunk. | 173 |
| 0150:31 | CM-1 | What an ice. | 174 |
| 0150:55 | CM-1 | This speed is getting slower—it was a hundred two hundred one hundred and ninety now one hundred seventy. | 171 |
| 0152:02 | CM-1 | Do you see that? | 158 |
| 0152:08 | CM-1 | It's severe icing up. | 158 |
| 0152:10 | CM-1 | Captain— | 158 |
| 0152:11 | CAM | Various warning sounds during the last 40 seconds. | 158 |
| 0152:25 | CM-2 | Captain, pull up! | 221 |

*1.2. Weather information*

One of the WSR-88D, doppler weather radar information is used in the investigation. This radar site is located in Mt. Wufan, Taipei County (RCWF, located 295 kilometers northeast of the accident site and 55 kilometers east of RCTP). Post-accident weather analysis indicates that an area of higher echo intensity about 25-45dBz was moving east-northeasterly with the clouds in the northern

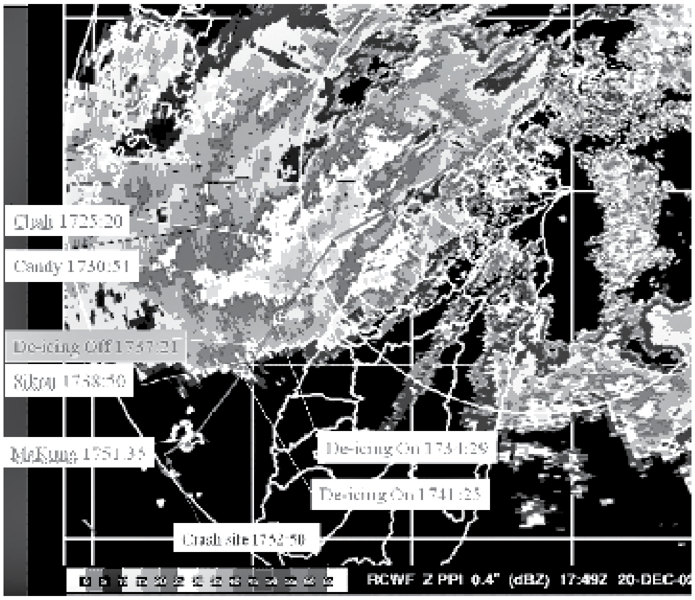


***Figure 1. Supposition of GE791 flightpath and doppler weather radar PPI image.***

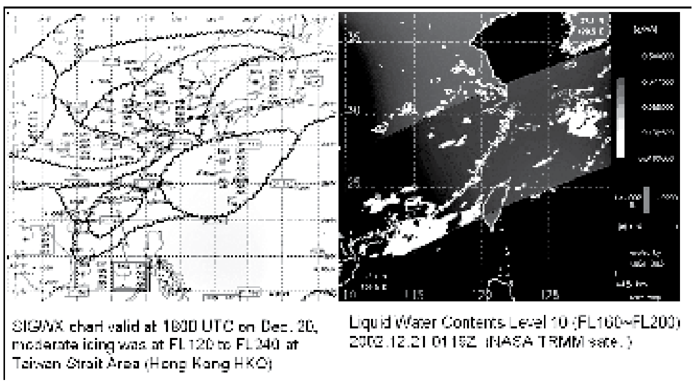


***Figure 2. Comparison of SIGWX chart (valid at 1800 UTC) and liquid water content between FL160 and FL200 (near accident time).***

part of Taiwan Strait—with a length of 200 kilometers and width of 100 kilometers and located from FL60 to FL120. Tops of the highest cloud layer that overlaid the area were about 35,000 feet MSL. GE791 flew above the area from before waypoint "CHALI" to waypoint "CANDY." Figure 1 depicts the superposition of GE791 flightpath and weather radar PPI1 image.

During the accident time, clouds above the freezing level with supercooled liquid water could have existed as both the Hong Kong Observatory and Tokyo Aviation Weather Service Center marked moderate icing on the significant weather charts. Figure 2 shows the SIGWX chart valid at 1800 UTC on December 20—moderate icing indicated at FL120 to FL240 and moderate turbulence located from FL20 to FL380 in central and north Taiwan and the sea area of northeast Taiwan. After the accident, investigation teams obtained the liquid water content (LWC) information from NASA's TRMM2 satellite. Its data revealed that the significant icing droplets at the accident area (from waypoints "CANDY" to " MAKUNG") had an average value of LWC greater than 0.13 g/m3.

## II. Summary of recent ATR 42/72 incidents/accidents

The ATR 42 and ATR 72 aircraft service history was examined by the Safety Council, with emphasis on incidents/accidents involving severe icing conditions. Eight occurrences (including GE791) involved the ATR 42 and 72 were reported since 1994. To gather as much information on the ATR severe ice encounters, an analysis of the seven previous severe icing events was collected and analyzed. (See Table 1, page 28.)

1. *American Eagle Flight 4184, Roselawn, Ind., U.S.A., Oct. 31, 1994—Accident, ATR 72-212, NTSB*
**Deicing Equipment:** Standard deicing boots.
**Probable Cause:** Aircraft loss of control, attributed to a sudden and unexpected aileron hinge moment reversal that occurred after a ridge of ice accreted beyond the deicing boots.
The Roselawn accident has been largely discussed and studied by the NTSB and the aviation community.
After the Roselawn accident, the manufacturer decided
- to extend the outer deicing boots, to prevent the formation of any ridge of ice in front of the aileron.
- to provide the flight crew with the means, discovered during such tests, to recognize the entry into severe icing conditions (side window, ice evidence probe, speed decay).
- to provide updated procedure for flight in severe ice conditions such as autopilot disengage and starting the escape maneuver maximum of thrust available to the engines.
- to provide the crew with the adequate procedures for aircraft recovery in case of upset.

The entire ATR fleet, including the TNA ATR 72-200 Flight GE791, had the modified boots, ice evidence probe, updated procedures in the flight manual, including the indication of the means to detect severe icing conditions and the flight procedures when it occurs.

2. *Near Cottbus, Germany, Dec. 14, 1998—Incident, ATR 42-300, BFU*
**Deicing Equipment:** External wing boots extended + flap extension allowed above VFE.
**Probable Cause:** The crew lost control after the aircraft entered and continued operation in severe icing conditions outside Appendix C. The crew had failed to associate icing of the forward side windows with severe icing phenomenon.

3. *Trans States Airlines approach to Lambert-St. Louis International Airport, MO, U.S.A., Jan. 7, 1999—Incident, ATR 42-300, NTSB*
**Deicing Equipment**: External wing boots extended + flap extension allowed above VFE.
**Probable Cause**: The flight crew noticed ice shapes during approach (altitude 3,000 ft) on the side windows and aircraft deceleration. The aircraft was flying in identified severe ice conditions (visual cues). The AFM procedure was updated to prohibit the approach in severe ice condition with flaps 30.

4. *Near Berlin-Tegel, Germany, Jan. 28, 2000—Incident, ATR 42-300, BFU*
**Deicing Equipment**: External wing boots extended + Flap extension allowed above VFE.
**Probable Cause**: The aircraft had entered atmospheric conditions of severe icing for which it is not certificated. Application of the AFM procedures implemented for such encounter allowed the flight crew to exit these severe icing conditions and to continue a safe flight and landing.

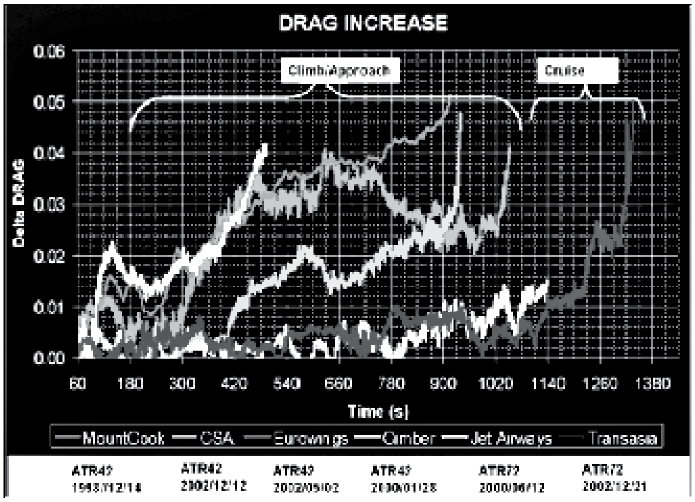


*Figure 3. ATR 42/72 extra drag due to ice accretion versus time (1998-2002).*

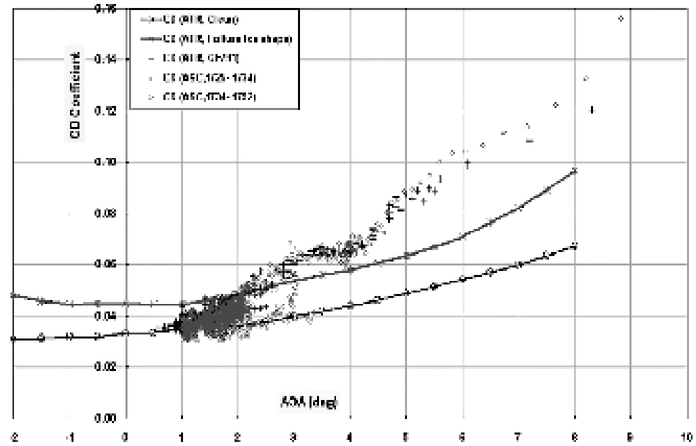


*Figure 4. The extra drag of GE791 due to ice versus time (-o-: clean configuration, -*-: deicing boots inoperative, + : GE791 ice accretion).*

5. *Jet Airways over the Indian Ocean, June 12, 2000—Incident, ATR 72-212A, ATR*
**Deicing Equipment**: External wing boots extended + flap extension allowed above VFE. Median wing boots extended + AAS3 new flashing logic.
**Probable Cause**: After prolonged exposure to icing conditions with the airframe deicing OFF, the aircraft lost 25 knots of speed followed by a mild roll of 15 degrees.

6. *Air New Zealand over New Zealand, May 2, 2002—Incident, ATR 72-212A, ATR*
**Deicing Equipment**: External wing boots extended + flap extension allowed above VFE. Median wing boots extended + AAS new flashing logic.
**Probable Cause**: Aircraft encountered icing conditions during climb. The crew noticed ice shapes on the side windows and decreasing rate of climb. The non-application of AFM severe icing emergency procedure (icing speed increase by 10 knots and autopilot disengage) led the aircraft to the angle of attack where aerodynamics anomalies appeared. The subsequent crew action of quickly reducing the angle of attack recovered to its normal situation.

7. *Czech Airlines, Dec. 12, 2002—Incident, ATR 42-400, ATR*
**Deicing Equipment**: External wing boots extended + flap extension allowed above VFE. Median wing boots extended + AAS new flashing logic.
**Probable Cause**: The crew noticed ice shapes on the side windows and decreasing rate of climb and continued operation in severe icing conditions and stalled with uncommanded roll excursion.

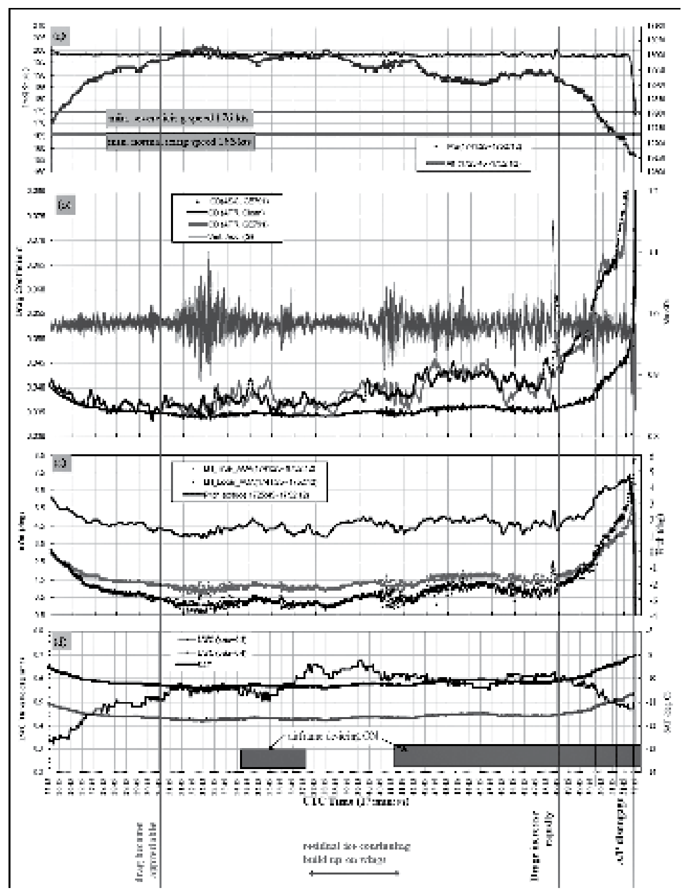

*Figure 5. GE791 performance data plot due to ice accretion versus time (airspeed, altitude, OAT, drag, and severe icing threshold value of LWC).*

## Summary of analysis

- In case numbers 1, 2, 3, 4, 6, and 7, the flight crews recognized the severe ice conditions through side window cues for all incidents except number 5, for which the report is not available but the flight analysis and the increase of drag level clearly indicate that the aircraft flow through severe ice conditions.
- All events occurred while the aircraft were flying into severe ice conditions with autopilot engaged, which is not in agreement with procedures in aircraft AFM.
- In all events except number 1 (Roselawn because of small drag) and number 3 (severe ice encounter in approach, no rate of climb or speed reduction), the aircraft experienced rate of climb or speed decay, which are a means to recognize severe ice conditions.
- The ice protection system was on Level III, which means that AOA, engine, and airframe protection on, except for number 5 where airframe anti-ice system was off and the flight was most likely in severe icing condition.
- All aircraft were equipped with the extended boots (except num-

ber 1), which prevent the formation of ridge of ice in front of aileron, which was the cause of Roselawn accident.

The drag variation versus time of the last six ATR 42/72 occurrences and GE791 related to icing condition is plotted in Figure 3.

The Roselawn accident is not included in Figure 3 because of the very small amount of drag created by severe ice. The ice that accumulated was only in front of aileron, and the roll upset was created by the influence of this ridge on the aileron hinge moment variation. All other events have a very high drag increase with large speed reduction.

## III. Performance and flight dynamic of the flight in ice accretion

The performance analysis was obtained through a comparison between FDR recorded parameters, and simulation parameters computed with the clean aerodynamic model adding the drag and lift degradation up to match FDR data.

*3.1. Icing speed determination*

Post-accident analysis indicates an estimated weight of 20,800 Kg and the indicated airspeed with autopilot engaged at 202 knots. For a clean configuration of the ATR 72-200 at this condition, its 1g stall speed is 116 knots (Vs,1g). The designed stickshaker speed will be 1.3 times of 1g stall speed of 151 knots. According to FCOM, the minimum icing speed of the ATR 72-200 is designed as 1.43 times of 1g stall speed of 166 knots, and severe icing speed is 176 knots (plus10 knots of the minimum icing speed).

The left and right AOA ($\alpha_{Local}$) recorded were not the true AOA ($\alpha_{True}$) but could be modified to the true AOA with the formulation below:

$\alpha_{True} = 0.6262 * \alpha_{Local} + 0.98$ (degree), with flap $= 0$

There are two stall warning measures of the ATR 72, one is the **primary stall warning,** which will active the cricket aural alert and stickshaker; another is the s**econdary stall warning**, which will push the stick to a lower AOA. For clean configuration and no ice polluted on the wing, both stall warnings will be triggered by a true AOA of 8 degrees and 10.6 degrees, respectively.

*3.2. GE791 performance analysis of ice accretion*

The lift and drag during cruising phase were calculated base upon the FDR parameters and, weight and balance information of GE791. There are two methods to balance the aircraft's lift and weight during cruising. One is to increase airspeed by increasing engine power; the other is to increase lift (CL) by increasing angle of attack (AOA). Therefore, the increase of lift will also increase the drag. Equation (1) describes the relationship of lift and weight.

$$W = L = 0.5\rho V_{tas}^2 C_L \quad (1a)$$

$$C_L = C_{L,0} + C_{L\alpha}\alpha$$
$$CD = CD{,}0 + C_L^2/\pi e AR;\ AR = b^2/S \quad (1b)$$

Figure 4 plots GE791's extra drag due to ice versus time, from cruising at 18,000 ft until the autopilot became disengaged. The result is consistent with those derived by the manufacturer as indicated in Figure 4.

During cruising at 18,000 ft (0125:00-0152:12), GE791 airframe deicing conditions, airspeed, altitude, outside air temperature, drag, and angle of attack versus time is plotted in Figure 4 (a) through (c). Figure 5 illustrates the lift-drag ratio versus true angle of attack.

Due to the effect of ice accretion, the lift and drag variation of GE791 is discussed below:

**Time 0125:00-0134:28**

At 0124:56, the aircraft climbed to its cruising altitude of 18,000 ft. At 0132:34, its airspeed was 201 knots. Prior to the first activation of airframe deicing, airspeed decayed to 197 knots, and outside air temperature was about minus 12 degrees C, with vertical acceleration variation about 0.12G. Figure 5 shows that at 0131, the drag, due to ice accretion, become appreciable. From 0132:30 to 0134:28, the aircraft probably flew into clouds and encountered light to moderate turbulence. During this period the airspeed was 199 ± 2 knots, the lift-drag ratio was 11.4, AOA was 1.0 degree and pitch attitude was 1.5 degrees.

The Safety Council believes that GE791 encountered icing at 0131 and the variation of 0.12G in vertical acceleration was due to light to moderate turbulence.

**Time 0134:29-0141:24**

At 0134:29, according to the CVR, a sound of a single chime was recorded. FDR data indicated that the flight crew immediately activated the airframe deicing system. Thirty seconds later, the aircraft decelerated to 194 knots (0135:03), the lift-drag ratio was 14.3, true AOA 1.4 degrees, and pitch attitude was 1.9 degrees. At 0136:19, the indicated airspeed was back to 199 knots, which indicated the airframe deicing system was effective.

At 0138:08, the indicated airspeed resumed to 200 knots and was maintained until 0138:22. From 0138:22 to 0141:24, the airframe deicing system was switched off and outside air temperature was minus 11 degrees C. A vertical acceleration variation of 0.1 g, indicated the aircraft was probably in the clouds again and encountered moderate turbulence. FDR data indicated the airspeed decayed from 200 knots to 195±2 knots, the lift-drag ratio was 11.6, true AOA was 1.3 degrees, and pitch attitude 1.2 degrees. During this stage, the icing accretion caused about a 5% decrease in the lift-drag ratio. Figure 5 shows after the switch off of the airframe deicing system, extra drag due to icing accretion increased about 20 counts than the clean configuration. At 0140, the drag count increase to 50 counts.

After the airframe deicing system was switched off, it is highly probable that the residual ice on the wings caused the drag to be higher than clean configuration about 50 counts, with the lost of lift-drag ratio about 5%.

**Time 0141:25-0152:12**

(a) 0141:25-0145:20

At 0141:21.7, according to the CVR, a second single sound chime was recorded. At 0142:25 (3 second after the single chime), the flight crew reactivated the airframe deicing system. The outside air temperature was minus 10 degrees C. Four minutes after the second activation of the deicing system, the indicated airspeed decelerated from 196 knots to 186 knots, the lift-drag ratio was 11.3, true AOA 1.8 degrees, and pitch attitude was 2.1 degrees.

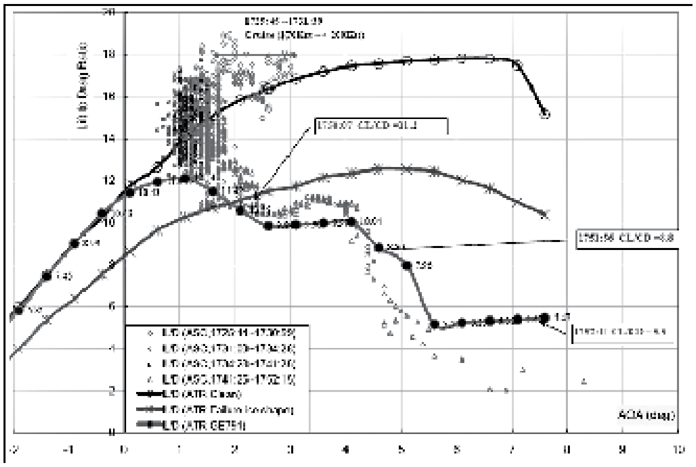


*Figure 6. The lift-drag ratio of GE791 due to ice accretion versus true AOA.*

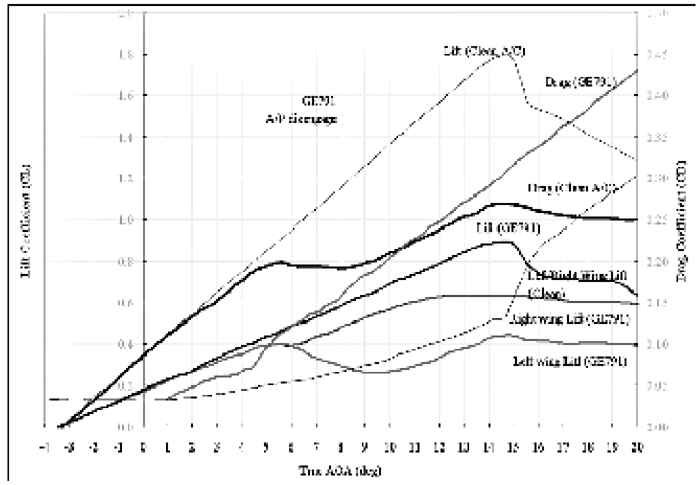


*Figure 7. GE791 FDR data plot during the roll upset.*

During this stage, icing accretion caused about a 20% decrease in the lift-drag ratio.

**(b) 0145:20-0150:30**

At 0144:47 (3 minutes 25 seconds after the second single chime), the indicated airspeed was 188 knots. At this moment, CM1 mentioned, "It's iced up quite a huge chunk." During the next 4 minutes, no discussion in the cockpit on icing was recorded.

From 0145:20 to 0147:30, the airframe deicing system continued "ON," and the indicated airspeed resumed from 188 knots to 192 knots. The indicated airspeed was maintained at 190±2 knots until 0148:26. From 0148:27 (7 minutes after the second single chime) till 0150:30, the indicated airspeed decayed from 191 knots to 174 knots. At this moment, CM1 mentioned, "Wow, it's a huge chunk." Figure 5 indicates at 0149 that the extra drag due to ice accretion increased about 100 counts, and increased continuously thereafter with a faster rate until the autopilot disengaged.

When the true AOA was greater than 2.2 degrees (after 0150:17), the lift-drag ratio was below critical condition (failure ice shape) as shown in Figure 6. At 0150:30 (9 minutes after the single chime), the indicated airspeed decreased to 174 knots, the extra drag due to ice accretion increased about 200 counts, the lift-drag ratio was 10, true AOA was 3 degrees, and pitch attitude was 3.5 degrees. During this stage, the ice accretion caused about a 39% decrease in the lift-drag ratio.

The ATR performance analysis report (Ref. No. 2) draws similar conclusions. This phenomenon was a clear sign that GE791 encountered a severe icing condition worse than icing certification requirements of FAR/JAR 25 Appendix C.

**(c) 0150:30-0152:11**

At 0151:21, the indicated airspeed decelerated to 166 knots, the extra drag due to ice accretion increased about 210 counts, the lift-drag ratio was 10, true AOA was 3.9 degrees, and pitch attitude was 4.0 degrees. During this stage, the ice accretion caused about a 42% loss in the lift-drag ratio.

At 0151:49, CM1 mentioned, "Sixteen thousand." Two seconds later, CM2 contacted the Taipei Area Control Center: "Taipei control trans Asia seven nine one request descend maintain Flight Level one six zero."

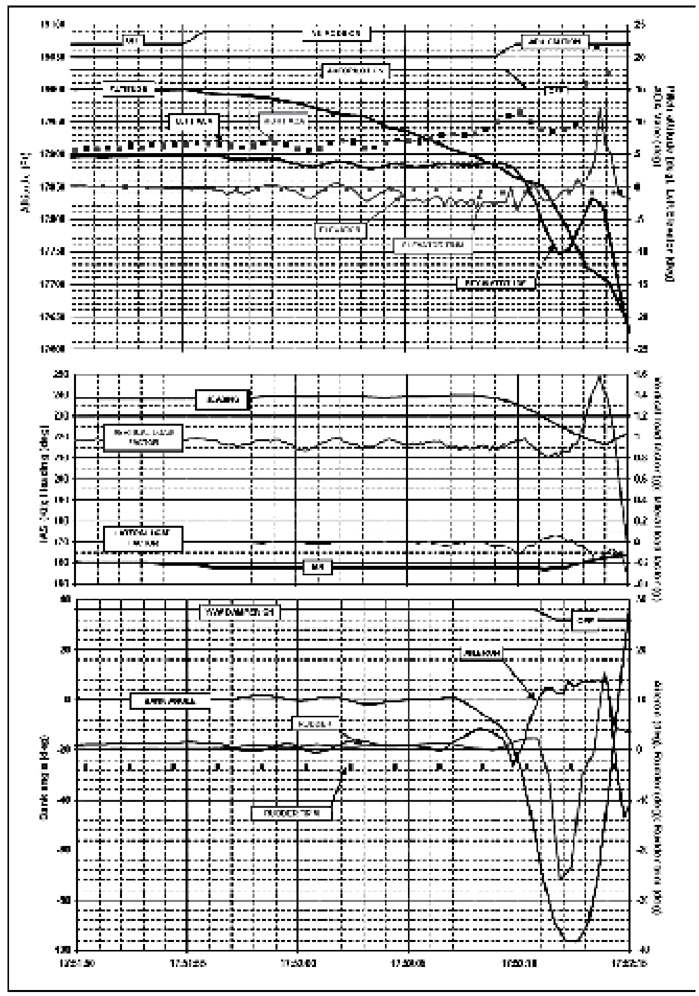

*Figure 8.The lift and drag coefficients versus true AOA (ATR 72 clean and GE791 ice polluted).*

**Beginning of the descent** (Refer to Figure 7)

At 0151:56 according to the FDR readout data, the crew initiated its descent. The aircraft began to lose altitude (about 6 ft/second), and the speed decayed to 159 knots. The extra drag due to ice accretion increased about 360 counts, the lift-drag ratio was 8, the true AOA was 5.0 degrees, and the pitch attitude was 4.8 degrees. During this stage, ice accretion caused about a 50% loss in the lift-drag ratio.

**At 0151:56-0152:07**
Despite an increase of the descent rate (to about 720 ft/minute) at 0152:05, the indicated airspeed was 158 knots. The selected vertical speed (VS) stopped the speed decay but was insufficient to increase airspeed.

From 0152:07 up to the autopilot being disengaged (0152:10.5), the aircraft began banking to the left (with 5.6 degrees roll rate) despite an autopilot aileron order (up to 4.4 degrees, then reduced to 2.5 degrees) to counter this roll to the left.

At 0152:10.5, the indicated airspeed was 158 knots. At 0152:11, the lowest airspeed value of 157 knots was recorded. The extra drag due to ice accretion increased about 500 counts, the lift-drag ratio was 5.5, true AOA was .3 degrees, and the pitch attitude was 2.0 degrees. During this stage, the ice accretion caused about a 64% loss in the lift-drag ratio. The indicated airspeed decayed from176 knots (minimum severe icing speed) to 158 knots in 1 minute and 50 seconds.

*3.3. Performances during roll excursion*
After the autopilot was disengaged, GE791 entered the roll excursion and rapid descent, as indicated in Figure 7.

Figure 8 shows the drag and lift versus true AOA computed during the speed decay and the roll excursion. It can be observed that at about 4.5 degrees of true AOA, the severity of the ice induced flow separation on the wing, which caused a loss in lift and an increase drag.

At about 5.5 degrees of true AOA and few a seconds before the autopilot was disengaged, the loss of lift and the increase in drag clearly indicate that the left wing of GE791 is entering a stall. The drag and the loss of lift continued to increase up to the maximum AOA (at 0152:14, 15.07 degrees true AOA). From the activation of stickpusher (at 0152:13.75, 12.83 degrees true AOA) until maximum AOA, the AOA decreased rapidly. Due to the time delay to recover from lift, the flow remained separated on the wing—inducing a further additive drag of 600 counts.

## IV. Conclusions
Performance analysis results reveal that significant icing occurred after 01:31, supporting evidence includes the acceleration fluctuation (light to moderate), drag increase of about 15 counts, higher echo intensity of weather radar, and TRMM satellite observation data. At 0132:35, the flight crew first observed the ice on the side window, and then activated the airframe deicing system.

When GE791 encountered ice accretion at FL180, the drag increase caused an airspeed decay by 10 knots in the first 25 minutes and a drag increase of 100 counts (the equivalent of an increase of 35% of aircraft drag than normal flight conditions).

The amount of drag increased of about 500 counts 4 minutes prior to the autopilot being disengaged (equivalent to +170% of drag increase than normal flight condition), and the airspeed decayed to 158 knots. Prior to the autopilot being disengaged, the aerodynamic behavior of the aircraft (lift/drag) was degraded about 40%.

Based on CVR/FDR data, and performance analysis, the Aviation Safety Council believes that GE791 most likely encountered severe icing condition worse than icing certification requirements of FAR/JAR 25 Appendix C. ◆

Table 1 appears on the following page.

## Reference
GE791 Occurrence Investigation Report, "In-flight Icing Encounter and Crash into the Sea, Transasia Airways Flight 791, ATR 72-200, B-22708, 17 kilometers Southwest of Makung City, Penghu Islands, Taiwan. December 21, 2002" ASC Report No.ASC-AOR-05-04-001, April, 2005.

## Endnotes
PPI:1 Plan Position Indicator.
TRMM:2 Tropical Rainfall Measuring Mission.
3 Amber caution light and icing AOA light.

## Table 1. Previous ATR 42 and 72 Incidents/Accidents1994-2002

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Date occurred | 1994/10/31 | 1998/12/14 | 1999/1/7 | 2000/1/28 | 2000/6/12 | 2002/5/2 | 2002/12/10 | 2002/12/21 |
| A/C model | ATR 72-212 | ATR 42-300 | ATR 42-300 | ATR 42-300 | ATR 72-200 | ATR 42-400 | ATR 42-400 | ATR 72-200 |
| Investigation agent | NTSB | BFU | NTSB | BFU | ATR | ATR | ATR | ASC |
| Before event-autopilot | ENGAGE | ENGAGE | ENGAGE | ENGAGE | ENGAGE | ENGAGE | ENGAGE | ENGAGE |
| Event alt. FL | 80 | 135 | 30 | 30~ 60 | 170 | 160 | 166 | 180 |
| Event airspeed (knots) | 184 | 155 | 142 | —— | 175 | 153 | 146 | 157 |
| Flap position (degrees) at the event | 15 -> 0 | 0 | 30 | 0 | 0 | 0 | 0 | 0 |
| Minimum icing speed corresponding to A/C flight condition | 157 | 148 | 118 | 148 | 155 | 153 | 154 | 166 |
| Minimum severe icing speed corresponding to A/C flight conditions | 167(*) | 158(*) | 128(*) | 158 | 165 | 163 | 164 | 176 |
| Event AOA (degrees) | 5.2 | 11 | -1.2 | 7 | 5 | 8 | 10.4 | 11.2 |
| AOA/SP icing alarm threshold | 11.2 / 15.3 | 11. / 21.55 | 11. / 21.55 | 11. / 21.55 | 11.2 / 15.3 | 11.2 / 15.3 | 10.4 / 13.5 | 11.2 / 15.3 |
| Visual cues reported | N/A | side window cue | side window cue | side window cue | side window cue | N/A | side window cue | side window cue |
| Flight phase | initial descend after holding | climb | approach | climb | cruise | capture cruise FL | climb | initial descent after cruise |
| Ice effects on aerodynamics | aileron hinge moment | asymmetric stall | elevator pitch down | no event | asymmetric stall | asymmetric stall with moderate roll | asymmetric stall | asymmetric stall |
| Ice protection system | Level III | Level III | Level III | Level III | Level II | Level III | Level III | Level III |
| Airframe deicing Activated | 25 min | 12 min | 22 min | 8 min | OFF | 17 min | 12 min | 18.5 min |
| A/C model hardware status | BASIC | CONF=1 | CONF=1 | CONF=1 | CONF=1+2 | CONF=1+2 | CONF=1+2 | CONF=1+2 |
| A/C model procedure status | BASIC | PROC.=1 | PROC.=1 | PROC.=1+2 | PROC.=1+2 | PROC.=1+2+3 | PROC.=1+2+3 | PROC.=1+2+3 |
| % Drag count due to icing conditions. | 40 | 500 | 500 | 400 | 150 | 520 | 480 | 500 |
| Probable cause | A/C loss of control, attributed to a sudden and unexpected aileron hinge moment reversal that occurred while in holding at flap 15 degrees after a ridge of ice accreted beyond the deice boots. | The crew lost the control after the A/C entered and continued operation in severe icing conditions for which the A/C is not certified. The crew had failed to associate icing of the forward side windows with the severe icing phenomenon. | During approach phase the crew noticed ice shapes on the side windows and A/C deceleration. The A/C was flying in identified severe ice conditions (visual cues). A moderate pitch down and roll occurred when flap extended to 30°. | The A/C had entered atmospheric conditions of severe icing for which it is not certificated. Application of the AFM procedures implemented for such encounter, allowed the flight crew to exit these severe icing conditions and to continue a safe flight and landing. | After prolonged exposure to icing conditions with the airframe de-icing OFF, the A/C lost 25 Knots of speed followed by a mild roll of 15°. | A/C encountered the icing conditions during climb. The crew noticed ice shapes on the side windows and decreasing rate of climb. The non application of AFM severe icing emergency procedure led the A/C to angle of attack where aerodynamics anomalies appeared. The crew action of quickly reducing the AOA recovered a normal situation. | The crew noticed ice shapes on the side windows and decreasing rate of climb continued operation in severe icing conditions and stalled with uncommanded roll excursion. | The A/C had entered atmo-spheric conditions of severe icing for which it is not certificated. The non-application of AFM severe icing emergency procedure, which led the A/C to stall AOA. |

Level II = Anti-ice ON and Level III = Airframe deicing ON

CONF 1 = External wing boots extended + flap extension allowed above VFE

CONF 2 = Median wing boots extended + AAS new flashing logic

PROC 1 = Side window cue + Hold prohibited in icing with flap extended + exit and recovery procedures

PROC 2 = Minimum icing +10 knots when severe icing + new severe icing cues : Decrease of speed or ROC

PROC 3 = Deicing ON at first visual indication of ice accretion and as long as icing conditions are present

(*) for reference only: introduced by DGAC AD 1999-015-040(B) R1 (reference to Proc.2)

# Are the ACAS /TCAS Safety Improvements Sufficient?

By Dipl. Ing. Johann Reuss, Bundesstelle für Flugunfalluntersuchung
(German Federal Bureau of Aircraft Accidents Investigation)

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ACAS II (known as TCAS II) is a last-resort safety net designed to prevent mid-air collisions. It alerts the flight crew and provides Resolution Advisory (RA) maneuver indications when it computes a risk of collision. TCAS should increase the safety of air transport.

But we know that in one of the major accidents in Europe this last-resort safety net was not successful. TCAS was not able to prevent a mid-air collision.

Nowadays a major question is: Are the TCAS safety improvements sufficient?

## The mid-air collision

On July 1,2002, a collision between a Tupolev TU154M, which was on a flight from Moscow, Russia, to Barcelona, Spain, and a Boeing B-757-200, on a flight from Bergamo, Italy, to Brussels, Belgium, occurred north of the city of Ueberlingen (Lake of Constance). Both aircraft flew according to IFR (instrument flight rules) and were under control of ACC Zurich. After the collision, both aircraft crashed into an area north of Ueberlingen.

A total of 71 people were on board the two airplanes, none of whom survived the crash.

The German investigation team (BFU ) identified the following immediate causes:

- The imminent separation infringement was not noticed by ATC in time. The instruction for the TU154M to descend was given at a time when the prescribed separation to the B-757-200 could not be ensured anymore.
- The TU154M crew followed the ATC instruction to descend and continued to do so even after TCAS advised them to climb. This maneuver was performed contrary to the generated ACAS/TCAS RA.

The following systemic causes have been identified:

- The integration of ACAS/TCAS II into the system aviation was insufficient and did not correspond in all points with the system philosophy.
- The regulations concerning ACAS/TCAS published by ICAO, and as a result the regulations of national aviation authorities, operational and procedural instructions of the TCAS manufacturer, and the operators were incomplete, not standardized, and partially contradictory.
- Management and quality assurance of the air navigation service company did not ensure that during the night all open workstations were continuously staffed by controllers.
- Management and quality assurance of the air navigation service company tolerated for years that during times of low traffic flow at night only one controller worked and the other one retired to rest.

## TCAS investigation

An essential part of the investigation done by the German Federal Bureau of Aircraft Accident Investigation (BFU) was the investigation of TCAS. The accident was not prevented even though both airplanes were equipped with TCAS II, Version 7. One of the major questions in this investigation was Why was TCAS not able to prevent the mid-air collision?

Based on the results of the technical TCAS investigation,

- the TAs and RAs in both airplanes were triggered according to the design of the CAS logic,
- the B-757-200 complied with the RA, and
- the TU154M crew did no comply with the RA.

The resulting question was Why did the TU154M crew not follow the TCAS instruction?

The answer to this question was found in the areas of human factors and regulations. The regulations concerning TCAS published by ICAO (Annex 2, Annex 6, Doc. 8168,…) and, therefore, also regulations of national aviation authorities and operational and procedural instructions of the TCAS manufacturer and the operators were incomplete, not standardized, and partially contradictory.

**For example:**

Annex 2:
In Annex 2 (Rules of the Air) procedures for the utilization of TCAS were not sufficient and allowed room for interpretation. The wording concerning TCAS allowed a deviation from the right-of-way rules in case of a TCAS RA. It did not make clear the required consequent action to be taken by the pilot in case of an RA.

Annex 10:
The note "*Contrary pilot response" […]* was adequate and clear. However, its placement in Annex 10 was unfavorable as this An-

nex contains mainly technical specifications. A better place for this instruction would have been Annex 2 or Doc. 8168.

Doc. 8168, PANS-OPS:
The procedures were insufficient and unclear.
With the statements "*assists pilots in operation of the aircraft*" and "*Nothing in the procedures shall prevent pilots-in-command from exercising their best judgment and full authority in the choice of the course of action to resolve a traffic conflict*" ( 3.1.1. and 3.1.2 of Doc. 8168) the pilots were given freedom of decision, which according to the TCAS philosophy must not be granted.

TCAS 2000/TCAS II Traffic Collision and Avoidance System Pilots Guide:
The specifications of the TCAS manufacturer's "Pilots Guide" regarding the TCAS system philosophy and the necessary procedures that ensure a safe function were not described distinct enough. The wording "*TCAS 2000 is a backup to the ATC (Air Traffic Control) system and the "see and avoid concept*" could be interpreted that ATC takes priority over TCAS and that TCAS is designated to be implemental or a substitute. It was not made clear in the description of the system philosophy that TCAS is exclusively meant as a "last line of defense" for the avoidance of a collision and that in this stage TCAS advisories must be disconnected from instructions given by ATC controllers.

TCAS 2000 Pilots Guide does not state clearly enough that the safe separation accomplished through ATC and the tasks of TCAS are two different functions. It is not clear that TCAS is not part of the conceptual design of ATC.

TU154M Flight Operations Manual:
The passage "*For the avoidance of in-flight collisions is the visual control of the situation in the airspace by the crew and the correct execution of all instructions issued by ATC to be regarded as the most important tool. TCAS is an additional instrument that ensures the timely determination of oncoming traffic, the classification of the risk and, if necessary, planning of an advice for a vertical avoidance maneuver*" made clear that ATC has the highest priority in the avoidance of collision risks.

### Safety recommendations

To solve the above-mentioned problems, the BFU has released the following TCAS-related safety recommendations:

*Safety Recommendation No. 18/2002 (released on Oct. 1, 2002)*
ICAO should change the international requirements in Annex 2, Annex 6, and PANS-OPS (Doc. 8168) so that pilots flying are required to obey and follow TCAS Resolution Advisories (RAs), regardless of whether contrary ATC instruction is given prior to, during, or after the RAs are issued. Unless the situation is too dangerous to comply, the pilot flying should comply with the RA until TCAS indicates the airplane is clear of the conflict.

The BFU has released on May 19, 2004, the following safety recommendations:

*Safety Recommendation No. 06/2004*
ICAO should ensure that rules and procedures regarding ACAS are uniform, clear, and unambiguous. Compliance should be ensured in the ICAO Annexes 2, 6, the PANS, and the guidance material. The procedure for pilots should include the following elements:

In the event of an ACAS Resolution Advisory (RA) to alter the flightpath, pilots shall:
- respond immediately and maneuver as indicated, unless doing so would jeopardize the safety of the airplane.
- never maneuver in the opposite direction to an RA, nor maintain a vertical rate in the opposite direction to an RA.

*Safety Recommendation No. 07/2004*
ICAO should ensure an high level of acceptance and confidence of pilots in ACAS by improving education and training. Therefore, the Attachment B to State Letter AN 11/19-2/82 should be transferred in a PANS (Procedures for Air Navigation Services).

*Safety Recommendation No. 08/2004*
To enhance the performance of ACAS ICAO should initiate the development of down-linking RAs to ATC, using such technologies as SSR Mode S and Automatic Dependent Surveillance-Broadcast (ADS-B).

*Safety Recommendation No. 16/2004*
Utilizing its own mechanism and international resources available, ICAO should ensure that all ACAS/TCAS users are consistent in their response to the equipment advice. ICAO auditing processes must pursue compliance with its ACAS SARPs and training objectives at all levels within the aviation industry.

*Safety Recommendation No. 15/2004*
The Federal Aviation Administration (FAA) should ensure that the TCAS 2000 manufacturer rephrases the TCAS 2000 Operating Manual to reflect the TCAS system philosophy and the international TCAS regulations and operating procedures in a unambiguous and consistent manner.

### Responses to the safety recommendations by ICAO

In light of these recommendations, the Air Navigation Commission at the first meeting of its 167th session in October 2004, considered proposals for the amendment of Annex 2–*Rules of the Air* and authorized their transmission to Contracting States and appropriate international organizations for comment.

The proposed amendment to Annex 2 is envisioned to be applicable from Nov. 23, 2006.

The intent of two safety recommendations above had been fulfilled by Amendment 12 to PANS-OPS, which became applicable on Nov. 27, 2003. As part of amendment 12 of the PANS-OPS, the guidance material has been superseded by pilot training guidelines introduced into attachment A to Part VIII of PANS-OPS, Volume I.

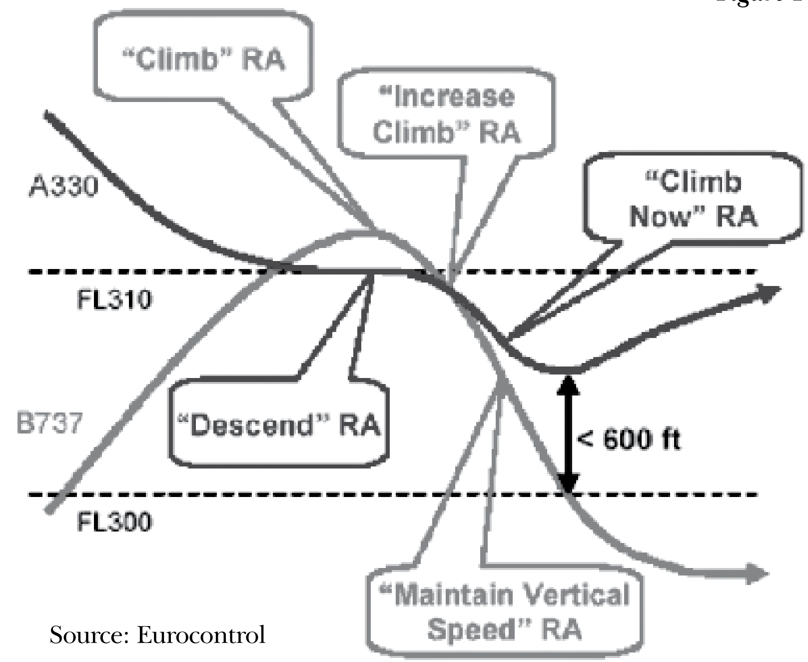
The feasibility of downlinking RAs is under review by the Surveillance and Conflict Resolution Panel (SCRSP) of the Commission.

ICAO will ensure that all ACAS users are consistent in their response to the indications of the equipment and that ICAO auditing processes pursue compliance with ACAS standards and recommended practices (SARPs) and training objectives at all levels within the aviation industry.

### Incidents after the Ueberlingen accident

The accident in Ueberlingen triggered an intense discussion regarding the philosophy, functioning and limitations of TCAS. At the latest with the publication of the investigation report it be-

*Figure 1*




Source: Eurocontrol

came clear that with TCAS, procedural compliance is of utmost importance. A safety hazard appears when a crew does not comply with a TCAS RA or even reacts contrary to it.

Even after the Ueberlingen accident, the BFU received reports of several incidents and serious incidents where pilot reactions regarding TCAS RAs were either wrong or not ideal.

*Example 1:*
On June 28, 2005, an Airbus A319 on a flight from Moscow to Amsterdam had received clearance to descend from FL340 to FL260. They traveled in the upper northern German airspace. A French transport-category airplane on a flight from Paris to St. Petersburg was on a conflicting track. The ATC controller did not see it on his radar. The controller was made aware of it by an STCA (Short Term Collision Avoidance) indication. He instructed both airplanes to fly an evasive maneuver. The Airbus A319 complied with the ATC instruction. The airplane on the conflicting track, however, did not but followed a TCAS instruction.

Why just one of the two aircraft complied to the TCAS instruction is subject of an ongoing investigation.

*Example 2:*
Due to a coordination problem between two sectors, a Boeing B-737 was cleared to climb to FL320 against an A330 that had been cleared to descend to FL310 on a conflicting track.

The controller issued late instructions to the B-737 to descend immediately to FL320.

Simultaneously, both aircraft received coordinated RAs: the A330 had a "descend" RA and the B-737 a "climb" RA.

The A330 flight crew immediately informed the controller and initiated a descent whereas the B-737 flight crew decided to ignore their "climb" RA "*since [they] had intruding aircraft visual.*" Instead, they continued a steep descent while initiating an evasive turn.

The maneuver of the B-737 in the opposite direction to the "climb" RA forces both TCAS units to reverse the RA directions. As a result, the minimum distance is 0.9 nm at less than 600 ft according to radar data and 300 m at the same level according to the B-737 pilot, who filed an airprox.

Simulations conducted by Eurocontrol indicated that if the B-737 flight crew had followed the "Climb" RA, the vertical distance would have been greater than 800 ft, and there would have been no reversal RAs nor subsequent altitude crossing.

This event occurred in February 2004, after the PANS-OPS had been revised to avoid such scenario**.**

## FODA (Flight Operation Data Analysis)

After the collision near Ueberlingen and the subsequently triggered discussion regarding TCAS problems, several airlines have taken data from ordinary flight operations and analyzed them with the help of FODA. This was undertaken in order to get some information regarding the frequency of TCAS RAs and their compliance.

The analysis of one airline, for example, showed that

- in about 3% of all TCAS RAs, initial navigation occurred in the wrong direction,
- in more than 6% of all TCAS RAs no reaction at all occurred, and
- in 5% of all TCAS RAs, only a heavily delayed reaction occurred.

It is of importance that crews of this particular airline had been sensitized regarding TCAS events and that procedures had been established and reactions to TCAS indications had also been trained during simulator sessions.

Analysis of the flight data indicates that this is not about consciously ignoring TCAS RAs but rather a misunderstanding und misinterpretation of TCAS indications.

The predominant amount of observed cases were RAs with the indication "Adjust Vertical Speed." "Adjust Vertical Speed" always asks for a reduction of the vertical speed, which means a flattening of the flightpath. However, the instruction "Adjust Vertical Speed" could be interpreted to mean increase or decrease vertical speed.

## Misinterpretation of the TCAS philosophy

Even though philosophy and importance of TCAS have been clearly communicated after the accident near Ueberlingen, the analyzed data show in some cases a wrong understanding of TCAS indications.

Experience has shown that in some cases, flight crew are tempted to make their own traffic assessment based on the traffic display information and to maneuver in anticipation of ATC instructions.

The TCAS traffic display can be misinterpreted since it provides only partial information, it has limited accuracy, and it is based upon a moving reference. It has not been designed for the purposes of self-separation or sequencing, and using it for these purposes is inappropriate and could also be hazardous.

## Safety-related conclusions

The above-mentioned accident in Germany, the very similar serious incident in Japan (Jan. 31, 2001) and several incidents after the fatal accident have turned out that there is a need for a TCAS improvement. The aviation industry, the authorities, organizations, and TCAS users have to understand and consider the following conclusions:

• In case of failure by ATC to provide safe separation between aircraft, TCAS provides an *independent* safety net in preventing mid-air collisions.

• TCAS is an effective system, but its ability to fulfill its role is entirely dependent on correct and timely flight crew responses to collision avoidance maneuvers calculated and displayed by the system.

• The procedure for pilots has to include the following elements:
—In the event of an TCAS Resolution Advisory (RA) to alter the flightpath, pilots shall respond immediately and maneuver as indicated, unless doing so would jeopardize the safety of the airplane.
—Never maneuver in the opposite direction to an RA, nor maintain a vertical rate in the opposite direction to an RA.

• The regulations concerning TCAS published by ICAO and as a result the regulations of national aviation authorities, operational, and procedural instructions of the TCAS manufacturer have to be standardized, clear, and unambiguous.

• Pilots should be aware of the updated TCAS procedures and know how to apply them correctly, through reinforced training.

• TCAS is not a "plug and play system." There is a need for a good aircraft system integration and design of displays. Training including simulator training for pilots is inalienable.

• The mission of aviation safety investigators should be
—to be aware of still-existing TCAS problems,
—to investigate and analyze TCAS occurrences, and
—to communicate safety-related deficiencies and improvements. ◆

## References

BFU Final Report AX001-1-1-2/02
Eurocontrol ACAS II Bulletins No. 5 and No. 6

# Flight Data Analysis— A New Approach

By Dieter Reisinger, Quality Manager Flight Operations, Austrian Airlines, Vienna, Austria; Simone Sporer, Psychologist, FH Joanneum/University of Applied Sciences, Department of Aviation, Graz, Austria; and Gernot Knoll, Electronic and Communication Engineer, FH Joanneum/University of Applied Sciences, Department of Aviation, Graz, Austria

***Dr. Dieter Reisinger*** *is a pilot with Austrian Airlines and holds the position Quality Manager Flight Operations since 2001. Before his career as an airline pilot, Reisinger worked as an aeronautical engineer in research. He has a safety background as a former Head of Flight Safety for Lauda Air. He has received training at TU München, Universität der Bundeswehr München, and he is presently working on his M.Sc. in flight test engineering and evaluation at NTPS, Mojave, U.S.A. Reisinger has logged more than 5,000 flight hours with type ratings on CRJ, B-737, and B-767 aircraft. (Dr. Reisinger made the seminar presentation.)*

***Simone Sporer*** *received a master of science in psychology at the Karl-Franzens-University in Graz, Austria, in 2002. She is currently employed as a scientific research assistant in the Department of Aviation at the University of Applied Sciences in Graz, Austria. Her main field of activity is in flight safety, especially with threat management and human error of pilots. She is simultaneously working on her doctoral degree in psychology at the Karl-Franzens-University in Graz, Austria. Her Ph.D. thesis is concerned with decision-making and mental workload of pilots. (Photo not available.)*

***Gernot Knoll*** *received his Dipl. Ing. (FH) at the University of Applied Sciences in industrial electronics in Kapfenberg, Austria, in 2002. His diploma thesis was written on the topic of Baluns for mobile applications in cooperation with EPCOS in Deutschlandsberg, Austria. From 2002 to 2004, he worked at CTR (Carinthian Tech Research) AG. His main field of activity was in high-frequency measurement and antenna design for passive SAW-sensor devices. He is currently employed as a scientific assistant in the Department of Aviation at the University of Applied Sciences in Graz, Austria. He is simultaneously working on his doctoral degree in engineering. (Photo not available.)*

## Abstract

Research is presently being conducted that allows pilots to do their own flight data analysis. The advantage is that pilots can add crucial information such as threats, threat management, error, and error management to the flight data. The idea is that each pilot runs his personal statistics; in the desire to strive for a perfect flight, a self-improving process will be initiated. There are certain problem areas, such as efficient data transfer, data security, and suitable data entry. The system does not substitute present flight data monitoring (FDM) programs but rather intends to complement them.

## 1. Introduction

Flight Data Analysis (FODA), the method of retrieving data from an aircraft data recorder and performing a post-flight analysis for the purposes of detecting operational exceedances or to detect unfavorable engineering data, has been in use with major airlines for a rather long period. British Airways, Air France, and Lufthansa are among the first who used the FODA method. FODA celebrated its 30-year anniversary not too long ago. The requirement for flight data analysis is reflected in the International Civil Aviation Organization (ICAO) Annex 6. As part of ICAO standards and recommended practices (SARPs), the organization already has issued a recommendation that suggests aircraft with a maximum takeoff weight (MTOW) greater than 20 tons (44,100 pounds) be part of a flight data monitoring program. It went into effect January 2005. Under Annex 6, Part 1, ICAO now intends to make the recommendation a standard, applicable to aircraft with a MTOW greater than 27 tons (59,535 pounds). The recommendation would still apply to aircraft weighing between 20 and 27 tons.

Among safety experts, FODA is a well-agreed method and is one cornerstone in an airline safety management program. FODA comes under different names; sometimes the term FDM (flight data monitoring) or FOQA (Flight Operations Quality Assurance) is used, although the latter term implies more then just flight data analysis.

Despite being an accepted method, today's FODA, in the opinion of the authors, has some significant disadvantages. The goal of this paper is to point out these and present an idea on how the system could be improved with the aim to make a contribution to the safety statistics.

## 2. Drawbacks of present-day FODA

One of the drawbacks of today's FODA is the fact that any analysis depends on what has happened in the past. First an operational exceedance has to have occurred before it can show up in a statistics. Therefore, strictly speaking, FODA is not a proactive way of enhancing safety. No doubt that it is much more proactive than the traditional "kick-the-tin" approach that dominated the early days of accident investigation. However, it would be nice to have a truly proactive tool (see Figure 1 and Figure 2). In Figure 1, a typical FODA process is shown; in Figure 2 the modified FODA process is shown.

A second disadvantage is the fact that the statistics typically do not take into account the individual pilot's weak spots. In other words, the data cannot be customized and, therefore, a training program cannot be tailored to the specific needs of a pilot. This needs some further explanation: A typical process of how the data are handled through the airline departments is depicted in Figure 1. A line maintenance engineer typically retrieves the data storage media (optical disk, PCMCIA card, etc.) at a prescribed interval, e.g., after arrival at the home base. Then the data are fed into a

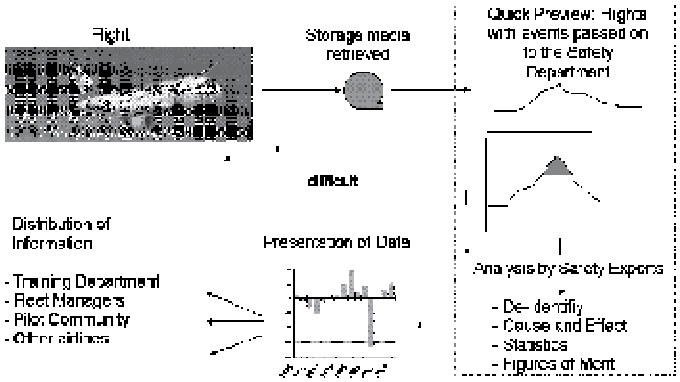



***Figure 1. Typical FODA process. After quick preview, files with exceedances are passed to the flight safety department for detail analysis. Deidentified data are then distributed.***

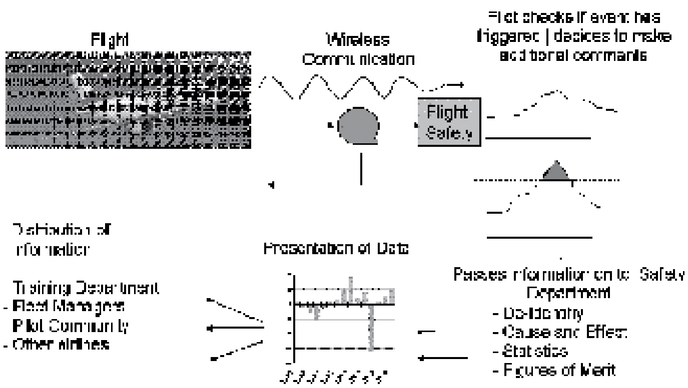



***Figure 2. Modified FODA process. The pilot adds data before they are deidentified and passed on to the flight safety department. The pilot keeps his personal statistics.***

server and a scan is performed for operational exceedances. Those data sets containing exceedances are passed on to the safety department, where a number of specialists, typically with the involvement of type-rated pilots, look at the event, classify it, and run statistics. The results are then in most cases either passed on for internal safety magazines, as a guideline for those who design simulator sessions in flight training departments, or in some cases shared among other airlines.[1] All this by no doubt is valuable.

This process takes time, which leads to the third disadvantage: Today's FODA process, from the occurrence to the point where the end-user (the pilots) gets results, is lengthy.

A fourth disadvantage is the fact that in many cases there is no information on threats[2], threat management, errors[3], and error management as done by the crew (for definition: the University of Texas Human Factors Research Group, 2005). Basically, this is because in most airlines, due to union constraints, the data are deidentified. The safety department in many airlines cannot establish a direct line of communication with the crew that experienced the exceedance.[4]

Klinect et al (1999) took data from operational safety audits and came to the following interesting conclusions. The highest percentage (39%) of external threats was in the descent/approach/landing phase of flight, 22% of the external threats occurred before the aircraft left the ground in the preflight/taxi phase of flight (see Table 1). Furthermore, at least 72% of flight segments had at least one external threat. The distribution of flight crew errors by phase of flight (see Table 2) shows the most flight crew errors also

***Table 1. External Threats by Phase of Flight (Klinect et al, 1999)***

| *Phase of Flight* | *Percentage of External Threats* |
|---|---|
| Preflight/Taxi | 22% |
| Takeoff/Climb | 28% |
| Cruise | 10% |
| Descent/Approach/Land | 39% |
| Taxi/Park | 1% |

***Table 2. Distribution of Flight Crew Errors by Phase of Flight (Klinect et al, 1999)***

| *Phase of Flight* | *Percentage of Errors* | *Percentage that Were Consequential* |
|---|---|---|
| Preflight/Taxi | 23% | 7% |
| Takeoff/Climb | 24% | 12% |
| Cruise | 12% | 12% |
| Descent/Approach/Land | 39% | 21% |
| Taxi/Park | 2% | Insufficient data |

occur in the descent/approach/landing phase of flight.

## 3. FODA—the new approach

As of today, more and more airlines equip their pilots with modern laptop computers for obvious reasons: performance calculation, information sharing, electronic library (see Figure 3). These powerful machines could easily handle the post-flight data analysis of one's specific flight. The idea is to give the pilot the data, let him do the analysis, and rely on his self-evaluation capability. In addition, the pilot could add information such as threats, threat management, errors, and error management. Further, he could run his personal statistic and see if unfavorable trends on his part develop. This could then further lead into "custom tailored" simulator sessions.

IATA operational safety audit (IOSA), Standard ORG 3.3.3, by the way, prescribes that an operator should have a program to gather safety data through systematic observations of flight crew performance during normal line operations. In the opinion of the authors, the suggested method could be an acceptable one but not the only means to meet that standard.

### *3.1. Ability for self-evaluation*

Most pilots we have met try to do a perfect job. They have a passion for their profession and strive for no less than a perfect flight. It seems intrinsic to a pilot's nature to attempt to ever enhance his skills. If something goes wrong, here we do not mean an accident, but rather a minor imperfection, a lapse or slip (Reason, 1990), an operational exceedance, or anything that in sum could lead to an incident, pilots tend to know very accurately why things went wrong and what they could have done better. A good example is the debriefing of a simulator session: when asked by the instructor, a pilot will typically recall most of his mistakes even over a 4-hour simulator session and will be inclined to see his performance worse than the other individuals would do.[5] In other words, without scientific proof, pilots seem to be able to critically self-evaluate their own performance.

### *3.2. Flight experience issue*

In general, experience in terms of total flight hours is a key figure. Pilots with more total hours are generally regarded to be more competent compared to those with fewer hours. So what, if any, is the value of letting a very experienced pilot do a self-analysis?

It is generally known that even very experienced pilots are not immune to mistakes, to bad decisions, to disregarding aircraft limitations, etc. They might at times even have difficulty with the handling of the aircraft. Certainly, even among experienced pilots unfavorable trends can develop, such as a tendency for landing long in an attempt to land soft, flying approaches to the limits, etc. These tendencies will go undetected—with typically only two to four simulator sessions a year and only one annual line check, it is highly unlikely that an outsider, such as a check pilot, picks up an unfavorable trend on these rare occasions. Crews are composed of ever-different combinations of first officers and captains, so even a peer will not be able to detect a trend and let the other pilot know (apart from the fact that very likely a first officer would not debrief a captain in most airline cultures on these issues, unless the captain asked for feedback). One person who for sure can tell whether unfavorable trends develop, provided he has the right tool, will be the individual pilot himself. So in summary, it seems that giving the flight data to pilots, from the student pilot to the experienced pilot, will have its merits.

### *3.3. Threat and errors*

Why is it essential to feed FODA data with threats and errors? This is best highlighted by some real-life examples, where today's FODA program would very likely give a wrong clue or insufficient background information, unless the pilot is brought into the loop.

**Example 1**

The pilot accepts a short line up by the air traffic control (ATC). The option would be a delaying vector due to heavy inbound traffic. Due to high energy, the approach is unstabilized.

Note: FODA will only show an unstabilized approach and the fact that the aircraft turned in early at exceedingly high energy; it will not tell that the short line up was offered by ATC and that it was accepted because the pilot wanted to avoid undue track miles with subsequent higher flight time (commercial pressure).

**Example 2**

late landing configuration (300 ft above aerodrome level [AAL]) during instrument landing system (ILS) approach—the pilot flying (PF) thought that the DME distance (distance measuring equipment) is reading to the threshold when in fact the station was 2 miles behind the runway. PF started configuration change too late. Initial crosswind turned into a tailwind, increasing during descent.

Note: FODA will only show late configuration/unstabilized approach but will not be able to detect the wrong mental picture of where the DME is located.

**Example 3**

The aircraft lands overweight.

Note: FODA will show the overweight landing. It will not show that the pilot decided prior to departure to tanker fuel for economic reasons and overlooked that he would have less fuel burn with ATC shortcuts.

**Example 4**

The VOR-DME approach was flown to the left of the inbound radial, with the aircraft generally too high and too fast, with a high sink rate almost until touchdown.

Note: FODA will show all of the above. It will not, however, tell that the pilots, after reading the preflight checklists, decided to clean their windscreens. In doing so, the window heat was turned off and was never turned back on. During descent, the window fogged up. Also, in the approach there was a discussion with ATC about what the correct inbound radial should be (the approach chart was in error). Thirdly, with a major shortcut, the aircraft started high. The discussion with ATC led to late configuration and resulted in a slightly higher altitude over the initial approach fix, which—together with the partly fogged up windshield—caused the less-than-perfect approach.

These real-life examples show that when FODA data are enhanced with pilot information, not only will the statistics still be produced, but the enhanced data will also be useful in decision-making courses," typically part of a captain's course.

### *3.4. Additional advantages*

It seems that pilots develop a special ability to recall details of their flights well until after landing. For example, a pilot would surely remember that he almost exceeded a maximum bank angle of 30 degrees and was only "saved" by the proper callout of the pilot monitoring (PM) with his "check bank!" With today's FODA, the great benefit of SOPs cannot be proved, simply because a FODA will only show the exceedance, but not the approach to an exceedance: Giving the data to the pilot would enable us to mark out those phases of flight (and add comments) where such standard operation procedures (SOPs) were helpful.

A further advantage lies in the fact that we do not have to worry so much about proprietary data and confidentiality. The pilot produces the data; therefore, why shouldn't he own it?

## 4. Challenges to face

### *4.1. The pilot flying (PF)—pilot monitoring (PM) issue*

Surely, one would not like if the other pilot had access to data that show your own mistakes. So the question arises, whether the crew, the PF, or the PM should have access to the flight data on a specific leg. Technically the easiest thing would be to give both pilots the same data set and not have to worry about how to separate that data. The logic behind this is that whenever something goes wrong, be it minor, it is the crew who failed to do a proper job (crew resource management issue). Clearly, it has to be ensured with high confidence levels that data of previous flights are not accessible to later crews.

### *4.2. The data transfer issue*

Owning a laptop and having installed a flight data acquisition unit, an optical disc recorder, etc., on the aircraft is one thing, retrieving the data efficiently and timely is another. Wireless trans-

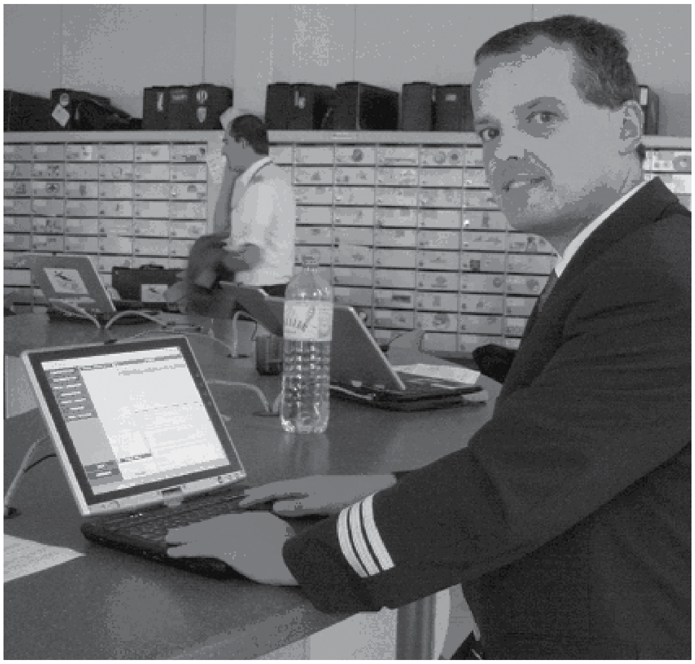


*Figure 3. Typical electronic information exchange. First officer is checking latest information with his laptop during preflight preparation.*

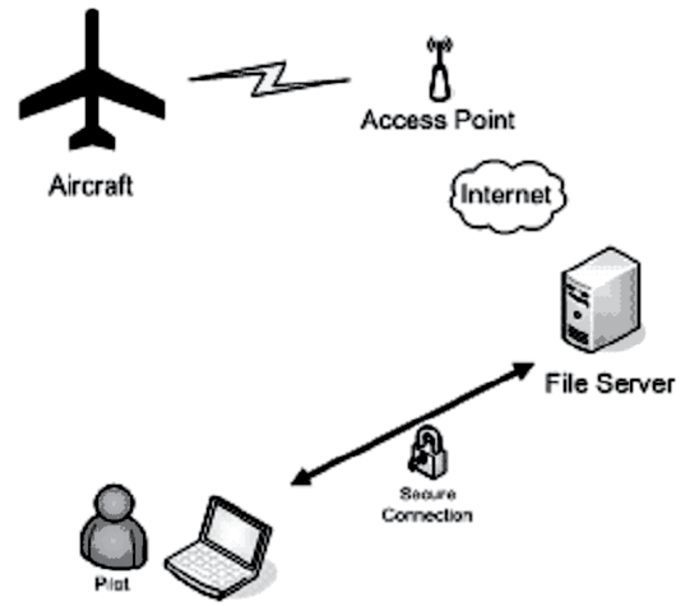



*Figure 4. Data transfer via WLAN access point at the airport.*

fer seems to be the ideal method, and in some airlines a global system for mobile communication (GSM) solution is already in place (however, this is a transfer between aircraft and the safety department, not the individual pilot). Because of its importance, the issue is dealt with in more detail below. (See Figure 3.)

### 4.2.1. Data transfer

In most airlines, the standard flight data transfer is done by staff. After landing, typically at the home base, a maintenance technician or in some cases flight safety personnel change the storage media and deliver it to a central data acquisition office. This process is fairly typical for optical disks or PCMCIA cards, which then need to be administered.

One company (Teledyne Controls) supplies WQARs (wireless quick access recorders). The system is called Wireless GroundLink©. It includes four to eight cell phones for data transfer and is already in use with some airlines, e.g., Ryanair. With such units, the transfer of data can be completed in 10-15 minutes after the aircraft has landed. Drawbacks of today's GSM are high cost and slow data transfer. Another transfer method is via wireless local area network (WLAN) interface from the aircraft to an access point on the airport. Avionica[6] supplies a WLAN QAR for transfer data over 802.11b (IEEE WLAN wireless local area network standard). The system offers a secure link from aircraft to company server (see Figure 4).

### 4.2.2. Data safety and encryption

Systems that enable efficient encryption of the data transfer between QAR and a server at this stage are still expensive. Public key (RSA-encryption) or a universal serial bus (USB) Hardware key could be used for access control once the data are on the server so that only the individual pilot gains access to his flight data. A typical general process for handling data after landing could be

1. Sort data—allocated data with flight number—select data that

*Figure 5. Research simulator at FH Joanneum/University of Applied Sciences, Graz, Austria.*

are relevant to pilots.
2. Encrypt data—pilot has the key on his laptop.
3. Access by pilot via Internet.
4. Data analysis by pilot (comments, threat and error management, deidentify, etc.).
5. Analyzed data transferred back on to server.

### 4.3. Outlier data

Quite often, spikes due to faulty transducers will appear as operational exceedances. Clearly, such "ghost events" must be reduced to avoid frustration among those doing the analysis.

### 4.4. Rapid input of comments

If pilots enjoyed writing lengthy text they would have chosen to be authors. In general, pilots do not like to spend much time in debriefings. So how should the data be retrieved, analyzed for exceedances, information be added and personal statistics be kept all within short time? One way would be to limit the need for free text and rather offer standard solutions for threats, threat management, errors, and error management. Klinect et al (1999) has developed a list of typical threats that flight crews face for the LOSA program that he developed. This could be useful.

#### *4.4.1. Pattern of evaluation*

The pilot's task is to comment the exceedances after the flight in a standardized way. In addition a pattern of evaluation has to be provided. With this pattern of evaluation, the causes of exceedances can be received. The already-mentioned threats and errors are considered as causes for parameter deviations. Until now it is not possible to identify all kinds of threats that have influence on the flight progress, e.g., wind conditions can be analyzed on the basis of the technical data; however, risky ATC requests can not be detected in the flight data. Commenting the parameter exceedances with consideration of the time axis (temporal process and exceedance in agreement) makes it possible to specify the time when countermeasures are initiated, the concrete kind of countermeasure, threats, or errors that almost lead to an exceedance (a deviation that is not yet classified as exceedance).

The development of the pattern of evaluation: There exists the possibility to provide a pure listing of possible causes (threats, errors) that, however, do not provide us with information about the mentioned recovery measures and the connection between deviation and recovery. Therefore, an alternative approach was chosen. Commenting is done over a time axis (as described). By the representation of temporal operational sequence it will be possible to receive the additional information specified above. Thus the cause for an exceedance is better analyzed. The disadvantage consists of the fact that no exhaustive categorization can be made at this point. Therefore, in the test-phase increased free text inputs are necessary. They will extend the predefined categories to a final standardized pattern of evaluation. After the end of the test phase the free text inputs should only capture a small part besides the standardized pattern of evaluation.

#### *4.4.2. Flight simulation study*

A flight simulation study is in progress to describe an event-time-diagram as the basis for the design of the pattern of evaluation (see Figure 5). This implies that the event-time-diagram will be the base for the creation of category formation as well as for the software's structure. Scenarios were developed, which can reproduce as far as possible a realistic flight progress. Different threats are integrated in the scenarios, e.g., unfavorable radar vectors, adverse weather. To lead pilots to errors is more difficult. Some threats are presented in a way that they can provoke errors, e.g., minimum decision altitude at ceiling. In the study particularly, two methods are applied that supplement each other—behavior observation and interview. In order to achieve the goals regarding the event-time-diagram and category formation, different background questions have to be answered.

Since human data processing is subject to all actions and reactions, our research is based on the model of human information processing of Wickens and Hollands (2000). The model provides a general framework for analyzing human performance.

One point consists of whether the flight crew perceives threats and errors during the flight and when they perceive them. Perception means to decode the meaning from raw sensory data (Wickens & Hollands, 2000), e.g., the deflection of the CDI (course deviation indicator) is not only a deviation of a coefficient but conveys the meaningful message "Danger, you are leaving the primary area!"

Another topic is how threats and errors are appraised. Is a threat always perceived as a threat right away? Perhaps some threats for some of the pilots are not threatening—they are just like routine operations. Some reactions (in our case threat management) are carried out almost automatically. For definitions in skill and rule-based and knowledge-based behavior, the reader is referred to Rasmussen (1983, 1986).

Even if threats are perceived correctly, there is a likelihood that a pilot happily accepts the threat in order to show his skills. In other words, he might be well aware of the situation and even without an obvious benefit (e.g., accepting a shortcut although the flight arrives early) takes up the challenge. In a classification, it would be necessary to look into the motivating factors.

Another question deal with the reaction that is shown regarding a threat or an error, as well as consideration of the background. The understanding of a situation, achieved through perception and augmented by cognitive transformations, triggers the selection of a response (Wickens & Hollands, 2000).

A last point is the general issue of whether the pilots were aware of the situation. "Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." (Endsley, 1995, p. 65). Situation awareness involves a correct appreciation of many conditions. The most relevant aspects in aviation are three-dimensional spatial awareness, system (mode) awareness, and task awareness (Wickens, 2002).

#### *4.4.3. Usability of the user interface*

So that time-saving commentating of exceedances is possible, apart from a standardized pattern of evaluation, a user friendly graphical user interface also is required, in which the pattern of evaluation is embedded.

The user interface will be examined and reviewed, to what extent it agrees with certain usability (Nielsen, 1998) principles. An example of these principles is the list of heuristics of Molich and Nielsen (1990).

- Simple and natural dialogue.
- Speak the user's language.
- Minimize the user's memory load.
- Consistency.
- Feedback.
- Clearly marked exits.
- Shortcuts.
- Precise and constructive error messages.
- Prevent errors.
- Help and documentation.

#### *4.5. Visualization*

FODA data are typically presented in x-y-plots, with time running along the x-axis. It takes a good deal of expertise to analyze graphs with multiple parameters shown on the y-axis (see Figure 6). In order to make things easier for the pilot who does a self-evaluation, a visual presentation of the instrument panel seems to be the preferred method of presenting data (see Figure 7).

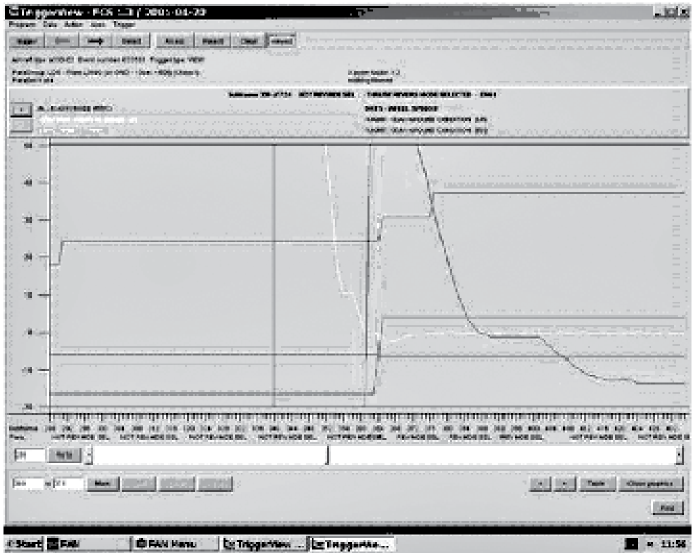


*Figure 6. Typical FODA print—multiple parameters on y-axis running along time.*

## 5. Conclusion

A new method of proactive data collection and analysis has been described. The idea is to give the pilot access to his flight data and let him enter threat- and error-specific information with the aim of gaining a deeper insight into why certain decisions were made. Rather than just running statistics across an entire fleet, a pilot runs his personal statistics with the aim of tailoring his training. ◆


## Acknowledgements

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*Figure 7. Visualization of operational exceedances will be the preferred method for displaying data to pilots.*

## Notes

1 A good example of information sharing is the pilot's reaction to the Traffic Collision Avoidance System (TCAS) Resolution Advisories; one major airline found a high number of reactions opposite to the TCAS RA command, causing other airlines to define trigger parameters and look for such events.

2 A threat is defined as an event or error that occurs outside the influence of the flight crew, increases the operational complexity of a flight, and requires crew attention and management if safety margins are to be maintained (the University of Texas Human Factors Research Group, 2005).

3 Flight crew errors are defined as a crew action or inaction that leads to a deviation from crew or organizational intentions or expectations (the University of Texas Human Factors Research Group, 2005).

4 The authors are well aware of the fact that in some airlines the Union itself does the analysis and will approach pilots individually to ask specific questions.

5 Partly this seems to be the case because pilots generally do not want to look better than they actually are, especially when talking to peers.

6 http://www.avionica.com/about_us.html.

# A Case-Based Reasoning (CBR) Approach for Accident Scenario Knowledge Management

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## 1. Introduction

Safety has always been a major concern throughout the history of aviation. One can even argue that the history of aviation has the same time line as the history of aviation safety research. However, as we look back and reflect on the accidents that have shaped modern aviation, as Guzzetti and Nicklas indicated, the old saying, "the more things change, the more they stay the same" continues to reveal itself through several landmark accidents that have redefined aviation safety [1]. In other words, there are *patterns* repeating themselves throughout the history of aviation accidents.

We may elaborate on this observation by arguing that studying the "types" of accident cases—not necessarily investigating "the" accident—has potential to contribute significantly to aviation safety research. What we have basically stated above is that aviation professionals—in particular, accident investigators—have been observing patterns in the causal interactions among the factors that contribute to separate accidents that have happened at different times.

Identifying these patterns and using them in a hybrid expert system to assist with causal modeling of aviation accidents is the objective of our study. The user profile for this expert system includes a broad spectrum ranging from the novice safety researcher with no particular background in aviation to the experienced aviation accident investigator.

Given an accident scenario, through a set of questions whose answers are inputs by the user to the computer, the case-based application determines a list of candidate cases (i.e., solution possibilities) that are retrieved from the accident case library with certain relevance factors attached to them. In other words, the retrieved cases are ranked with respect to their similarity to the current accident scenario.

This research and the prototype Case-Based Reasoning (CBR) tool as its final product is envisioned as a supplement to the research of the Aviation System Risk Model (ASRM) (Luxhøj et al, 2003) [2, 8, 9, 19] funded by the Aviation Safety Program Office (AVSP) of NASA under the contract numbered NAS1-03057. While overseeing the research and development of the future products and technology to improve aviation safety, the AVSP program office [3] had a pressing question: What is the anticipated safety impact of these technologies on the National Aviation System (NAS)? The ASRM research is set to address this question.

The analytical approach employed by the ASRM requires extensive usage of expert knowledge due to the lack of standardized hard data on aviation accident precursors and their interactions. Furthermore, due to the highly specialized nature of the subject matter, the experts whose knowledge is utilized are mostly aviation professionals, such as the FAA's aviation safety inspectors, airline pilots, and accident investigators, among others, with specific operational and regulatory backgrounds. Obviously their time is constrained. This reminds us of the fact that knowledge is expensive, especially so for the domain of aviation safety research.

For the past 2 years for the purposes of the ASRM research, approximately 40 separate sessions were conducted with approximately 30 subject-matter experts (SMEs) at more than seven different geographical locations. Considering this relatively high cost of expert knowledge, the motivation behind the current research originates from the legitimate need to make the expert knowledge more feasible. In this context, we searched for answers to the following two related questions.

- Can the knowledge elicited from the SMEs be reused?
- How can the existing knowledge base of the ASRM be capitalized on?

The answer lies within the concept of expert systems. In broad terms, expert systems are computer applications that mimic a human expert's reasoning process to assist the decision-making and problem solving [4]. A case-based reasoning approach is selected for the current research to address the two questions mentioned above and to build the expert system. In a nutshell, Case-Based Reasoning (CBR), as a paradigm for building expert systems, is based on previous observations and its process is to remember and adapt or to remember and compare [5].

The objective of this research can be summarized briefly as to build a CBR expert system that, given an accident scenario, uses previously elicited knowledge in the ASRM, in the absence of the SMEs, to achieve results comparable to the ASRM's. These results are first to identify candidate NASA/AVSP products pertinent to the accident scenario and their impact on the accident precursors and second to identify accident causal models with partially populated conditional probability numbers.

The content of the initial seed for the case base of the prototype CBR is derived from the causal models or Bayesian Belief Networks (BBNs) of the 15 accidents that had been modeled in accordance with the ASRM process. The resulting prototype CBR tool can be considered as a hybrid expert system since it is composed of two different applications with different inference engines following different approaches of reasoning. The application (SpotLight™)[6] providing the user interface and the reasoning engine is a case-based system and it operates at a higher level as the main body of the expert system. Below the surface there is another application (HUGIN™)[7] that basically supplies the case library (or case base) to the upper level application. HUGIN™ is a BBN software to facilitate accident modeling by building up the knowledge base and to support knowledge acquisition from the SMEs.

## 2. Aviation System Risk Model (ASRM)

The ASRM is a risk-based decision support system prototype designed to evaluate the impacts of new safety technologies/interventions upon the aviation accident rate. An analytic generalization framework is employed throughout the process to develop an approach to model the multifaceted interactions of causal factors. Bayesian probability and decision theory are used to quantify the accident causal models and to evaluate the possible impacts of new interventions. The entire process is supported by expert judgments. Subsequently, the analytical methodology is packaged as a probabilistic decision support system. The subsequent decision support system is aimed to assist the evaluation of the possible impact of new technologies on aviation system safety [2, 8, 9, 19].

The current research benefits quite extensively from the analytical methodology used in the ASRM especially in the areas of accident causal modeling and a taxonomy of casual factors. In essence, most of the accident causal models developed earlier for the purpose of the ASRM are used as initial seeds for the case library (i.e., case base) for the prototype CBR decision support tool. Additionally, the indexing methodology developed for encoding accident cases into the case base of the prototype tool capitalizes the Human Factors Analysis and Classification System (HFACS) taxonomy as a starting point. However, the resultant CBR decision support tool delivers a new approach for accident causal modeling and candidate technology/intervention selection.

In the following section, we briefly discuss the approach employed throughout the ASRM study to model aviation accidents into Bayesian Belief Networks (BBNs) that, consequently, are used as initial seeds for the case base of the prototype CBR tool.

### 2.1. Accident causal modeling process in the ASRM

As mentioned above, our domain of study is civil aviation. In particular, the prototype expert system built on the CBR approach is an expert system for causal modeling of aviation accidents. Thereby, the expertise needed to form the knowledge base (i.e., case base) comes from experts in the aviation field. During our study, while building the knowledge base, we had the opportunity of gaining access to highly qualified specialists from various departments of the Federal Aviation Administration (FAA) through many hours of sessions.

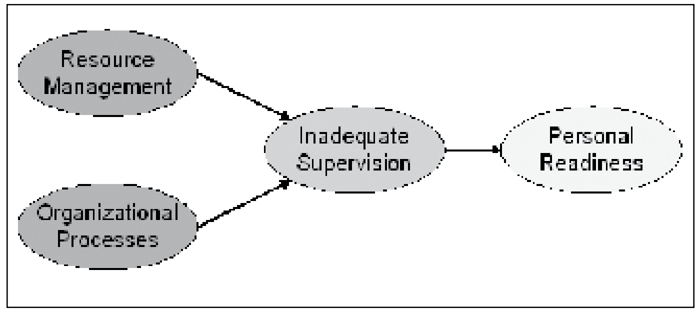


***Figure 1. Sample fragment of a typical BBN model.***

The knowledge elicitation process employed by the ASRM approach during these sessions is divided into two major elements or phases. In the first phase, using the National Transportation Safety Board (NTSB) accident final report as the starting point, the main effort focuses on structuring the causal modeling of the accident with causal factors determined and interactions between causal factors established. Throughout this phase, Bayesian Belief Networks (BBNs) are used as the modeling tool for the accident causal modeling. The second half (i.e., phase) of the session is devoted to eliciting conditional probabilities to populate the conditional probability tables (CPTs) of the BBNs developed in the first phase of the session.

***Case selection:*** The accidents that have been used to comprise the knowledge base of the ASRM were chosen among the U.S.-registered civilian aircraft accidents that occurred between 1990 and 1996. All the aircraft involved in these accidents were operated under either one of the three major FAA regulations, CFAR Part 121 (for scheduled commercial aviation), CFAR Part 135 (for unscheduled commercial aviation) or CFAR Part 91 (for general aviation), that govern almost all the civilian aviation traffic of U.S.-registered aircraft operated within or out of the U.S. airspace.

Furthermore, the accidents have been selected considering their "representativeness" of the body of civil aviation accidents. Overall, 20 accident case studies have been included in the knowledge base of the ASRM: four cases from the accident category "Loss of Control" (LOC), four cases from the accident category "controlled flight into terrain" (CFIT), three for "maintenance," three for "engine failures" (EF), three for "Runway Incursion," and three for "general aviation" (GA). However, as far as the case base for this research is concerned, only 15 accidents among these 20 are selected for inclusion as the initial seeds of the CBR tool. In particular, all GA cases and one case from each of the LOC and EF accident suites are excluded.

***Causal modeling:*** In the ASRM, the causal modeling of the individual accident is performed by means of Bayesian Belief Networks. For this purpose, a commercial BBN software (HUGIN) is used. To construct the causal model, the NTSB report of the accident in question is scrutinized. Causal factors mentioned in the NTSB reports as conclusions or findings are used as the building blocks of the causal model. To facilitate the causal modeling, the Human Factors Analysis and Classification System (HFACS) taxonomy is used throughout the modeling phase. A sample fragment of a typical causal model in the form of a BBN is presented in Figure 1.

The analytical modeling approach used in the ASRM is composed of five consecutive steps:

*i. Determine and describe the case scenario.*

In the first step, the accident case is selected through analysis of the FAA/NTSB accident database or through simply following the suggestions of the SMEs who are involved in the knowledge elicitation sessions. Usually, during this selection phase a one-page accident synopsis retrieved from the database is reviewed, if possible, with the SMEs who will be involved in the upcoming knowledge elicitation session.

*ii. Identify causal factors.*

Once the case-based scenario (i.e., the accident to be modeled) is selected, a preliminary model is built with causal nodes and links in place, to initiate and facilitate the meeting. This approach has been adopted after several trials where experience indicated that if the SMEs were introduced with a blank sheet to build the causal model, the knowledge elicitation process becomes inefficient and the resulting model does not facilitate further analysis, simply because different cases modeled by different groups of SMEs cannot be compared since SMEs do not use a common taxonomy for identifying the same causal factors. Therefore, in order to set some sort of anchor for the SMEs, HFACS is employed as the taxonomy for causal factors. Thus, throughout the session, the SMEs use an extended version of the HFACS, which additionally includes some basic governmental and environmental factors, such as the FAA and weather, to name the casual factors that have been identified for that particular accident case.

*iii. Construct influence diagram.* (See Figure 2.)

Once the SMEs determine the casual factors to be included in the causal model, the next step is to establish casual relations between individual factors. These relations or links between factors may not necessarily be a direct one. Since a link between casual factors is in fact a probabilistic relationship, there might be multiple paths connecting factors with each other. As a consequence, the number of the links might increase without a boundary if one explores every possible connection between factors within the causal model. Therefore, the SMEs are asked to address and retain only the most significant direct links. Due to an inherent quality of Bayesian Belief Networks, as long as there is a path between casual factors, information in the form of a conditional probability is transferred between them. In other words, if the SMEs identify a link whose existence can only be justified due to a latent relationship between factors, we check whether there exists another path that might address the same latent relationship between them and if it does, we ask the SMEs whether the links that are identified earlier can be replaced with this secondary path. According to the response, we either keep the link or exclude it without sacrificing the latent causal relationship between factors identified by the SMEs and without rendering the causal model too complicated for analysis. After finalizing the causal model, the SMEs select candidate NASA technologies or interventions and determine their impact on the model by identifying interactions between the individual causal factors and technologies. All the modeling is completed using the HUGIN™ BBN software, and all the reasoning behind the causal nodes, links, and the knowledge elicited is documented for future reference.

*iv. Define boundary conditions.*

After the causal model is completed, the next step is to elicit conditional probabilities to complete the Conditional Probability Tables (CPTs), which ultimately leads to assessing the overall likelihood and risk of the case-based scenario.

The process of eliciting the conditional probabilities is rather delicate. In order for the conditional probability numbers to be well-balanced within the context of the case-based scenario, some sort of boundary conditions that basically set an envelope for the number for both the numerator and denominator of the probability are required. These boundary conditions will, of course, be different for individual case-based scenarios but they need also be consistent within the same accident suite. For example, the boundary conditions set for CFIT Case 1 should be, in broader terms, not much different than CFIT Case 2 and CFIT Case 3. Like all the other knowledge included in the knowledge base of the expert system, the boundary conditions are also elicited from the SMEs.

The boundary conditions for an aviation accident case would include the operational conditions at a much higher and broader level rather than a detailed one. An example of a boundary condition is a typical medium-sized airline operator whose flight operations are on average conducted under FAR Part 121. This particular boundary condition will assist the SMEs to visualize the structure of the organization and scope of the operations under which the accident aircraft including its flight and cabin crew were operated. Another boundary condition would be the governing environmental conditions at the time of the accident, such as day or night, normal or severe weather conditions.

*v. Elicit conditional probabilities.*

Following the boundary conditions, the probability elicitation phase of the process begins. In this phase, SMEs are asked to provide probability numbers for every individual conditional probability comprising the conditional probability tables. However, since the process and the method used during the probability elicitation falls beyond the intentions of the current research, no further details have been supplied within this document. Luxhøj and Kuturu (2004) provide the details of the probability elicitation process.

## 3. The case base

The process of accomplishing a complete accident causal model through the ASRM approach is neither quick nor simple. Although the process itself is well-structured and supported with sound analytical research, every single causal model in ASRM is the product of long hours of discussions within the research team and carefully managed sessions with the SMEs [8, 9, 10, 19].

Our CBR approach aims to capitalize on the knowledge base of the ASRM, namely the 15 accident causal models, by using them as initial seed values for its case base. Thereby, without using the same analytical method, the CBR system would be able to use the knowledge base inherited from the ASRM to produce solution possibilities for any accident scenario query. Ultimately, the system retrieves cases from its case base as solution possibilities in terms of how similar they are to the current accident, for which a causal model is sought after.

For the purposes of this research, an "initial seed" case base is composed of "complete causal models" of 15 ASRM accident cases and some "clusters of causal factors" derived form these 15 accident models. These cases are selected from five different accident categories representing the majority of commercial civil aviation accidents. The five accident categories and the accidents composing them are as follows:

*Controlled flight into terrain*

• Case # 1: Aloha Island Air, Inc., Flight 1712, De Havilland Twin Otter, DHC-6-300, N707PV, Halawa Point, Molokai, Hawaii, Oct. 28, 1989.

• Case #2: Controlled Collision with Terrain. GP Express Airlines, Inc., Flight 861, Beechcraft 699, N118GP, Anniston, Alabama, June 8, 1992.

• Case # 3: Controlled Flight into Terrain. American Airlines Flight 965, Boeing 757-223, N651AA, Near Cali, Colombia, Dec. 20, 1995.

*Loss of control*

• Case # 1: Loss of Control. Air Ontario Flight 1363, Fokker F28 1000, Dryden Airport, Ontario, Canada, March 10, 1989.

• Case # 2: Uncontrolled Impact with Terrain. Fine Airlines Flight 101, Douglas DC-8-61, N27UA, Miami, Florida, Aug. 7, 1997.

• Case # 3: Takeoff Stall in Icing Conditions. USAir Flight 405, Fokker F-28, N485US, La Guardia Airport, Flushing, New York, March 22, 1992.

*Maintenance*

• Case # 1: Explosive Decompression—Loss of Cargo Door in Flight. United Airlines Flight 811, Boeing 747, N4713U, Honolulu, Hawaii, Feb. 24, 1989.

• Case # 2: American Airlines, Inc., DC-10-10, N110AA, Chicago-O'Hare International Airport, Chicago, Illinois, May 25, 1979.

• Case # 3: Britt Airways, Inc., d/b/a Continental Express Flight 2574 Inflight Structural Breakup, EMB-120RT, N33701, Eagle Lake, Texas, Sept. 11, 1991.

• Case # 4: Inflight Loss of Propeller Blade, Force Landing, and Collision with Terrain, Atlantic Southeast Airlines, Inc., Flight 529, Embraer EMB-120RT, N256AS, Carrollton, Georgia, Aug. 21, 1995.

*Runway incursion*

• Case # 1: Northwest Airlines, Inc., Flights 1482 and 299, Runway Incursion and Collision, Detroit Metropolitan/Wayne County Airport, Romulus, Michigan, Dec. 3, 1990.

• Case # 2: Runway Collision of Eastern Airlines, Boeing 727, Flight 111 and EPPS Air Service Beechcraft King Air A100, Atlanta Hartsfield International Airport, Atlanta, Georgia, Jan. 18, 1990.

• Case # 3: Runway Collision Involving Trans World Airlines Flight 427 and Superior Aviation Cessna 441, Bridgeton, Missouri, Nov. 22, 1994.

*Engine failure*

• Case # 1: Uncontained Engine Failure/Fire, ValuJet Airlines Flight 597, Douglas DC-9-32, N908VJ, Atlanta, Georgia, June 8, 1995.

• Case # 2: Uncontained Engine Failure Delta Air Lines Flight 1288, McDonnell Douglas MD-88, N927DA, Pensacola, Florida, July 6, 1996.

In the initial seed for each accident case, along with the NTSB report, where available, a brief summary is provided. The summary includes factual information about the accident and the NTSB's conclusion regarding the root cause and contributing factors leading to the accident. Following the summary, the BBN models of the accidents are presented in the same format as the

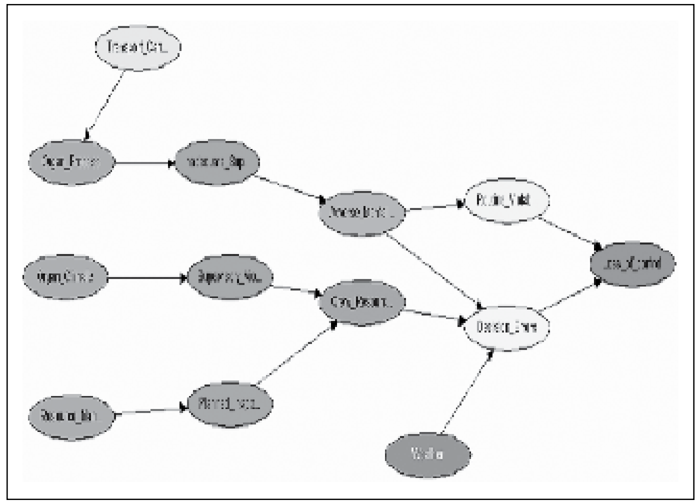

***Figure 2. BBN or causal influence diagram of a representative aviation accident case.***

ASRM, meaning that they are built based on the revised HFACS taxonomy and according to the modeling and knowledge elicitation process described in the previous section and they include some candidate NASA AVSP technologies/interventions.

### 3.1. Clusters of causal factors

The 15 accident cases selected from the ASRM are the source of the content of the initial seed. However, quantitatively, this does not mean that the total number of causal models or cases in the initial seed will only be 15. Luxhøj and Kardes [11] indicated that some of the accident causal models (i.e., BBNs) in the ASRM contain common causal model clusters and argued that a hierarchical BBN approach can be implemented on the current ASRM case library. The current research assumes, by a quite similar way of thinking, that not only the compete causal models of the accident cases in the ASRM but also the clusters of the causal factors derived from a complete causal model can be utilized as a legitimate case for the case base of the intended CBR system.

However, there is another aspect of creating clusters. Most CBR-based applications face, at their early stages of development, a pressing issue. In order for the CBR application to perform up to the expected criteria, the number of cases comprising the initial seed of the case base should demonstrate a certain level of coverage for the domain of interest [12, 13]. In other words, the cases within the initial seed should provide enough exposure with regard to the problem domain. Otherwise the CBR system would not be able to present solutions that are relevant to the current problem [14, 15].

Considering the limited number of accident cases, namely 15, composing the initial seed, its representativeness of the vast aviation accident domain might, in fact, be an issue. As long as the veracity of the performance of the CBR system is concerned, the number of cases per accident suite is more substantive than the total number of cases included in the initial seed. Ultimately, for a "runway incursion" accident scenario a legitimate solution possibility can only be retrieved from the case base among the cases that are also categorized as "runway incursion." A "controlled flight into terrain" case cannot be a legitimate solution possibility for a "runway incursion" scenario. Therefore, due to the compartmentalized nature of the problem domain, the initial seed comprised of 15 cases acts, in fact, as five separate case bases. For the purpose of extending the coverage of the case base only, this research uses causal factor clusters as a legitimate source of cases to be included into the initial seed. To summarize, the case base of the CBR system makes use of the ASRM as its initial seed, by utilizing its knowledge base in two different forms, complete accident causal models and clusters of causal factors.

As the name implies, *complete accident causal models* are the representations of the accident cases as a whole, meaning that all the contributing causal factors and their compounding interactions are identified and all the mitigating technology and/or interventions that may have a possible impact on the accident are determined. The 15 accident BBNs included in the initial seed are complete accident causal models.

When the complete causal models of the accident cases in the ASRM and the methodology to construct them are investigated, one observes *clusters of causal factors* recurring across different cases of existing accident suites. These clusters are patterns in the otherwise unique structure of causal factors of a specific accident.

In the context of the current research, a causal factor cluster is defined as an assembly of causal factors and technology and/or interventions that they by themselves form an acyclic (i.e., unidirectional) graph. However, the combination of causal factors comprising a cluster is not chosen randomly. As discussed above, the recurring patterns within the confines of a particular accident category constitute the theoretical background of the methodology to identify and form a cluster.

The pattern analysis performed in an accident category is quite straightforward. First, the names of the causal factors comprising the causal model of the accidents in a category are listed. Next, the causal factors that recur in all of the cases comprising that specific accident category are identified. Then, the remaining causal factors that are common in any number of accident cases in the category are determined, thereby leaving the causal factors that are unique and specific to a single case out. Figure 3 depicts the results of such an analysis performed on the causal factors of the BBNs of three CFIT accidents from within the initial seed.

The methodology used by this research to identify and form clusters for any given accident category can be summarized as follows. Assuming that there are three accidents constituting the accident category—

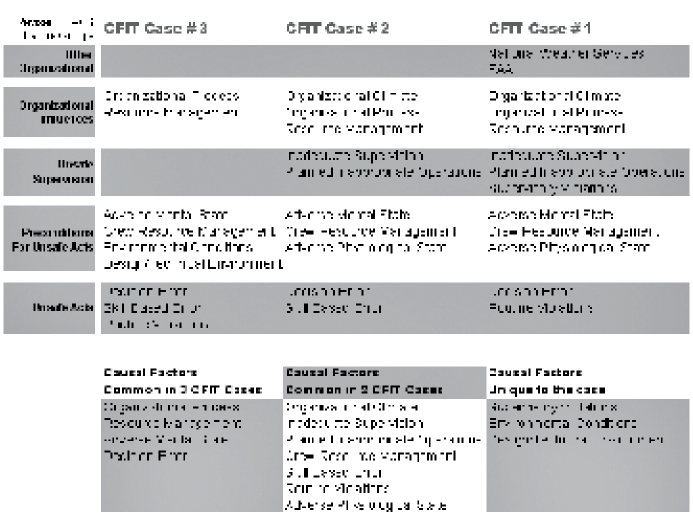


***Figure 3. The list of the causal factors of three CFIT accident models and the categorization of common causal factors.***

- The clusters are formed from the causal factors that are common in all three accident models.
- The links connecting the common causal factors to each other are used to build the basic network structure of the cluster.
- If there exists a gap between the link structure of the cluster, in other words, if all causal factors selected cannot be connected by means of direct links to form a single cluster from the accident model, then a causal factor recurring only in two of the accident models can be utilized to establish the missing link and to form one cluster per accident model. This approach is taken to keep the number of clusters derived from an accident model to a minimum. It also helps to keep the structure of the identified pattern intact. If the structure of the pattern is fragmented, this may hinder the relevancy of the cluster, rendering it useless as a legitimate solution possibility for a given accident scenario of that accident category. If the gap cannot be filled by including causal factors recurring in more than half of the accidents models forming the accident suite (for example, as far as the CFIT accident suite of the initial seed is concerned, this means that the causal factor to be used to fill the gap should be common in two CFIT cases), separate clusters representing the unlinked parts of the pattern can be formed instead of a single cluster. However, one should note that each "partial" cluster should consist of at least two causal factors and one NASA technology/product.
- The NASA technologies linked to the causal factors that are selected to build the cluster are included in the structure of the cluster. In order to declare a cluster as a legitimate solution possibility for the prototype tool, at least one NASA technology/product should be included in the structure of the cluster.
- Finally, if there exists a link connecting the consequence mode in the original accident model to the cluster, it is also included in the cluster.

In this context, three clusters are formed, one cluster per complete CFIT model, and included in the initial seed of the prototype CBR tool's case base. Each cluster is built on the four causal factors identified in Figure 3 as "common in three CFIT cases." The already-existing links between these common clusters are employed to connect them together to form a network. If a gap exists between some causal factors that cannot be connected directly by existing links, one of the seven causal factors identified in Figure 3 as "common in two CFIT cases" is utilized to fill the gap and to form a single cluster from that particular CFIT case. Next, the technologies/products that have direct links to the causal factors comprising the clusters are identified and included in the structure of the cluster. Finally, if there exists a direct link from one of the causal factors in the cluster, the consequence node (i.e., CFIT or mishap node) is also added in the cluster. The clusters that are constructed in accordance with the preceding methodology are presented in Figures 4, 5, and 6, respectively.

As presented in Figure 3, the causal factors that are common across the CFIT accident suite of the ASRM are

- organizational process,
- resource management,
- adverse mental states, and
- decision errors.

The cluster for the CFIT Case # 1 is based on these four causal factors. However, when the existing link structure among these casual factors is investigated, it is obvious that, by using them only, a single cluster representing the common pattern cannot

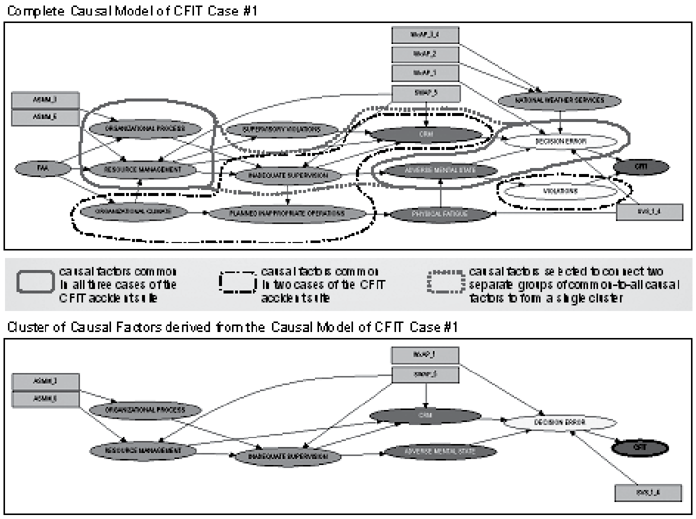


*Figure 4. The cluster derived from the BBN model of the CFIT Case #1 Aloha Island Air Flight 1712.*

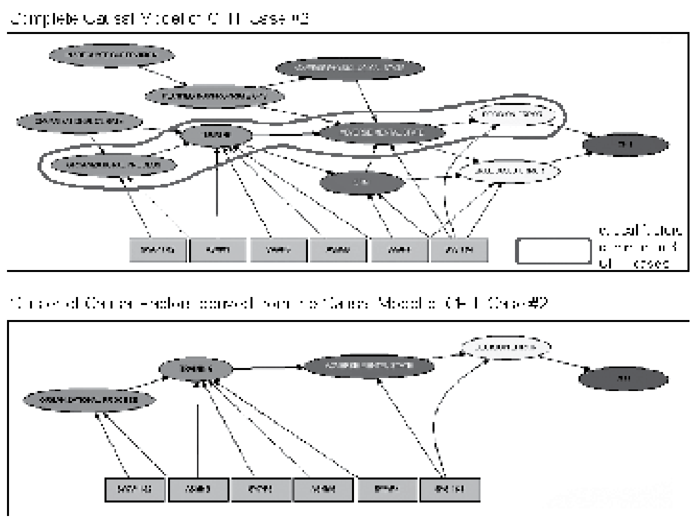

*Figure 5. The cluster derived from the BBN model of the CFIT Case #2 GP Express Airlines Flight 861.*

be constructed. Therefore, the causal factors those repeat in only two cases of the CFIT accident suite are investigated next.

As listed in Figure 3, they are

- organizational climate,
- inadequate supervision,
- planned inappropriate supervision,
- crew resource management (CRM), and
- violations.

When the link structure of the complete model in Figure 4 is studied in detail, one can identify "inadequate supervision" and "crew resource management (CRM)," from the above list, as the causal factors that can be utilized to bridge between the gap of two unconnected groups of common causal factors, namely the gap between the group "organizational process" and "resource management" and the group "adverse mental state" and "decision error." Since both causal factors, i.e., "inadequate supervision" and "crew resource management (CRM)," could be used to bridge the gap, instead of choosing one, both are utilized to form the cluster presented in Figure 4.

The method illustrated in the preceding paragraphs recommends the derivation of only a cluster per accident case, when possible, to utilize the full extent of the power of representativeness that the pattern identified within the accident suite entails.

The cluster formed from the CFIT Case # 2, GP Express Airlines Flight 861, by employing the same methodology is presented in Figure 5.

Notice that, in Figure 5, the four causal factors identified earlier as common across the CFIT accident suite, can easily be connected without introducing any additional secondary causal factor of secondary importance to form a single cluster.

Finally, Figure 6 depicts the cluster derived from the CFIT Case #3, Atlantic Southeast Airlines, Inc., Flight 529. The same situation applies for the CFIT Case #3, and the four common causal factors comprising the recurring pattern within the CFIT accident suite of the ASRM can directly be linked to each other. However, notice that the original structure of the complete causal model for CFIT Case #3 has two separate causal factors for "adverse mental state" and "decision error." Since this redundancy is intentional and had been introduced by subject-matter experts (SMEs) to acknowledge two distinct forms of "adverse mental state" and "decision error" pertinent to the causal structure of the case, it is preserved while forming the cluster.

### 3.2. Composition of the domain model and indexing

In order for the CBR system to recognize the BBN of an aviation accident as it is modeled in the ASRM, the BBN needs to be literally translated into a language that the system understands.

The causal models (i.e., BBNs) in the ASRM present more details about the attributes of the particular aviation accident breadthwise than depthwise. However, this seeming shallowness on the descriptive plane is by design. The ASRM avoids drilling down into the minute details and case-specific attributes of the particular accident, thereby employing the analytic generalization (i.e., inductive) approach [16] as an integral part of its methodology. Analytic generalization enables the ASRM to embark on representative analysis of accident suites, such as determining possible NASA technologies/interventions and anticipating decreases in the accident rate, rather than confining itself within the strict boundaries of the accident case.

However, the correct and accurate representation of the accident, along with the appropriate amount of detail regarding the case-specific attributes of the particular accident in the case base of the CBR system, is crucial. Hence, the approach used by the CBR system is to improve upon the original vertical levels of the ASRM BBN models, thereby boosting the descriptive qualities of the existing ASRM models and to facilitate their inclusion into the case base of the prototype CBR tool. These improved descriptive qualities of the accident models are required for developing a proper indexing scheme and consequently a reliable retrieval process.

This improved process to describe the individual causal factors of the BBN models constitutes the foundation of the indexing methodology to represent individual cases to the case base of the prototype tool. Furthermore, this indexing method also facilitates the retrieval of a candidate case by the CBR tool.

The performance of the CBR system is largely affected by the accident cases included in its case base. We can consider the case base—whatever its content at that particular time is—as the domain of interest of the system, and, therefore, this domain of interest is simply the cases in the case base. On the other hand,

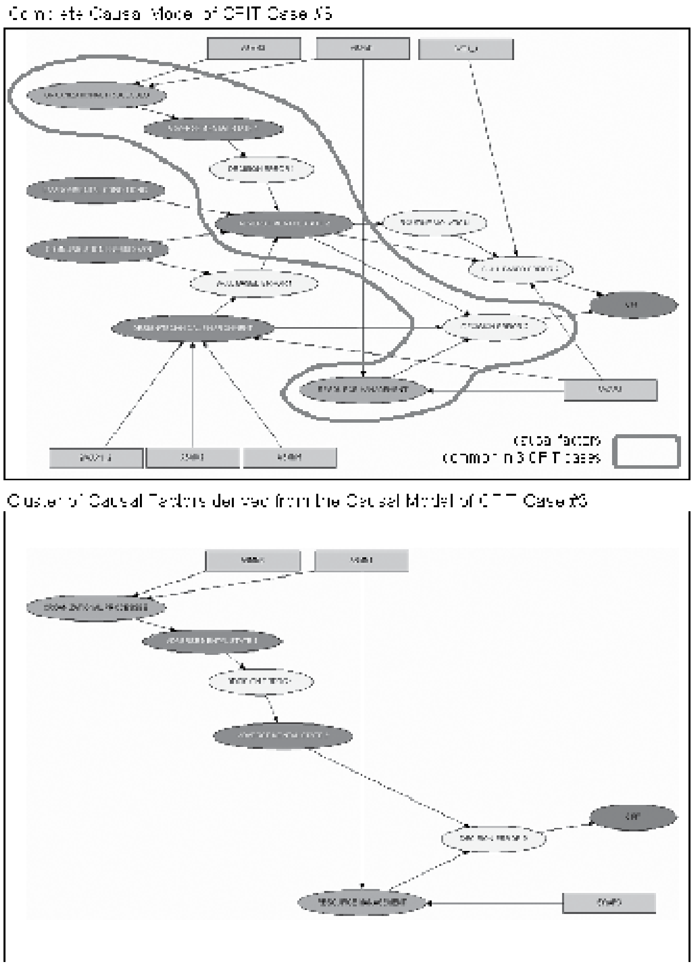


*Figure 6. The cluster derived from the BBN model of the CFIT Case #3 Atlantic Southeast Airlines Flight 529.*

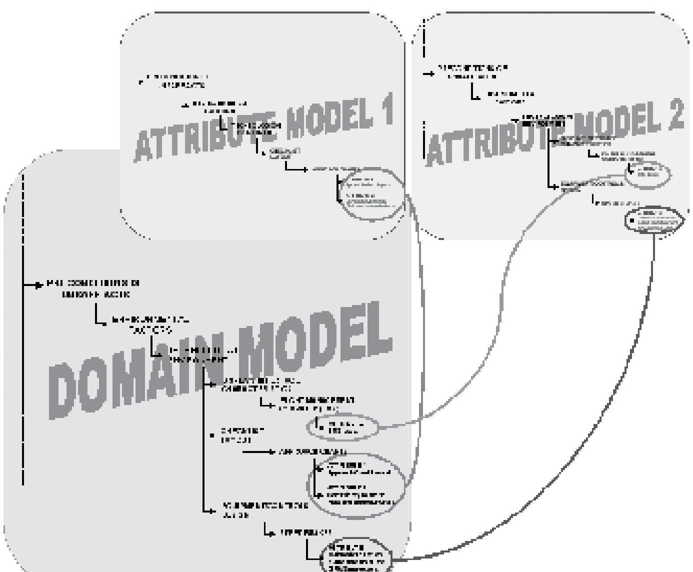


*Figure 7. Composition of the domain model.*

these cases are no longer in the form of a causal model. We can refer to the original causal model in the solution possibility as they are presented by the system, but the original models are exclusively for the use of the system user. In broad terms, we manipulate the BBNs of the ASRM and form, first, attribute models for each BBN and then, merge them in to a meta-attribute model just to encode them in a format that enables us to form a case base for the CBR system. Since the meta-attribute model presents a single, well-structured, yet perpetually improving, hierarchical model for the domain of interest of the tool, in a sense, we let the meta-attribute model define the domain of interest of the system.

The indexing methodology that we use in our research relies heavily on how well and detailed the domain of interest is structured. For this purpose, we developed the domain model approach that combines the concepts of the meta-attribute model and the domain of interest to represent the aviation accident cases that are to be included into the case base.

The domain model (Figure 7) is basically a hierarchical structure of many descriptive branches ending with at least one attribute representing an individual fact or finding with regard to the cases of the case base. Each attribute is followed by a question that, in fact, inquires about that particular attribute. These questions are simple binary logical variables with possible values "yes" or "no." Each accident case can be defined as a set of observations. Observations are attributes with values defined (i.e., the questions pertaining to the attribute are answered). In this context, the questions are employed to facilitate the indexing of individual cases into the case base. They are also utilized to develop a conversational CBR tool with the specific objective of building causal models for aviation accidents.

The above-mentioned methodology for indexing and representing aviation accidents in to the case base of a CBR system is illustrated in detail by Oztekin and Luxhøj (2005) [17].

## 4. The prototype CBR tool

In this section, we focus on the prototype tool itself and its workings. To reiterate, the objective of the current research is to develop a prototype decision support system based on case-based reasoning to assist the aviation accident causal modeling process. The causal modeling process also includes determining candidate mitigating NASA technology/interventions.

### 4.1. The domain and case editors

The domain model is used by our approach as the primary tool to index the individual cases in to the case base. A sample fragment of the actual domain model used by the prototype tool is shown in Figure 8. Each descriptive branch ends with at least one attribute representing the individual failure mentioned in that particular ASRM causal model. Then, each attribute is followed by a question that, in fact, defines the failure (i.e., attribute). These questions forms simple binary logical variables with possible values "yes" or "no," meaning that the particular failure is present or absent in the problem (i.e., accident case) that the user currently investigating.

The questions are also employed to facilitate the indexing of individual cases in to the case base. Each accident case can be defined as a set of observations. Observations are attributes with its value defined (i.e., the questions pertaining to the attribute are answered). A case is indexed in to the case base by following these simple steps.

The attributes corresponding to facts and finding of the accident case are identified within the existing domain model to form a set of attributes defining that particular accident.

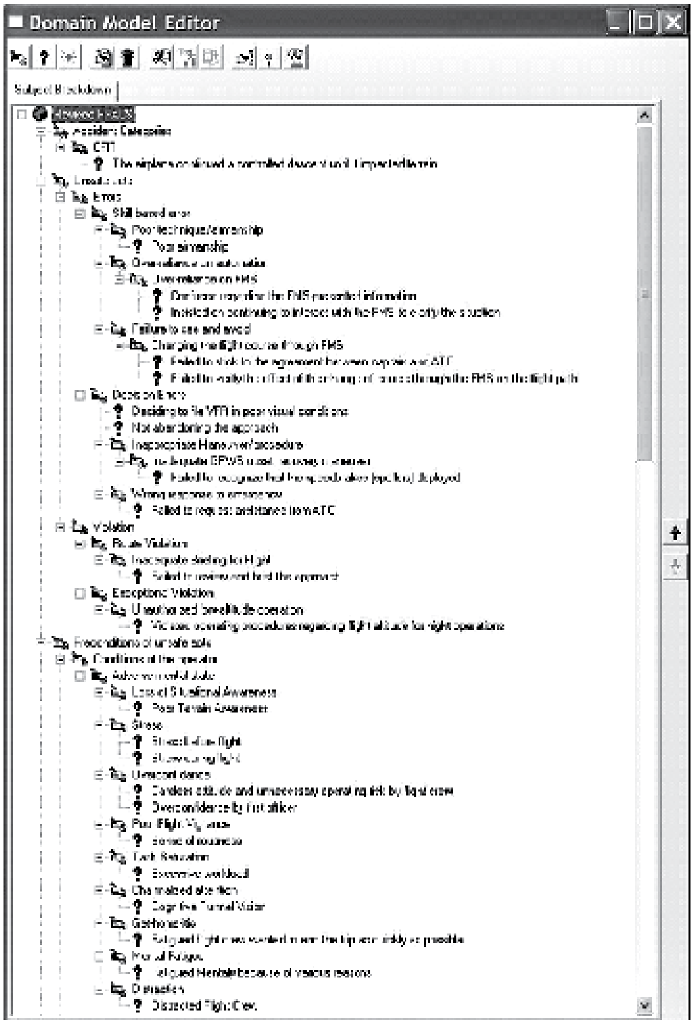


*Figure 8. Domain model of the prototype tool as it is presented in the domain model editor (partial model is displayed).*

The attribute questions are answered within the context of the accident.

If any major aspects of the accident are not addressed by the domain model, those aspects are included in the domain model as new attributes. By doing so the domain model is updated regularly.

As far as the case-based reasoning mechanism is concerned, the tool has two components, the case base and domain editing tool and the reasoning tool/user interface. As the name implies, the case base and domain editing tool is for structuring and maintaining the existing case base and domain model and for this purpose the CaseBank software is used. The domain model discussed in detail in the previous section is presented in Figure 9 in the format as it is structured for the domain editor of the prototype tool.

The indexing and inclusion of a case into the case base is performed in the case editor. Figure 9 shows CFIT Case #1, Aloha Island Air Flight 1712 as it is indexed by means of building up a set of associated attributes (i.e., observations) along with their values assigned.

### 4.2. The reasoning tool and the user interface

SpotLight™ [6], a commercial CBR tool customized for aircraft maintenance diagnostics, is used as the reasoning tool and the user interface employed by the current research [15]. This section

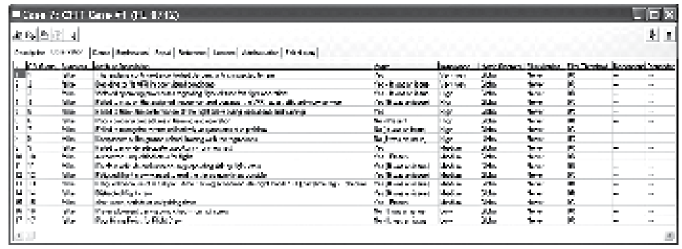

*Figure 9. Attribute set for Aloha Island Air Flight 1712 as indexed in the case editor.*

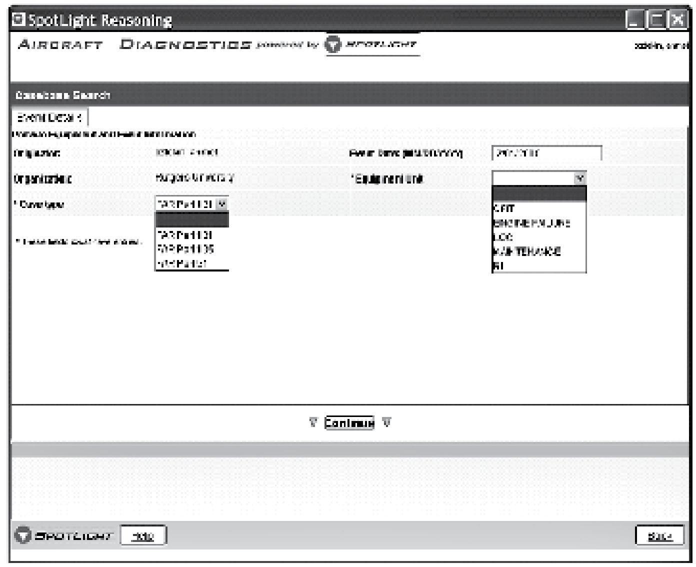


*Figure 10. On the event details screen, a pre-filtering of the case base is achieved by selecting the case type and equipment unit.*

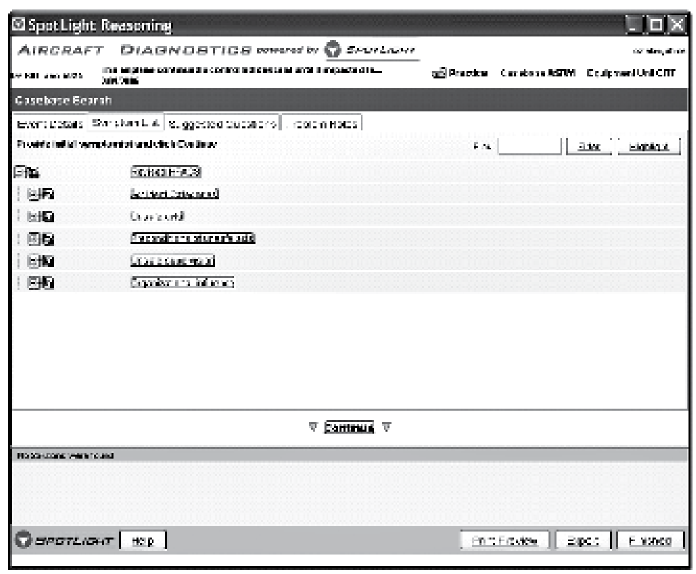


*Figure 11. The symptom list screen.*

discusses the prototype tool by considering it as a "beta" version of a *draft* product. In this context, the tool's intended usage is demonstrated in a "step-by-step" fashion employing screen-captures illustrating an actual run of the prototype tool.

On the opening screen, in order for the tool to perform an initial case base search for the purpose of pre-filtering it, the user identifies the event details of the current accident case by select-

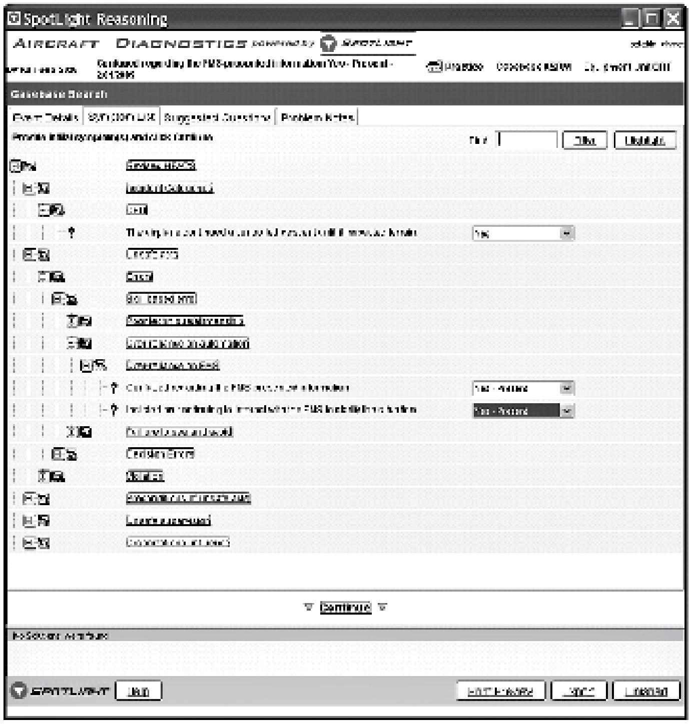


*Figure 12. Assigning initial symptoms for the current case.*

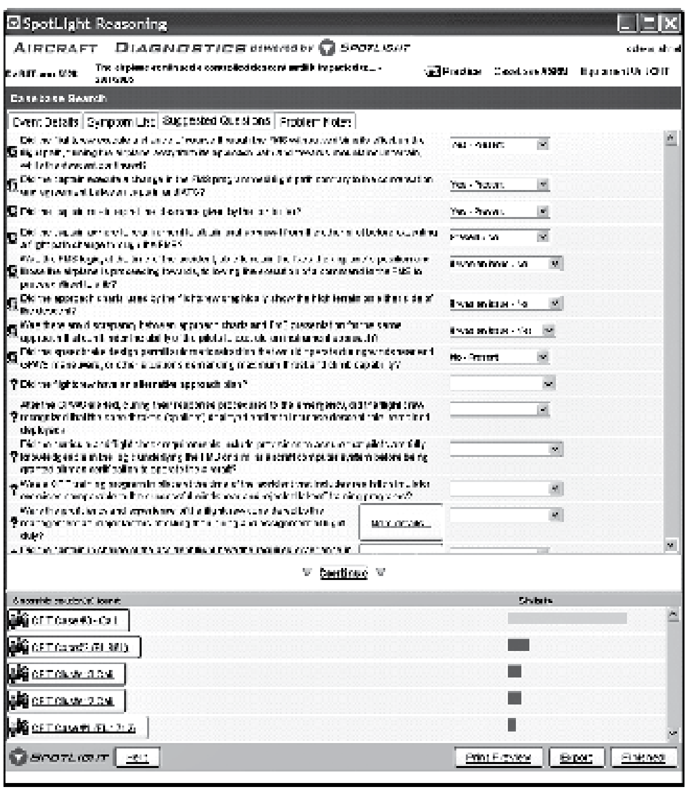


*Figure 13. List of suggested questions and first set of cases retrieved from the case base and ordered according to their relevance.*

ing first its case type among the three FAR Parts (i.e., Parts 121, 135, or 91) and second its equipment unit among the six accident categories (CFIT, engine failure, LOC, maintenance, or RI). The event detail screen is depicted in Figure 10.

The vocabulary used on the user interface of the SpotLight™

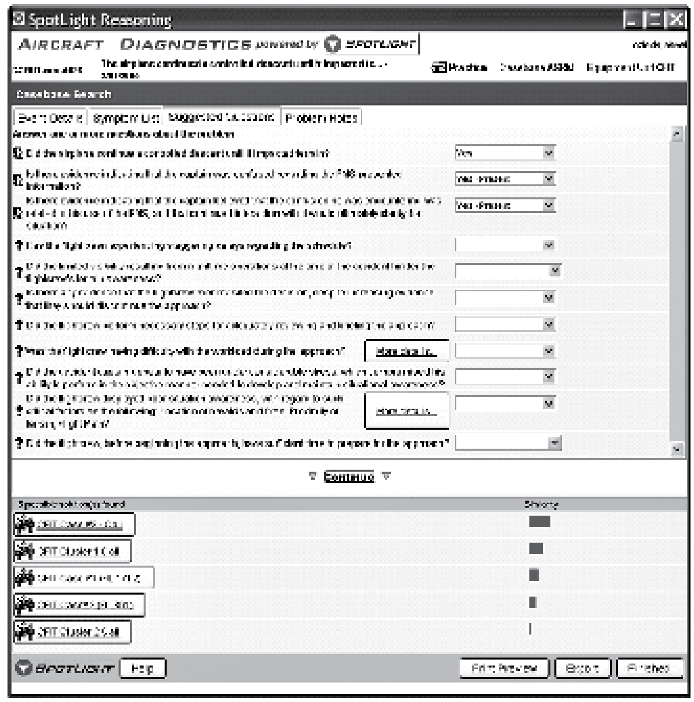


*Figure 14. A possible solution with higher similarity.*

is conceived with maintenance diagnostics in mind. Therefore, most terms, such as case type and equipment unit, do not fit to the context of aviation safety research. However, since this issue does not constitute a functional problem for the reasoning methodology and for the prototype tool, they are kept as is for the purpose of this research.

On the next screen, the user is asked to identify the initial symptoms regarding the current accident case. The symptom list screen introduces the domain model to the user in a compact form (see Figure 11) by only showing up the five main failure categories of the revised HFACS.

Here, the user is expected to provide some initial observations in relation to the particular accident case that he or she investigates. These initial observations may be as basic as the type/category of the accident—or they may be of the form of unsafe acts by the operator, such as errors or violations committed by the flight crew. Initial observations are entered by clicking on the particular failure type and selecting yes (or present) for the attribute mentioned specifically in the accident case (see Figure 12).

At this stage of the progression, as far as the numbers of the initial observations are concerned, there does not need to be many of them, necessarily. In most of the cases, providing only three accurate initial observations would be sufficient for the tool to select and order questions relevant to the accident case at hand and start the process of retrieving cases from the case base and rank them according to their calculated relevance score. Hence, after the user enters the initial observations, the tool generates a list of suggested questions and the first round of cases retrieved from the case base and ordered according to their relevance (see Figure 13).

On the suggested questions list screen, the user can scroll through the list of questions and answer the ones that apply to the current accident case. At this stage, the more questions that are answered by the user the more refined the possible solutions presented would be. Figure 14 depicts a sample case where after answering 12 questions the prototype tool refines the case re-

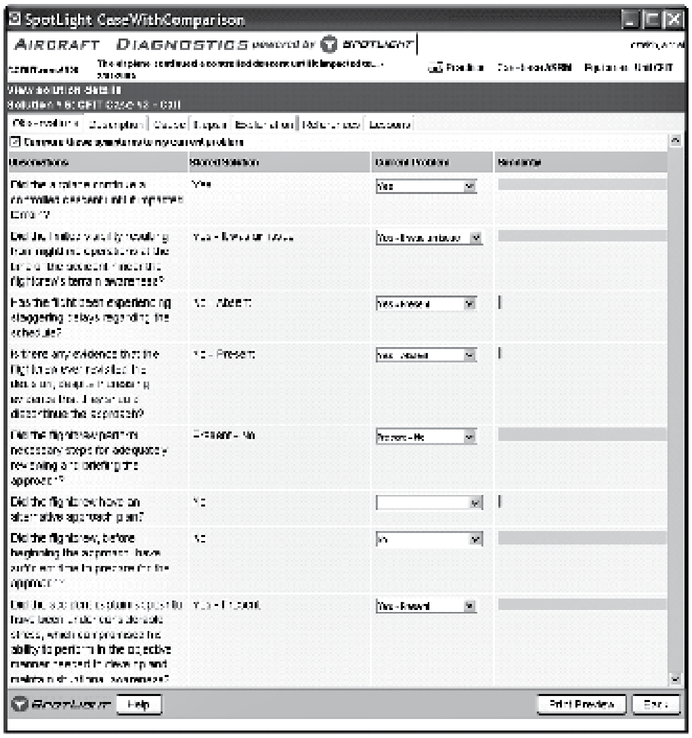


*Figure 15. Comparable symptoms of the proposed solution.*

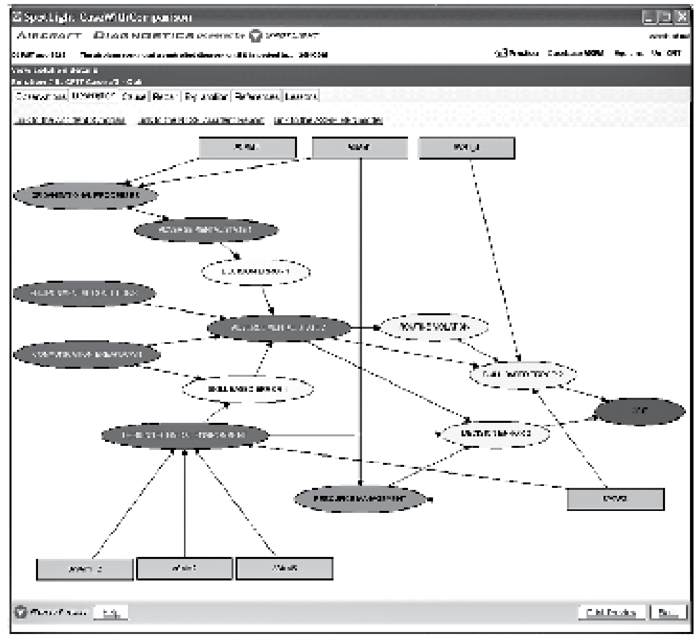

***Figure 16. The description tab on the solution details screen provides links to all the necessary information including the ASRM BBN model, NTSB accident report, and accident synopsis regarding the solution.***

trieval process and distinguishes and brings forth one of the cases, namely CFIT Case #3 Cali, with a much higher similarity than the rest of the solution possibilities.

If the user chooses to look into and further discover this solution possibility with higher similarity, all he or she would need to do is click on the link provided. Consequently, the solution details screen is reached. On this screen, the user can review the observations specific to the solution, compare them with his/her current accident case, and judge on the similarity calculated by the tool, hence accept or reject the solution (see Figure 15).

Furthermore, to facilitate a better understanding about the solution, on this screen under the description tap, the user is able to access by means of links provided to the original ASRM BBN model the NTSB accident report and other related information regarding the solution (see Figure 16).

Finally, we elaborate briefly on the intended user of the tool. However, it is worthwhile at this point to recall that the subject matter of the current research is to introduce an analytical approach and methodology for a conversational CBR tool. The tool's objective is to assist the user to identify/model the precursors (i.e., causal factors) and their interactions underlying a particular aviation accident along with some candidate NASA technologies/interventions for mitigating the effect of these precursors. In this context, as we have seen in the previous example, the user is presented with some solution possibilities (i.e., complete causal models or model fragments) ranked according to their similarity to the accident case that the user investigates.

This objective implies that the intended user is somewhat knowledgeable in the field of human factors analysis and aviation safety research. This inherent feature of the tool, although it might be improved by further effort, in fact reduces the steps required to run it and hence facilitates the process of identifying the solution possibilities. This feature makes the tool more suitable for users with a certain profile and background, thereby limiting its reach toward a broader user base. Therefore, having a basic introductory-level knowledge on HFACS and Bayesian Belief Networks may facilitate a better understanding for the user with regard to the steps followed by the user interface and reasoning process of the prototype tool.

## 5. Conclusions

In this study, we employ a CBR approach along with Bayesian Belief Networks (BBNs) to develop a computerized *hybrid* decision support tool whose main objective is to build *probabilistic* causal models representing the safety risk involved in aviation accidents. These probabilistic models focus on interactions among accident precursors and introduce candidate NASA technologies/interventions to mitigate their cumulative effect on the consequence, i.e., mishap.

Cases serve three sorts of purposes in CBR systems [18]:

- Cases provide context for understanding or assessing a new situation.
- Cases provide suggestions of solutions to problems.
- Cases provide a context for evaluating or criticizing suggested solutions.

In this context, we use 15 representative accident cases to comprise an initial seed for the case base of the prototype tool. The initial seed is comprised of three Controlled Flight Into Terrain (CFIT), three loss of control (LOC), four maintenance (MAIN), two engine failure (EF), and three runway incursion (RI) accident cases covering a wide spectrum of FAR Part 121 and 135 operations.

These accidents are modeled, in accordance with the Aviation System Risk Model (ASRM) process [19], into BBNs using an extended version of the Human Factors Analysis and Classification System (HFACS) taxonomy [20]. The ASRM process, including the identification of mitigating candidate NASA technologies and the derivation of conditional probabilities due to precursor interactions, is performed during knowledge elicitation sessions with subject-matter experts (SMEs), such as the FAA's aviation safety inspectors (ASIs) and experts from other FAA directorates, among others.

Consequently, within each individual ASRM model main clusters of causal factors are identified and included into the initial seed, thereby improving the case base of the prototype CBR tool both quantitatively and qualitatively. Finally, the 20 ASRM accident cases and the causal factor clusters are indexed into the case base by using a methodology developed on the revised HFACS used in ASRM.

The SpotLight™ [6] software is used as the reasoning engine and the user interface for the prototype CBR tool. The resulting product is a highly customized conversational CBR tool. The tool using the following progression determines the solution possibilities:

- The user selects the related FAR part and accident type.
- The user enters initial symptoms regarding the current accident case, such as operations under low visibility, extreme weather conditions or errors/violations by the flight crew.
- The tool presents a set of suggested questions and following the user's responses retrieve similar cases (i.e., complete accident models or clusters of causal factors) from the case base and presents them in an order determined by their similarity to the current accident.

By selecting any presented solution possibility, the user will be able to access all the information regarding the solution, such as the BBN model, accident synopsis, or full National Transportation Safety Board (NTSB) accident report. ◆

## 6. Acknowledgements

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# Airline Flight Data Analysis (FDA)—The Next Generation

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## Abstract

Flight data analysis (FDA) programs, or Flight Operational Quality Assurance (FOQA) as they are referred to in the United States, have been well accepted and increasingly implemented around the world among the airlines. These programs identify adverse events and trends so that the airline may investigate them to develop risk mitigating safety actions before a serious accident occurs. Thus, they are proactive in the cause of accident prevention.

Statistically, a large airline with a greater baseline of data has a better chance of identifying a problematic trend than does a smaller airline. Whether or not the analysis is done in the wake of an accident, the inherent complexities of analyzing flight data are no different. There is most certainly benefit for airlines in exploring how best to exploit the techniques coming from the use of FDA in accident investigation.

In the event of an accident, the relevant investigative authority publishes the results for the world to see. But all too often in the case of an internal airline incident identified through a FDA program, the information is not shared outside the airline in any systematic way. To unlock the true value of the FDA data, the international airline community must take another bold step in safety data management. Like the accident investigation community, the airlines must develop formal ways to share the lessons learned through FDA. While some of more advanced airlines are moving this way, it is especially important for that medium and smaller airlines benefit from a larger sample base. Web technology and improved flight data quality/quantity makes this goal more achievable than ever before, and IATA believes that it can play an important role to facilitate the next generation of FDA programs.

This paper will explore the issues related to sharing the safety intelligence gained from airline FDA and consider how this might be done in the next generation of FDA programs.

## Introduction

Accident investigation is based on the premise that by understanding the causes and contributing factors of an occurrence and disseminating this information in an effective manner to the international community similar accidents can be prevented. Indeed, sharing the lessons learned in airline safety has been a recurring theme with the International Society of Air Safety Investigators (ISASI) throughout the years and remains a core value within the international safety community. Flight data analysis (FDA) programs (or FOQA/FDM programs), now an International Civil Aviation Organization (ICAO) Standard, hold the philosophy that airlines need not wait for an accident to identify safety risks—that by routinely analyzing one's flight data, safety concerns can be effectively dealt with before they become catastrophic. The vast majority of accidents have been accidents waiting to happen. Accident precursors occur repeatedly, in such a way that it is simply a matter of time before the accident occurs, if the precursors are not identified and risks mitigated.

FDA programs allow airlines to identify more objectively predefined undesired states and conditions that, if not monitored, might ultimately culminate in an accident. In many ways, FDA is an "accident investigation without the accident," the only major distinction being the different trigger prompting the analysis and identification of necessary safety actions. The trigger for an accident investigation is the reaction to damaged aircraft, an injury, or fatalities. The trigger for FDA is proactive in the detection of an event or event trends identified in the data. In many ways, the airlines and the investigation authorities are attempting to tackle the same problem, but each approaching it from rather different perspectives (see Figure 1).

If an airline has an accident, the relevant authority will share

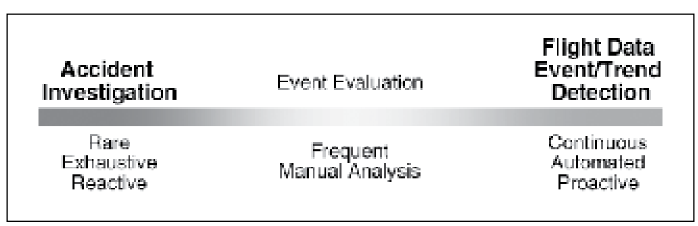


***Figure 1. Spectrum of flight data analysis. FDA programs in many ways can be considered "accident investigation without the accident." Investigators and FDA teams are all largely working in the middle of the spectrum, just coming at it from different perspectives.***

the investigation results within the aviation community, for the greater good. As a body accountable to the public, the facts and lessons learned are shared worldwide in the interests of safety. Would it, therefore, make sense to apply the same principles in sharing the lessons learned in airline FDA programs, naturally taking advantages of the anonymity of deidentified flight data? The sharing process should not be abandoned simply because the event did not culminate in an accident. It would be preferable to share the lessons learned in the context of FDA, which is by nature more benign in comparison to the sensitivity that is required in dealing with data and safety intelligence associated with a major accident. When no one is hurt and no reputations are on the line, it should be far easier to share the lessons learned.

This is a concept that has already been successfully applied to air safety report (ASR) data by IATA, under its Safety Trend Evaluation, Analysis and Data Exchange System (STEADES) programs. The next generation of FDA programs should explore a similar, systematic approach in which lessons learned can be shared, using the same guiding principles that have long been proven and accepted in the investigation and safety reporting community.

With the advent of the Internet, significant advances in recording technology and automatic wireless data transmission from the aircraft are being made. Once the data are recovered from the aircraft, it really does not matter if the data go 2 feet or 2,000 miles as long as the transfer is performed in a secure environment. These technologies make data seamlessly transferable around the globe. Analysis technologies have also advanced considerably making web-based analytical tools very practical, giving users access to information and results from virtually anywhere in the world, at any time, regardless of the location of the FDA program office. Traditionally, airlines have developed in-house FDA programs, but with these new technologies comes the opportunity for a paradigm shift based on the same principles and protocols that have brought success in the STEADES program.

To share the lessons learned in a systematic manner ultimately requires an international database structure that can be accessed by the various stakeholders throughout the aviation community. This includes not only airlines, but also aircraft manufacturers and potentially investigation authorities and regulatory bodies. To unlock the true value from FDA, the safety intelligence gained must be disseminated worldwide. In general, the international investigation community has excelled in accident investigation. The effective dissemination of results, on the other hand, has been an obstacle not easily overcome. The great majority of the aviation safety community does not necessarily read accident reports, which often contain an overabundance of information, making it a challenge to quickly find the portions of interest to such a diverse audience. These impediments persist, despite the advancing quality and thoroughness of accident reports. This is primarily because it is still difficult to communicate intimate accident sequence details effectively.

The challenge is to communicate the factual details of the event, incident, or accident in a readily accessible and intuitively useable format. The critical "what" happened of the occurrence is unchanging; there is only one set of facts. The derived "why" the event happened, describing causal factors and persistent threats to safety, is, however, not unique. For every "what," there can be a dozen "whys" with lots of room for different opinions. It does not necessarily matter who is right in this interpretation—as long as the end result is that the "what" of the occurrence is not repeated. In order to accomplish IATA's goal of reducing the accident rate (hull loss rate among Western-built aircraft) to below 0.65 per million sectors flown, the effective communication of the "what" not only from accidents but incidents, but ultimately, communicating the "what" from FDA programs will be essential. Looking to one key area of communication in the next generation, flight animations can play a key role here by clearly communicating the essential components of an occurrence, with all the necessary detail. They are compelling, stimulating, and enjoy much greater prospect of being used by safety officers, crew, and supporting staff than the traditional written accident report.

The Transportation Safety Board of Canada released an excellent and comprehensive multi-volume report on Swissair Flight 111, which crashed off of Peggy's Cove, Nova Scotia, Canada, in September 1998. The FDR/CVR investigation group for that accident generated a very detailed and comprehensive flight animation that included the air traffic control recording synchronized with the animation and the relevant portions of the CVR transcript in subtitles (one of the authors of this paper was the Flight Recorders Group chair at the time of the accident). The animation was used extensively internally to understand the sequence of events within the team. The TSB has never released the flight animation, in part perhaps due to a substantial process in place designed primarily to produce a hard copy report, and in part due to sensitivities over the inclusion of ATC recordings and CVR transcript information. Arguably, the majority of safety professionals around the world have not read the Swissair report, and even for those who have, comprehension and retention of the details is difficult due to the complexity of the investigation and the shear magnitude of the report. Yet these same people are the proponents for safety changes within their respective operations. The short animation sequence is a very effective means of communicating the factual sequence of events and, in particular, communicating some of the human factors aspects and can also serve to augment the portion of the written report that deals with the sequence of events. The scope for misinterpretation of the written words within any report is always greater than when witnessing the factual sequence directly, and the scope to identify additional valid "whys" when witnessing the factual sequence is also normally greater than reading a report. The flight animation for Swissair Flight 111 gives the viewer an intimate appreciation of the factual sequence of events in the order as they occurred, and, like in any good movie, every viewing is likely to reveal new details—things you did not see before. With this sort of technology now readily available, it must be harnessed with the appropriate quality control measures (garbage in, garbage out) to achieve global data sharing of the intimate details of often complex and time-sensitive sequences.

There is so much more information available from the accident investigation community, incident reporting systems, and FDA programs that needs to be effectively shared if the accident rate is to be further reduced. While accident investigation reports must have their place, due regard must be given to those who are not be in the position to read them fully. Invariably and unfortunately those most interested in the detail of these reports are not managers at the sharp end of aviation but liability and legal investigators. The airlines and the industry at large, nonetheless, need access to the facts in order to exercise their safety responsibilities. Results inputted into a database, accessed via the web, have a far better chance of being immediately useful to the

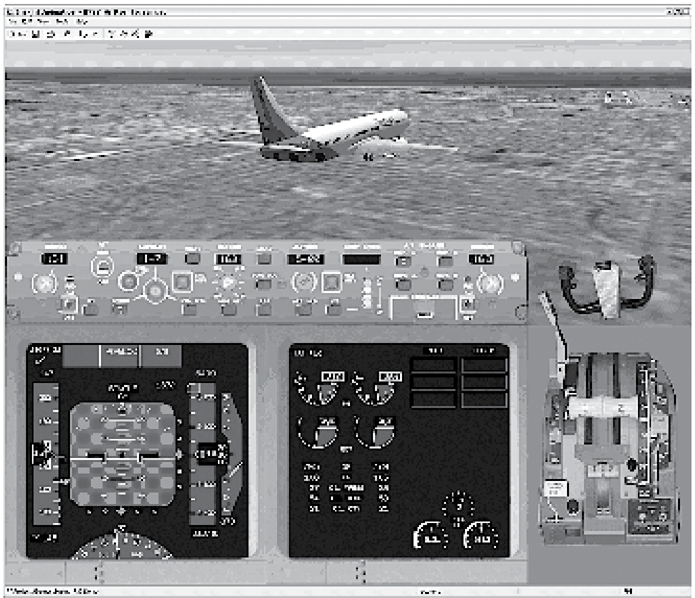

*Figure 2. State-of-the-art flight animations can communicate detailed information in a highly intuitive manner.*

international safety community. This is due to their ability to perform searches without having to read an entire report to find the relevant material. The results generated through an FDA program need to adopt a similar approach and make extensive use of database technology to both analyze and disseminate information. New database architectures make it possible to link pictures, animations, PowerPoint briefs, pilot reports, etc., with the source flight data and current web tools allowing users to generate readily statistical results, increasing the potential associated with such an international database (see Figure 2).

**Third-party FDA service—facilitating data sharing**

Another promising step being taken by some airlines, which has great potential for international data sharing, is in the area of outsourcing FDA. The most common concern with regard to outsourcing an airline FDA program is the perception that it entails an unacceptable loss of intimacy with the data. There is the feeling that the data cannot, for security and crew union reasons, be sent off site. Not least, there is the worry that legal issues, such as data ownership and government accessibility, would prohibit such a system. First and foremost, the issues of where the data physically reside and the ownership of data are unrelated. Flightscape, an organization that has been operating an FDA service for 2 years, has recently partnered with IATA, a longstanding contributor and leader in safety data management and analysis (SDMA), to bring the vision of data sharing that much closer to reality. The flight data and results, residing at the third-party FDA service in Ottawa, Canada, are at all times owned by the airline regardless of the data's physical location. When the airline forwards the data electronically, it maintains a copy, ensuring that there is nothing preventing that airline from accessing its data for special or urgent cases, free of third-party involvement.

From the security perspective, experience has shown that a third-party service offers an additional insulating layer against inappropriate use of the data. If an airline is operating a program in-house and despite agreements that might be in place, senior management or the CEO may demand to view elements or the entirety of the data in a highly sensitive case, which can obviously put the employee in a difficult situation, as guardian of the data. If the airline is using a third-party service, the restriction and security of flight data are that much easier, since the work is being done off site, free of a direct line of authority. In the IATA FDA service model, the airline sends raw binary data downloaded directly from the aircraft, often free of human intervention. Because it is raw binary data that have yet to be decoded, the data are encrypted and highly compressed, making transmission very efficient and secure. Secure Internet technology, combined with at source encrypted raw data, yield a high level of overall data security.

Deidentification is another aspect of flight data handling that is somewhat misunderstood among the FDA community. The process of deidentification, in the United States, largely refers to the need to remove identifying parameters such as the flight number, flight date, or others that might allow an individual to trace the flight to an aircraft, sector, or crewmember. Raw binary data sent to the service provider have technically not yet been "identified" because they have not yet undergone processing. In this case, it is a simple matter of not processing the components of the data that could be used to identify the crew. In this case, it would require a considerable amount of effort to identify the crew, without access to crew schedules and information controlled exclusively by the airline. However, a neutral, recognized aviation body, such as IATA, can be essential in preserving the integrity of such safeguards.

Greater benefits to the third-party service model relate to the involvement of mid- to small-sized airlines. FDA programs are based on the identification not only of serious incidents, but also the sequence of important events that outline a developing trend that might lead to a serious incident or even an accident. Because trend identification is based on the statistical frequency of events, an airline with a small fleet can be statistically insignificant, possibly missing such trends. For example, if an airline only operates five aircraft, the odds of something happening or more so that a trend is accurately detected are magnitudes less than an operator basing results on 500 aircraft. The service model with an eventual formal sharing capacity with proper safeguards is, therefore, particularly important for smaller carriers who not only benefit from trends developed from pooled data, but also free themselves up from the cost associated with increased IT infrastructure and data analysis expertise, which could possibly delay or prohibit their involvement in FDA entirely. This assumes that a model is in place whereby multiple smaller airlines are able to share safety lessons and learn from each other. Offering a central service is a significant step in the right direction. Immediately, smaller airlines benefit from a service center employed by multiple airlines, giving them access to a team of experts with experience that few of these small airlines could match.

This has been seen recently with one of the current subscribing airlines. The airline experienced an uncommanded pitch-up event and asked Flightscape to assist in a detailed analysis of the event. While no one airline had encountered this event before, the analysts at Flightscape, some of whom are former accident investigators, had seen previous similar pitch-up events during their investigation career. The service provider searched the Safety Board databases for similar events and compared the flight data from previous investigations to that from the airline data. Within a few days of receiving the analysis request from the airline, Flightscape provided a detailed investigation report (accident investigation without the accident) suggesting that the problem may be related to a rigging issue. The airline followed up on the observation and confirmed the diagnosis. Not only was the third-party FDA service very helpful in supporting the airline trouble-shooting team, but a fresh pair of experienced eyes outside of the airline had been focused on the problem.

A third-party team dedicated to flight data analysis is entirely complimentary to the in-house safety team, but the arrangement takes additional advantage of a natural sharing environment to bring more value to the airline's flight data. Sharing, to a limited degree, occurs automatically by virtue of the fact that one team is seeing data from multiple airlines. Given that the data from these multiple airlines are in *one* database designed for the service, the potential to share the lesson learned is technically facilitated and only a small step away from becoming reality.

The IATA and Flightscape vision is to ultimately have one database whereby each airline can access its own data and reports but, additionally, can monitor trends that are affecting larger statistical populations (by type, location, etc.). Various other stakeholders might be granted controlled access to the appropriate portions, expanding the scope of participating members. Currently, the service model only interacts with individual airlines to facilitate their own FDA program. As the service matures, the more important objective is to design and implement an international trending capability whereby airlines can contribute results and provide controlled access to their data for broader-reaching studies across the airlines. IATA, as an association representing the airlines, has gained the trust and objective neutrality that the industry needs in order to pursue these goal. IATA currently receives more than 50,000 incident reports per year from more than 45 subscribing data providers through its STEADES program.

IATA STEADES also maintains the world's largest database of deidentified incident reports and provides a secure forum for the analysis, trending, and general inquiry of the leading indicators of industry safety in order to develop a comprehensive list of prevention strategies. Expanding upon the STEADES program and establishing an FDA program is a very natural and logical next step for IATA. The combination of FDA results with incident reporting trends across a large body of airlines has potentially large safety payoffs. Outside stakeholders might also eventually have controlled access to such a database to help further industry safety initiatives. For example, aircraft manufacturers might access data or safety intelligence specific to their aircraft across fleets to study trends related to the operation of their aircraft, engine, or likewise. All this would be done under the very tight supervision of IATA with appropriate privacy and quality controls.

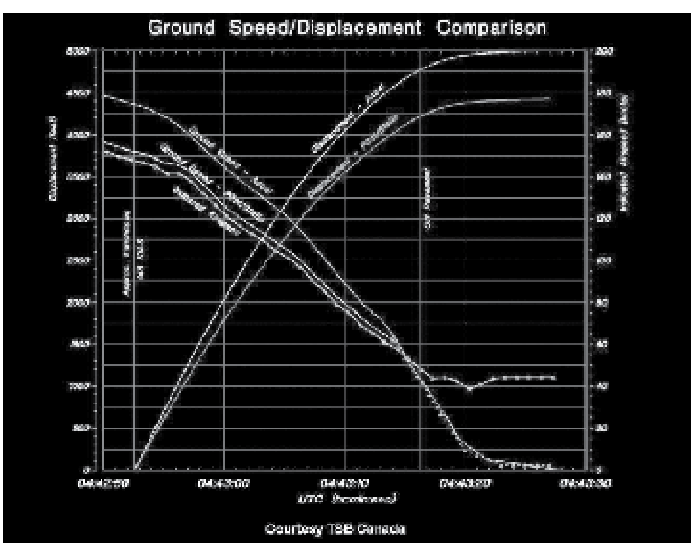


*Figure 3. Example of displacement calculation using a single integration of ground speed and a double integration of accelerations showing a 500-foot difference after 23 seconds.*

Regulatory authorities, especially within their research areas, engaged in formulating legislation or policy might use the database to validate the effects of their work on airline safety. Similarly, investigation authorities could find the database useful in order to expand the scope of any safety action considered within a given accident investigation. Such a database would assist the authority in determining if its accident was truly a one-off occurrence or an accident that was "waiting to happen," in turn providing guidance and direction to the investigation.

A possible impediment to such a system is the natural and healthy reluctance of an airline to allow someone else to use its data for fear that the data will be used against them or to deny their competitive business advantages. With some discussion and through mutual understandings, this obstacle can be overcome in several ways. For example, the database can be designed such that when an aircraft manufacturer is looking at data across airlines, it is impossible to tell which airline the data have come from, a margin of security which has already been incorporated into the STEADES program. Airlines can also control when and what is accessible by those outside of the airline itself either through manual approval or automatic logic. It is important to distinguish between sharing the flight data and sharing the lessons learned. Sharing the lessons learned should be easier to achieve and yield the greatest benefit, based on the success that has been seen in accident investigation and incident report sharing. Investigation authorities and programs such as STEADES do not share flight data, but share the lessons learned in the investigation and most importantly, are able to suggest prevention strategies and safety actions to those most directly concerned (see Figure 3).

**The challenges in sharing flight data**

There are several challenges to be addressed in sharing flight data, many of which stem from the inherent technological differences. These differences can be seen between FDA systems in

- parameter nomenclature, instrumentation accuracy, recorder resolutions, and sampling rates.
- filtering and processing of the data, while airborne and by the ground station.
- data acquisition units across different aircraft fleet.
- data sources for the same or similar parameters.
- algorithms and techniques for deriving parameters (see Figure 3).
- event and incident definitions.
- unit standards and conversion calculations.
- user operational environments.
- safety and reporting cultures.
- use and knowledge of statistical systems.

All of these subtle differences may make it extremely difficult to compare data across airlines, especially when concerned with the need for proper statistical sampling and sound trending technique. Lack of standardized event criteria and statistical methodology compounded by misaligned analytical process and the technical diversity of flight data are all significant challenges. Nonetheless, there are valuable processes that can apply more broadly to the co-

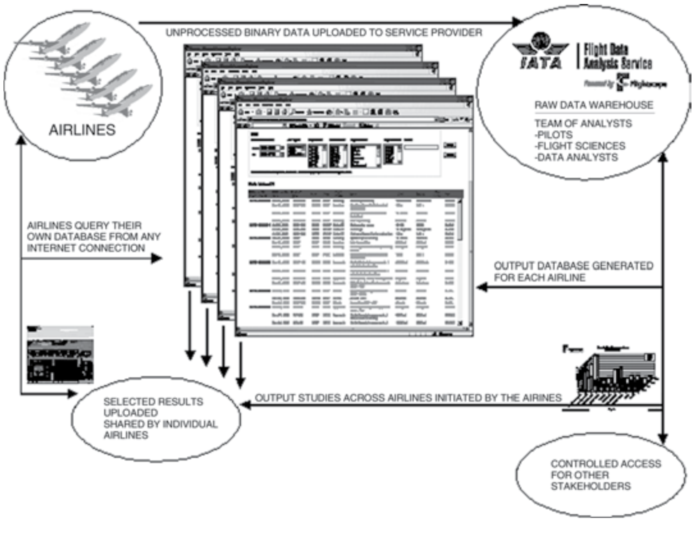


***Figure 4. Diagram of IATA FDA service, allowing individual airlines access to their own results as well as access to a global pool of safety information and lessons learned, with potential access by other stakeholders.***

ordination of controlled access to flight data across the airlines. Manufacturers' interest in validating engine performance is an excellent example of where an authorized external body might develop an exercise-specific algorithm, to be applied as a query to flight data from several airlines of differing aircraft type and model in order to extract relevant and useful events. A central service provider attempting to validate a problem for just one airline, especially one with a small fleet, could benefit greatly from the confirmation that such a problem exists with other airlines, by applying the same algorithms across the entire data set (see Figure 4).

With the challenges and benefits of such a data-sharing system clearly outlined, a partnership of stakeholders must be formed to drive forward the implementation of an agreed-upon methodology and standardization process. Many of the same issues that have necessarily been addressed in data sharing through the IATA STEADES Program will apply to flight data sharing, with infinite opportunities for alignment between both of these systems. IATA has played a principal role in the development of a common set of incident "descriptors," to be used in the classification of air safety reports (ASR), cabin safety reports (CSR) and ground handling reports (GHR). IATA has also been an active participant in the Federal Aviation Administration's (FAA) Global Aviation Information Network (GAIN) initiative, pushing to develop standards and guidelines for the effective maintenance and communication of safety data systems. The concept of data sharing in FDA should be considered as the younger brother, or perhaps a prototype version of the work that has been done with incident reporting systems. These previous efforts to smooth out the difficulties in incident data sharing should serve as a model for the creation of new FDA sharing guidelines and best practices, tailored to suit its specific technical demands. There is much value in aligning FDA and incident analysis, where one system could serve well to corroborate, compare, or complement the lessons learned from the other.

The importance of developing a simple, yet effective, methodology for dealing with the technical aspects of flight data sharing will be paramount to the success of such an initiative. Certain considerations, which have already been addressed in incident reporting such as data de-identification, can be easily overcome by selectively deleting, or stripping out parameters that would be sensitive to flight crews, operators, or any other entity that might be subject to identification and potential reprisal. As in incident reporting, a strong safety culture is based upon a non-punitive system of safety monitoring. The STEADES Program can again be used as an example of some of the work that has been done to address these issues. ASRs, CSRs, and GHRs submitted to the STEADES database are stripped at source of several fields that could be used to identify crew or operator, prior even to coming before the eyes of an analyst. Several data-handling issues have also been tackled in operating the STEADES Program.

The STEADES database, which currently contains more than 300,000 records, has had to surmount challenges in both ensuring compatibility with existing and external software systems (and descriptor hierarchies), as well as the effective management of large volumes of data within one system. The analyst's ability to extract meaningful results from a large volume of data is only as valuable as the querying tools available. It is perhaps unrealistic to presume that an analyst could comb through and validate the volumes of data collected through a large-scale FDA process.

Just as the STEADES analyst uses descriptors, key fields, and keywords to optimize a search, FDA would need to establish a standard for the classification and storage of pertinent events in flight data. Standard event "descriptors" would be necessary, with the event detection algorithms, parameters reported, and several supporting components standardized for input into the global database.

Early attempts at defining the exceedance parameters necessary for global trending and the methodologies by which these parameters would be recorded have been made by a consortium of airlines under the Proprietary Operational Data Sharing (PODS) Committee. The Committee has addressed the possibility of using software, such as the MAXVALS and SNAPSHOT programs developed by British Airways and SPIRENT in the mid 1990s, literally to take "snapshots" of an agreed-upon set of parameters where the maximum value of one parameter exceeds the threshold value. The software has been successfully used within the BA flight safety program, and has generated interest among many of the world's major airlines. Examples of the program's potential can be seen in the comparison of data across several airlines (see Figure 5), allowing airlines to measure their performance directly against the in-

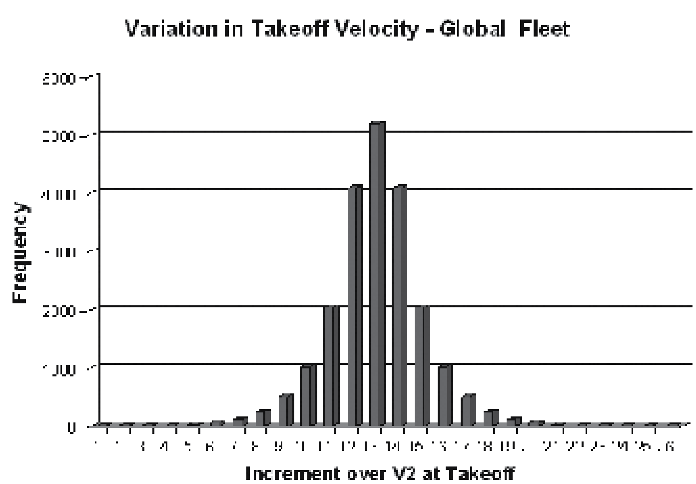


***Figure 5. Example of the potential of globally pooled data in comparing aircraft operations across fleets, operators, etc.***

dustry norms. The growth of such a model may contribute to the overall success of a program such as the IATA FDA service and global data sharing throughout the industry.

The coordination of the data-sharing initiative finds IATA well placed to serve as a liaison between industry stakeholders in driving forward with best practices guidelines and FDA standards development (see Figure 6). IATA maintains regular communication with many of the stakeholders who are heavily invested in the development of FDA and is, with the launch of the IATA FDA service, poised to reach out to newcomers in FDA. The ICAO, member States, and their respective regulatory agencies have already played, and will continue to play, an active role in the support, mandating, and enforcement of safety standards through legislation. Air navigation service providers (ANSP), airport authorities, and other members of the airline infrastructure will all be able to participate in and directly benefit from the analysis performed on flight safety within their respective domains.

Likewise, airframe and powerplant manufacturers will retain an essential role in the evolution, understanding, and analysis of aircraft-specific safety issues. They will certainly benefit from a broader platform of information on which to base their maintenance and development programs. Given the heavy reliance upon complex hardware and software components in FDA, software providers will have to be aligned to the common goal of data integration in order for the data-sharing initiative to be successful.

Finally, perhaps the most important stakeholder, the data-generating airlines, will be both the creator and consumer of all of the benefits cited in this paper. They will be essential in creating a statistically significant, critical mass of data and feedback, upon which a truly global system of data sharing can be built. Although each data-sharing stakeholder plays a unique role in the progress of the initiative, all are strongly united in a campaign to reduce the accident rate, a shared goal.

**Conclusion—sharing the lessons learned**

Many airlines having excellent in-house programs with experienced staff may not be in a position to outsource their FDA program for a variety of reasons. Even in these cases, the international community needs to take the steps toward establishing the necessary infrastructure for sharing the lessons learned, ultimately benefiting service clients, in-house operators, and the greater safety community as well. Whether airlines operate in-house or outsource part or all of their FDA program, the industry as a whole needs to begin sharing the wealth of insight that flight data provides in a more formal and open environment. Airlines operating in-house programs will be able to contribute the IATA system so that all subscribing airlines can benefit from this information (see Figure 6).

The ICAO accident investigation sharing model works well and can be effectively applied to FDA programs if airlines are convinced of its value. This value should apply beyond FDA programs to align with incident reporting systems, such as STEADES, the only differentiation being the manner in which the problem is identified. As in an accident investigation, the most effective means of sharing these lessons learned is by posting the relevant facts, subsequent analysis, and safety actions performed to a common repository for others to access and query. A balanced approach to data confidentiality and anonymity is the keystone to successfully accomplishing this task, ensuring that the exchange is simply of safety information in a secure, informative setting. The amount of information relayed through

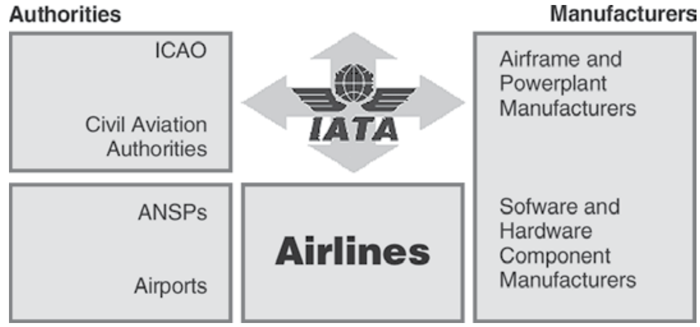


***Figure 6. IATA is well placed to serve as a liaison between industry stakeholders.***

such a data-sharing system is at the discretion of the user and the greater community, with the option of selective deidentification always available. In other words, the lessons learned can be *based* on a true story without necessarily detailing the entire true story. A "true" story is a requirement in accident investigation because of the potential impact on liability and corporate reputations that need not apply in a high-volume anonymous safety-oriented environment. The emphasis is on the dissemination of accurate and relevant safety information, while ensuring a secure and beneficial forum in which these processes are performed.

Technically, there is no such thing as FDA data or FOQA data, despite the fact that some there are frequent references to "FOQA data." More correctly, it is flight data that are being used for the purpose of FOQA or FDA. This may appear to be simply a matter of semantics, but it is important to understand the fundamentals in order to pursue the ambitious goal of organized data sharing since misuse of the terminology at the outset may lead to confusion and misinterpretation. Flight data have many uses, including maintenance, FDA/FOQA, or incident and accident investigation. Concerns surrounding the sharing of FOQA *data* are more likely to be concerns about sharing fight data. Flight data are just one source of facts in the overall system of safety trend identification. As these trends are discovered throughout the industry by several independent operators, the act of sharing them via an international mechanism will be the next major initiative for the improvement of global aviation safety. IATA and Flightscape, together with the airlines and investigative community, are already taking this next step.

With industry cooperation and technical coordination within a partnership of trusted organization, we can collectively bring FDA programs to the next generation and provide airlines with access to a tool which will extract even more value from their flight data. The larger airlines can help smaller airlines just as much as a collection of smaller airlines can provide a critical mass to increase their collective opportunity to identify problems. By forming a system of exchange among manufacturers, infrastructure service providers, regulatory agencies, and the airlines, IATA will also help to bring value to the data-sharing exercise. A truly international system coordinated by a trusted agency facilitates the technical and institutional requirements in data sharing by providing a globally accessible database to all stakeholders. The advent of flight data analysis has had a profound effect on those airlines that have pioneered the FDA movement. The airline industry needs to take this initiative to the next generation, which is the global systematic sharing of the lessons learned in FDA, with the overarching ambition of improving operational efficiency and reducing the accident rate. ◆

# Investigation of Causes of Engine Surge Based on Data in Flight Operations Quality Assurance Program

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**Abstract**

Possible causes of engine surge are investigated by using the engine performance models that are established with the operational flight data through a fuzzy-logic algorithm. The algorithm maximizes the multiple correlation coefficients for the flight data. Two four-engine jet freighters, with one reported to exhibit minor engine surge, are examined. The predicted performance based on the numerical model indicates that the exhaust gas temperature shows large excursions along the flight trajectory. Excursion is assumed to have occurred if the indicated exhaust gas temperature exceeds the model prediction by 5 degrees Celsius. The potential problem is predicted to be in the high-pressure turbine section and has been verified by the maintenance records. It is also shown that sensitivity derivatives of exhaust gas temperature with engine speeds can be used to indicate the responsiveness and the relative health of an aircraft's engines. These sensitivity derivatives indicate the effects of operational conditions and environments over a significant time period. The same approach is also applied to four-engine jet transport airplanes. Although only one airplane out of 10 examined in this paper has been reported to encounter minor engine surge, all 10 airplanes are considered so that a more representative engine performance model can be established. Based on this performance model, the reported engine surge is determined to be caused by atmospheric disturbances, such as turbulence, as all four engines exhibit the same phenomenon at the same time. The other two airplanes, without reported events, appear to exhibit the same engine surge phenomenon, in addition to an anomaly in exhaust gas temperatures.

## 1. Introduction

Engine surge (also called compressor surge) is the result of a compressor blade stall and may be caused by engine deterioration, ingestion of foreign objects, or severe engine damages (1). The instruments may show instantaneous high exhaust gas temperature because of low air volume passing through the combustion section, drop in engine pressure ratio, or engine speed changes. However, the event may be over quickly for the instruments to respond. In more serious situations involving multiple surges, on the other hand, it may take several seconds to recover if the conditions are recoverable. In the case of some severe engine damages the engine pressure ratio (EPR) will drop quickly; so will the engine speeds. The exhaust gas temperature (EGT) may rise momentarily. In the cockpit and on the digital flight data recorders, there may be indicator readings for the compressor rotational speeds, exhaust gas temperature, engine pressure ratio, oil and fuel status, pressure altitude, outside air temperature, etc. Since engine surge may represent "engine deterioration" as indicated earlier, for preventive purpose it is important to determine which engine parts may be responsible for the surge. However, to identify the defective engine parts based on only these indicator readings is not an easy task. Furthermore, it is not feasible in the scheduled maintenance inspection to ensure detection of seemly minor abnormalities in all critical engine parts. One example in this regard was the uncontained engine failure during takeoff suffered by an MD-88 transport aircraft on July 6, 1996, in Pensacola, Fla. It was caused by the fracture of the engine's front compressor fan hub, which in turn was the result of the failure to detect a fatigue crack with the fluorescent penetrant inspection process (2). Since the degradation of the engine's performance very much depends on the operational environments, a maintenance program following only the standard recommended schedules will not be adequate for all operators. Therefore, additional systems for abnormality detection are needed to complement the maintenance program.

For early detection of abnormality in engine parts, the current popular technique is to analyze the engine sensor data through an engine health monitoring system. Engine health monitoring has been implemented and utilized for more than the last two decades. The main problem in these techniques has been false alarms. Therefore, all recent advances in monitoring technology have been in developing new software to analyze the sensor data.

Recently SmartSignal Corporation has applied a modeling technique to aircraft engine condition monitoring. The method is based on comparing actual signals with signal prototypes with the residuals examined for the stochastic components (3). The signal prototypes are estimated based on empirical data. General Electric has developed a Remote Diagnostics System. In all these "model-based monitoring" methods, the proprietary "nominal engine models" are needed. These nominal engine models are typically established with test cell data.

More recent research has been focused on applying artificial intelligent (AI), or digital filtering, techniques to monitoring engine components (4-7). Neural network has the advantage of good performance even in the presence of noise contamination and/or partial information (7). In these techniques, more sensed parameters are typically employed, such as low-pressure compressor spool speed, high-pressure compressor (HPC) spool speed, HPC inlet temperature, combustor inlet temperature and pressure, bypass duct static pressure, fan exit static pressure, interturbine pressure, fuel flow, nozzle area, and variable bypass duct area. The health parameters to be predicted include the efficiencies of fan, HPC, high-pressure turbine, low-pressure turbine, etc. (5). Note that some of these needed parameters are not available in a typical flight data recorder of transport airplanes. Again, nominal engine models are required.

In the Flight Operations Quality Assurance (FOQA) program for commercial aircraft, the main engine parameters recorded in the flight data recorders are EPR, fuel flow, engine RPM, EGT, throttle position, vibration amplitude, and oil consumptions (8). These data are used in engine performance monitoring (EPM) of day-to-day operations. EPM is effective in providing early warning information of ongoing or impending failures (9). These data will be used in the present investigation to identify possible deficiencies of engines that exhibit surges. It should be noted that no matter how minor an engine surge may be, frequent encounter of surges may very well damage the engine significantly, in particular the turbine blades.

As indicated earlier, in all existing monitoring techniques, proprietary nominal engine models, and possibly empirical data banks, are needed. However, these models and data banks may differ from the installed engine models because of the type of operations, such as flight cycles and total hours of operation, and the operational environments, such as hot and humid versus cool and dry, salty air versus cleaner air, etc. In addition, operators' experience in engine types and usage cannot be easily incorporated. Therefore, in the present technique, the available FOQA data in flight operations will be directly used in establishing the engine models and, at the same time, identifying the causes or consequences of engine surges. The engine model for engines of the same type is set up only once by using data from several airplanes. In other words, the present performance prediction of an individual engine is based on comparison with the average of several engines of the same type on several airplanes. Since no engines will fail suddenly without prior symptoms of abnormalities, one purpose of the present system is to prevent total failure from occurring by early detection of these symptoms.

## 2. Engine data

As indicated in the preceding section, the engine health identification and monitoring technique in this paper is based on utilizing the FOQA data. The sampling rates in the digital quick-access recorders for flight operational parameters are low, ranging from 8 Hz for the normal acceleration to less than 1 Hz for wind speed. For the engine data employed in this paper, the recording rate is 1 Hz. Since the operational flight conditions vary in each flight, in the conventional monitoring methods the sensed parameters are first reduced to standard conditions in the nominal engine models according to some similarity rules (3 and 9). In the present method, the flight parameters are not normalized; instead they are used as indicated in the flight data recorders. The main reason for doing this is that the sensed parameters contained in the flight data recorders, such as the pressure altitude and outside air temperature, involve unknown biases and noise in different parts of the world. If they are used to determine the normalized RPM and EGT, which contain unknown biases and noises themselves, the results may become uncertain in the present "model-based filtering," which will be described in the following.

There are 12 sets of data for the 12 flights available in the present study. Two sets are for four-engine jet freighters, with one having pilot-reported minor engine surge, and the rest for four-engine jet passenger transport airplanes, with one pilot-reported engine surge. Those sensor parameters that are available and used in modeling in this paper are pressure altitude, flight Mach number, outside air temperature, airspeed, N1, N2, and EGT, where N1, and N2 are the low- and high-engine speeds, respectively, for the low- and high-pressure compressors and turbines. When the engine pressure ratio (EPR) is available, it is added to the list. For older airplanes or freighters, EPR may not be available. Data for each engine are extracted and arranged in the order shown above. The first four variables for all engines on the same airplane in the same flight are the same; but the last three variables may differ. To avoid using a huge data set, each data set is reduced in size by retaining one record for every two. This process can be repeated as many times as needed, in particular for the cruise flight where there are no significant changes in the flight parameters. Typically, the climbing flight should be emphasized. After this step, all data from all engines of the same airplane are added to form a data set for modeling. After a model is established from this set of data from one airplane, similar data from the second airplane can be added if part of the operational conditions of the second airplane is outside the ranges of the modeled aircraft.

## 3. Fuzzy-logic modeling

Since the recorded data in the flight data recorders are expected to contain random noise, unknown biases, and weather effects (such as rain, turbulence, icing, etc.), it is essential to use not only a nonlinear interpolation method in modeling, but also one that can filter these unwanted effects automatically. In Reference 7, neural networks were used for this purpose. In the present method, the fuzzy-logic modeling will be used based on the good experience of using it in the past. The fuzzy-logic modeling method employs the internal functions to make the model continuous, as compared with the fuzzy sets that show stepwise discontinuity. All values of the influencing variables shown above, such as the pressure altitude, are normalized to (0, 1) by using a range of values for each variable to be greater than what actually occur. The outcome variable, the EGT, is also normalized to be about 1.0, to avoid calculation with large numbers. This normalization is done internally in the code, not in the data preparation.

The main statistical parameter in the present method is the square of multiple correlation coefficients ($R^2$). If $R^2 = 0.95$, it means that 95% of the data can be explained by the established model (10, p. 220). Sum of the squared errors (SSE) can also be used to calculate the variance that is the best estimate of the standard deviation (11, p. 220). In fact, the confidence interval of the model prediction can also be estimated (11, p. 161). One approach to reduce the confidence interval width, and hence to increase $R^2$, is to remove identifiable sources of variability (11, p. 159). This latter approach will be used in the following to define the range of allowable prediction errors for the purpose of establishing a reference engine performance model based on engines' operational data.

### 4. Engine performance models

There are twelve sets of data used for demonstration. For convenience, these aircraft are identified as follows:
Aircraft #1: a four-engine jet freighter (Flight CAL XXX, TOW=736,925 lbs)
Aircraft #2: a four-engine jet freighter (Flight CAL XXX, TOW=849,002 lbs)
Aircraft #3: a four-engine passenger transport airplane (Flight CAL XXX, TPE-TYO, TOW=586,880 lbs)
Aircraft #4: a four-engine passenger transport airplane (Flight CAL XXX, TYO-TPE, TOW=588,480 lbs)
Aircraft #5: a four-engine passenger transport airplane (Flight CAL XXX, YVR-TPE, TOW=789,440 lbs)
Aircraft #6: a four-engine passenger transport airplane (Flight CAL XXX, TPE-YVR, TOW=788,160 lbs)
Aircraft #7: a four-engine passenger transport airplane (Flight CAL XXX, LAX-TPE, TOW=866,880 lbs)
Aircraft #8: a four-engine passenger transport airplane (Flight CAL XXX, TPE-LAX, TOW=787,840 lbs)
Aircraft #9: a four-engine passenger transport airplane (Flight CAL XXX, TPE-SFO, TOW=748,800 lbs)
Aircraft #10: a four-engine passenger transport airplane (Flight CAL XXX, SFO-TPE, TOW=856,960 lbs)
Aircraft #11: a four-engine passenger transport airplane (Flight CAL XXX, TPE-TYO, TOW=567,680 lbs)
Aircraft #12: a four-engine passenger transport airplane (Flight CAL XXX, TYO-TPE, TOW=601,600 lbs

Both Aircraft #1 and #3 have been reported by the Aircraft Communication Addressing and Reporting Systems (ACARS) or pilots to exhibit "short, minor engine surge." Our present purpose is to identify the cause or causes of the surge, and what parts of the engines may be responsible for the surge and, hence, require inspection before developing into a major failure. However, the history or frequency of surge encounter for each engine has not been collected and, hence, is unknown. The other airplanes or flights are needed to established the reference performance models.

Two engine performance models are set up to cover
Group #1: Aircraft #1 and #2
Group #2: Aircraft #3-#12

As indicated earlier, the FOQA data are arranged to include the following variables: pressure altitude, flight Mach number, outside air temperature, airspeed, N1, N2, and EGT.

For Aircraft #3-#12, the variables include EPR that is available only for these passenger aircraft: pressure altitude, flight Mach number, outside air temperature, airspeed, N1, N2, EPR, and EGT.

To avoid too much similar data being used in modeling to slow down the numerical convergence, typically the data are thinned by keeping one record in every two in such a way that the total number of records in climbing and partial cruise is approximately equal. The operator's experience in engine health is assumed to be such that $\Delta$(EGT) defined as $\Delta$(EGT) = reference EGT—sensed EGT is within (10,-5). In other words, the actual EGT reading should not exceed the reference EGT by 5 degrees C, nor below the reference EGT by 10 degrees C to be considered as being normal. In a study of helicopter engines, the accuracy of EGT sensing was taken to be 3 degrees based on the recommendation of a manufacturer's engineers (12). Here we assumed a more liberal value of 5 degrees C for transport airplanes' engines. The reference EGT will be provided by the present modeling. As explained in the last section, this will be called the model-based filtering.

*Model-based filtering*

In Group #1, data from all four engines of Aircraft #1 after thinning are employed in establishing the reference model. After $R^2$ remaining unchanged and change in SSE is small ($<10^{-7}$), the original data set is replaced with the filtered data set. This process continues until the filtered data set remains unchanged. Then data from the first engine of Aircraft #2 are added. This is needed because part of the operational conditions of Aircraft #2, such as the pressure altitude and outside air temperature, are outside the ranges of Aircraft #1. The squared correlation coefficient ($R^2$) for the final mixed data set is 0.9998.

For Group #2, data from all four engines of Aircraft #3 are employed in modeling. To cover a wider range of operational conditions, model-filtered data from Engine #2s of Aircraft #5, Aircraft #7, and #9 are also added. Furthermore, data points from the other aircraft with flight conditions not within the range of the combined data set are also incorporated subsequently. Altogether, there are 9656 data points. The final $R^2$ is 0.9983.

Note that not all defects can be detected through engine performance monitoring. However, the following malfunction modes, by Pratt & Whitney and reported in Reference 9, are useful in identifying those detectable malfunctions:

1. Failures due to air leakage from compressor cage will result in drop of EPR, and to regain EPR, fuel flow, EGT, and N2 would be increased.
2. Compressor contamination from salt water and oil leak will change the aerodynamic shape of airfoils and, hence, will increase EGT and N2.
3. Mechanical failures, involving a few blades or vanes, will increase N1 and N2 at a given power setting and, hence, EGT in high power setting.
4. Failures in combustion section, such as blocked fuel nozzles, fuel line leaks, burner, are difficult to detect, except when it is severe enough.
5. Failures in high-pressure turbines, such as broken blades, seal erosion, etc., will cause the turbines to absorb less than the desired work and result in drop in N2 and, increase in fuel flow and EGT at a given EPR. N1 is relatively unchanged.
6. Failures in low-pressure turbines will results in drop in N1 and increase in EGT and fuel flow at a given EPR. N2 is relatively unchanged.
7. Vibration: broken turbine blades will result in sudden change

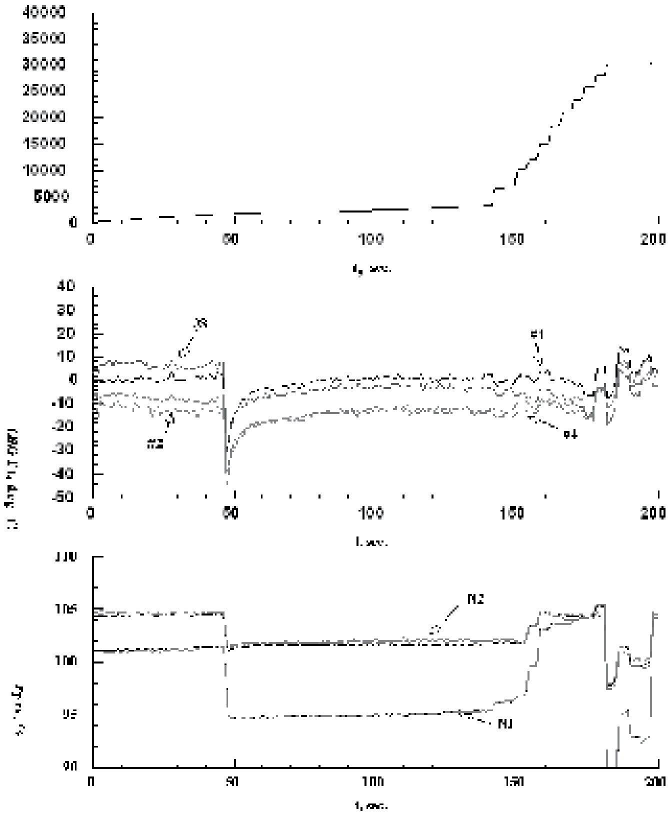

*Figure 1. Predicted engine performance of Aircraft #1.*

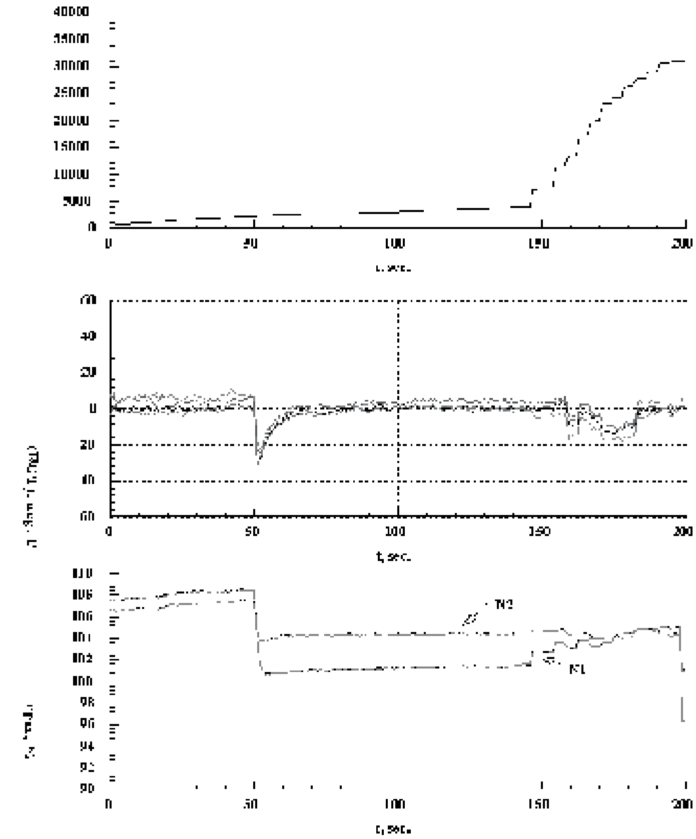

*Figure 2. Predicted engine performance of Aircraft #2.*

in vibration level, while a progressive change in vibration level indicates bearing malfunction.

8. Instrumentation error: trend in only one parameter is indicated. Note that a malfunction affecting the gas path will cause trends in at least two parameters.

9. Foreign-object damage (FOD): in case of extensive damage, it will be indicated by vibration and changes in the engine's normal operating parameters, such as a decrease in EPR and increase in EGT.

10. Recoverable compressor surge: drop in N1, N2, and EPR, but increase in EGT within a short time period, with all these parameters returning to normal conditions subsequently.

## 5. Results and discussion

In the figures presented below, all plotted parameters, except Δ(EGT) and the sensitivity derivatives (to be defined below), are directly obtained from the flight data recorders. It should also be noted that the present prediction method based on a reference model presumes that the measurement location of EGT for all engines is the same or very close.

*Group #1*

After the reference engine operational model is established, it is then used to predict the EGT for all engines under the operational flight conditions without filtering. The results in climbing flight for Aircraft #1 are presented in Figure 1. Around 50 seconds after the takeoff run, Figure 1 indicates that EGT exceeds the model-predicted values by a large amount. This is perhaps because the engines were throttled back (i.e., reducing RPM) and there is a time lag for the thermodynamic field to adjust. It should be noted that reducing the throttle is one technique in flight to recover from engine surges to a more normal operation. The results indicate that Engines #2 and #4 have much higher exhaust gas temperature (EGT) than the reference model prediction under the same operational conditions for all engines. For the purpose of comparison, the engine performance of Aircraft #2, though not reported to exhibit engine surge, will also be presented. Figure 2 presents the prediction for Aircraft #2 by using the same reference model. In this case, all four engines appear to be healthy as the actual EGT readings are not much different from the model prediction.

For trending purpose, it is desirable to have some numerical values to represent the overall performance in climbing flight. This is done by taking time-averaged EGT excursion, in other words, integrating Δ(EGT) with time and then dividing by the total time. For both aircraft, this is done within 0 to 200 seconds after takeoff. The results are presented in Table 1. A large negative value less than -5 degrees C means not "normal." As indicated in figure 1, N2 for both Engines #2 and #4 of Aircraft #1 are slightly higher than those for Engine #1, by about 0.5% based on the numerical data. The flight crew has reported "short, minor engine surge" in the flight under the present investigation. The conclusion of the present study is that malfunction Mode #5 may apply for the most part for this airplane's engines. That is, the abnormal EGT indication is most likely caused by abnormality in some high-pressure turbine (HPT) blades.

It should be remarked that after the present analysis was completed, the inspection maintenance records were checked. After several days of the flight, a borescope inspection of Engine #4 of Aircraft #1 revealed minor crack in the combustion chamber and slight HPT trailing edge and tip melting similar to those found

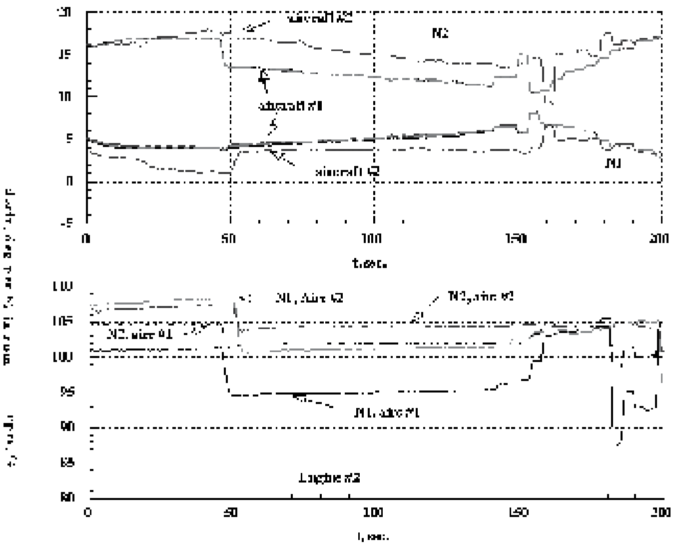


*Figure 3. Sensitivity derivatives for Aircraft #1 and #2.*

in a study of helicopter engines (12).

Although the engines of Aircraft #2 appears to be healthy, it is still of interest to determine the relative efficiency of compressors and turbines between these two aircraft through sensitivity analysis (13, p. 135). The results are compared in Figure 3. Because Aircraft #2 is heavier, it relies on N2 to generate more thrust. The sensitivity derivatives are defined as

Deriv1 = , deriv2 =

Figure 3 indicates that Aircraft #2 has larger deriv2 and hence is more responsive. Since deriv1 and derv2 for Aircraft #1 are still relatively largely positive, these results should corroborate the conclusion made earlier about Engines #2 and #4 of Aircraft #1; i.e., the abnormality was not caused by the aging process.

***Table 1. Predicted Time-Averaged EGT Excursion in Climbing Flight for Aircraft #1 and #2***

| Aircraft | Engine | Averaged EGT excursion, degrees C |
|---|---|---|
| #1 | 1 | -0.11 |
| | 2 | -11.91 |
| | 3 | -2.52 |
| | 4 | -11.83 |
| #2 | 1 | -1.84 |
| | 2 | -0.56 |
| | 3 | +1.51 |
| | 4 | -1.57 |

*Group #2*

As indicated earlier, data from several engines, not necessarily from the same aircraft, after thinning are utilized in modeling. The final $R^2$ is determined to be 0.9983, indicating that the resulting model can explain or represent more than 99.83% of the data. The predicted performance of Aircraft #3 is presented in Figure 4. Only results in the climbing and part of the cruise phases are presented. The main objective is to determine if engine surge occurred. From Figures 4(c) and 4(d), it is seen that both the RPM and EPR suddenly drop at around t= 500 and 3600 seconds and the decrease lasts several seconds before recovery. This phenomenon points to the occurrence of compressor surge. In fact, during the surge, airspeed stops increasing in climb or even decreases in level flight (see Figure 4(f)). The drop in RPM of the low-pressure compressor (N1) is much larger than N2. Note that N1 is a certified thrust-setting parameter. However, since all four engines suffered the compressor surge at the same time, the only

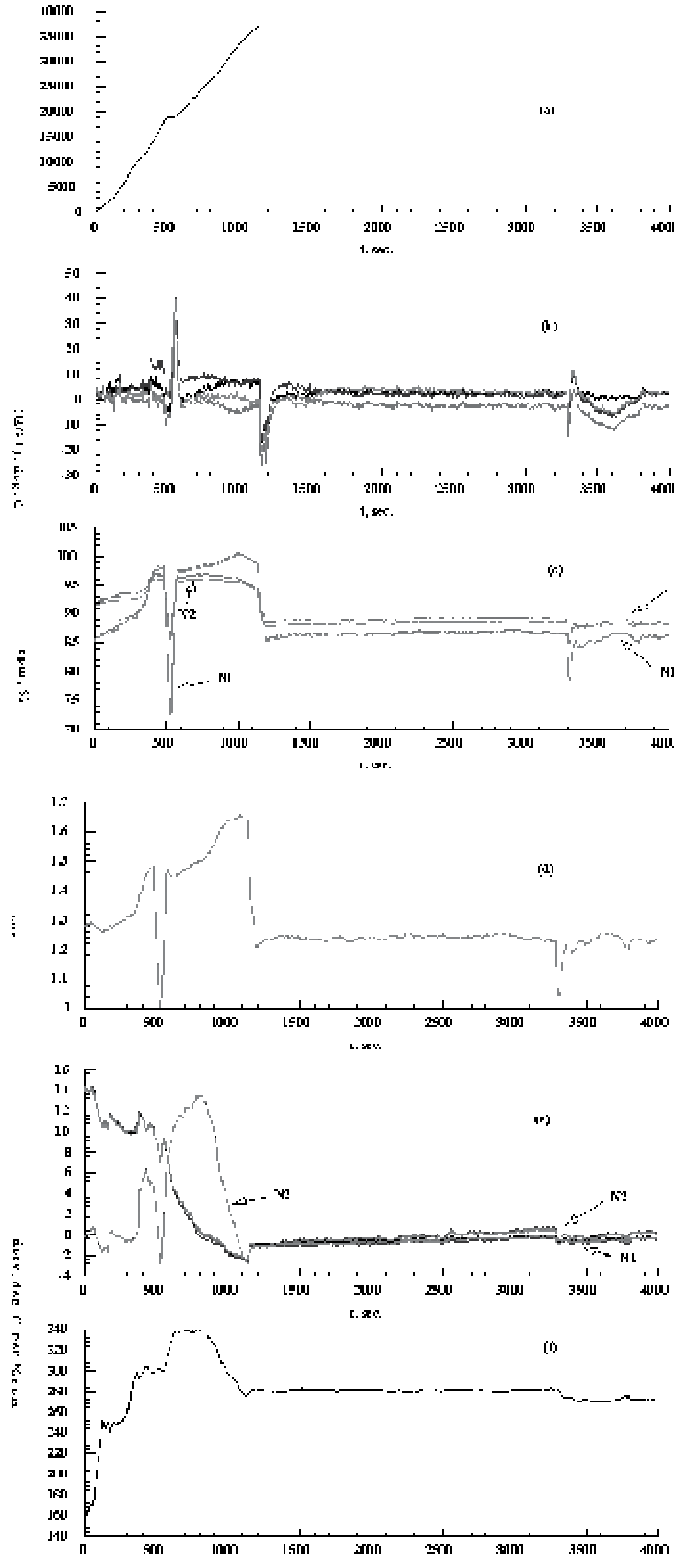


*Figure 4. Predicted engine performance of Aircraft #3.*

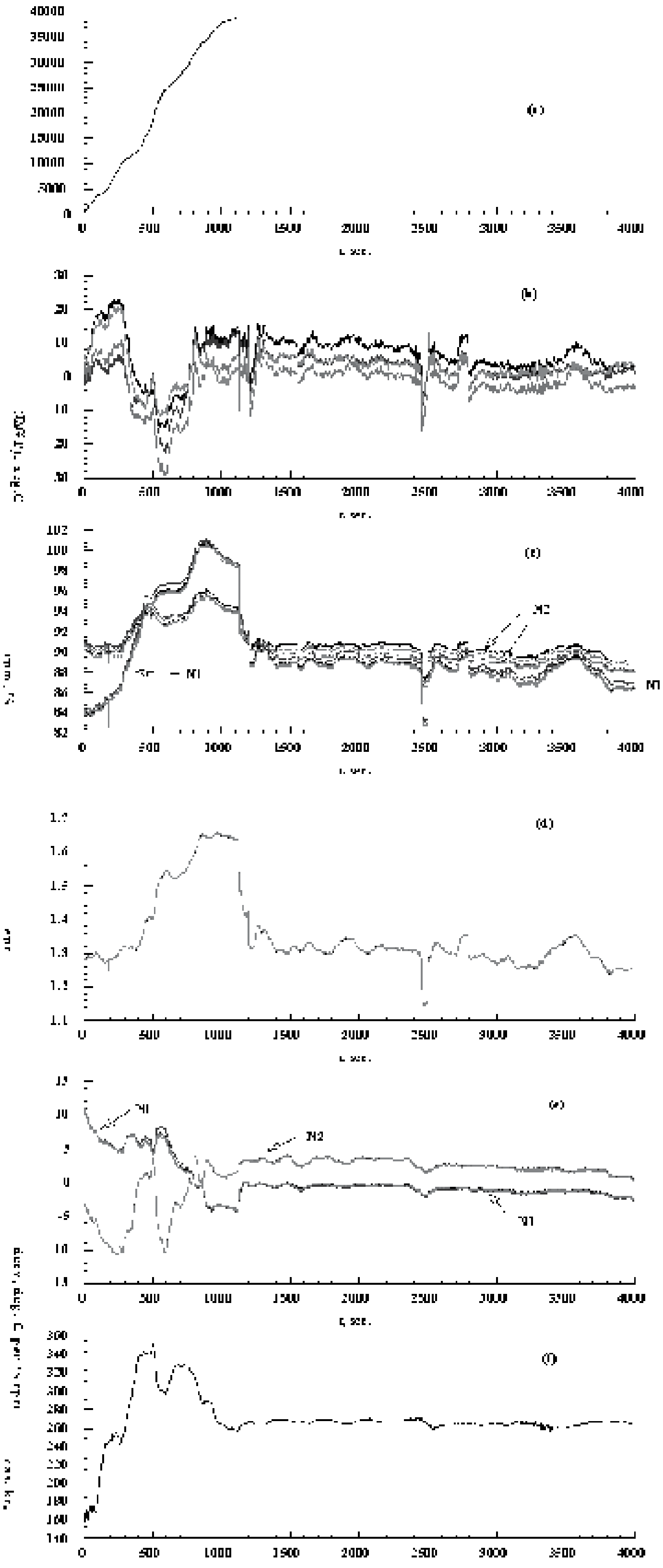

*Figure 5. Predicted engine performance of Aircraft #4.*

explanation for the surge is that it is probably caused by atmospheric disturbances, such as turbulence. The stall is less severe for the high-pressure compressor (N2); and there is still a large volume of air passing through the engine so that the exhaust gas temperature exceedance is not high at that moment.

As a byproduct of the investigation, it is possible to compare the general health of the engines. Engine #4 is seen to have the worst Δ(EGT); that is, the sensed exhaust gas temperature exceeds the reference values by a larger amount than other engines. In addition, N2 is higher (see Figure 4(c)). This implies that Engine #4 may have compressor contamination (Malfunction #2). As shown in Figure 4(e), both derv1 and derv2 in cruise are relatively small, implying either the engines were running at a nearly optimal condition or the engines were not responsive because of aging. Borescope inspection of the engine indicated anomaly of turbine blades, presumably as a result of frequent encounter of high exhaust gas temperature.

For Aircraft #4, the results are presented in Figure 5. From Figures 5(c) and 5(d), it is seen that N2 and EPR drop moderately at around t= 520 and 2500 seconds and the decrease lasts several seconds before recovery. The resulting exhaust gas temperature exceedance (- ΔEGT) is large, in particular around t=520 seconds (see Figure 5b). Again, this phenomenon points to the occurrence of compressor surge, even though this was not indicated in the ACARS report. The drop in RPM of the high-pressure compressor (N2) is larger than N1 around t=520 seconds. Therefore, at the first surge event, the stall is more severe for the high-pressure compressor (N2), and there is not enough volume of air passing through the engine. However, since all four engines suffered the compressor surge at the same time, again the only explanation for the surges is that it is probably caused by atmospheric disturbances. Note that there is another surge at around t=200 seconds of short duration.

Again, Engine #4 of Aircraft #4 is seen to have the worst Δ(EGT); that is, the sensed exhaust gas temperature exceeds the reference values by larger amount than other engines. In addition, N2 is higher (see Figure 5(c)). This implies that Engine #4 may have compressor contamination (Malfunction #2). Figure 5(e) shows that derv1 in cruise is small, implying probably the nearly optimal setting of operation.

*Additional results*

Typically, when there are no reported events, engine inspection is not performed, except in a standard scheduled maintenance. In the process of establishing the reference performance model, we found several aircraft or flights exhibiting engine surge similar to those in Aircraft #3 and #4. One notable one is Aircraft #9. Therefore, only this additional set of results will be presented.

From Figures 6(c) and 6(d), it is seen that there is a drop in RPM and EPR at around t= 1800 seconds. The exhaust gas temperature exceedance (-ΔEGT) is large (see Figure 6b), in particular for Engine #4. These phenomena indicate the occurrence of compressor surge caused by atmospheric disturbances because the surge occurs in all engines at the same time. Since the drop in N1 is much larger, the low-pressure compressor is more severely stalled than the high-pressure compressor. In addition, at t=2260 seconds, there is a slight, quick drop in N1 and EPR of Engine #4, indicating a single surge. Subsequently, the exhaust gas temperature of Engine #4 increases (see Figure 6b) and does not recover to the pre-event level. According to Reference 1, this excessive EGT of Engine #4 is indicative of either a major bleed air leak or severe engine damage, such as failure of HPT blades, or sensor failure. Larger EGT values for Engine #4 have also been verified by a direct inspection of the FDR data. Figure 6(e)

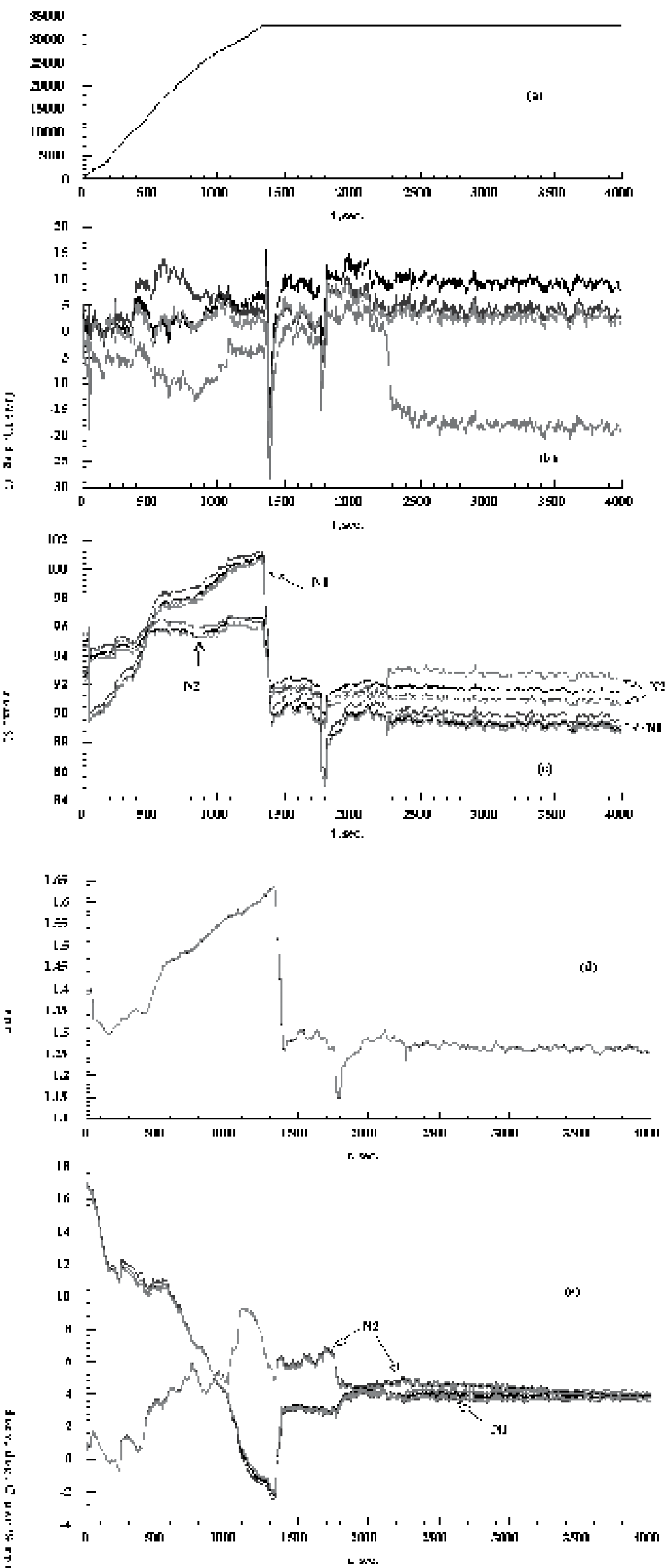


*Figure 6. Engine performance for Aircraft #9.*

indicates that both derv1 and derv2 are all positive, implying the engines were still relatively responsive when the surge occurred.

## 6. Concluding remarks

Engine performance models were established by utilizing flight data in the flight data recorders for two aircraft types. Twelve sets of aircraft flight data were employed, including two four-engine jet freighters and 10 sets for four-engine passenger transport airplanes. Performance reference models were obtained through model-based filtering and fuzzy-logic modeling. Based on the previously established malfunction modes, the model-predicted results could be examined to identify the causes of engine surge and failing engine parts as well. For the freighter aircraft with the reported surge event, it was predicted to be caused by the anomaly in the high-pressure turbines. For the passenger aircraft with the reported surge event, it was predicted being caused by atmospheric disturbances, with possible compressor contamination and some anomaly in turbine blades, based on the predicted high exhaust gas temperature. Both predicted events have been verified by engine inspection. The Other two passenger aircraft examined have exhibited similar surge events as well. However, the events were not detected by the existing monitoring system. ◆

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# Practical Human Factors in the Investigation of 'Daily Events'

By Paul Jansonius, Standards Pilot, Human Factors Training, WestJet Airlines, and Elaine Parker, Operations Manager, North Cariboo Air

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## History

In 2001 the companies that would become Air Canada Jazz were in the process of merging, and at that time the two authors of this paper worked for this newly "birthing" company.

The safety and human factors team in the "soon-to-be Air Canada Jazz" company was tasked to look at bringing human factors (HF) components formally into the incident database system. In this tasking, the following items were considered critical:

- make sure the data being gathered can be used (don't just collect it because we can),
- plan the feedback and utilization into the working system, and
- make the process as simple as possible so that the company will keep on doing it.

The team examined the human factors models that were in use in external database programs and found most of them to be fairly complex. They then examined the current model of human factors (the HF "tool box") that was being taught in the company's current company resource management (CRM) program.

The team tested the model using a real company event where a detailed investigation and good crew information was available and the crew was still willing to discuss the event. When utilizing the model on this test, the team concluded that the ability to track SUCCESSES, not just error/failure, was critical in learning about events.

Very few, if any, of the models the team encountered were able to do this and after the initial test this capability (recording successes) was considered a **need,** not a want, in determining the program.

The model that was chosen was an adaptation of the human factors toolbox the company was utilizing in the CRM program (the adaptation being recording the successes). A template was built into the computer program for use. Due to the complexities of merging four regional carriers and competing priorities the project languished for a while.

## Revitalized development

In the spring of 2004, WestJet and Jazz revitalized the concept of bringing the training in Human Factors (under CRM) into the investigation of incidents through the safety department.

Jazz had a draft of the human factors in its database from the preliminary work done in 2001. WestJet did not have anything in place.

Jazz determined there was no benefit to changing models, although there were disadvantages to the one they had (there are disadvantages to all of them).

As WestJet did not have a model in place, it was more able to select/design its own. However, WestJet was looking at the database for its incident management, and the human factors "built in" components needed to be considered. The built-in components were all fairly complex and were ruled out for that reason.

In the summer of 2004 Jazz, commenced "testing" of its system by investigating and entering human factors in a percentage of the files. In January 2005, based upon this testing, Air Canada Jazz began to "go live" and require the human factors analysis on specific files.

In 2004, WestJet built its model; in 2005 it has begun to test the model and the system.

## Basic definition

In developing their models, the two teams agreed that the following was critical:

- **The observable act**

All items recorded as HF must either be something that was an action or inaction (the individual did or did not do a thing that was observable) or a stated perception of the individuals themselves that could not be refuted by other facts in the investigation.

## Jazz model

The regional safety officer investigates all safety-related events from both a technical and human factors perspective. The safety officer writes a third-party narrative for general release that gives the step-by-step detail of the event. Actions taken after the event are recorded as are preventative measures taken. These fields in the database are common access. In a "behind-the-scenes" page, the human factors components are recorded.

After the investigation the human factors team meets to review the event. There must be a minimum of three people on the review team—the safety officer who investigated, a member of the company resource management development and training group, and an employee representative from the pilot association. Air Canada Jazz found this "tri-partied" group to work exceptionally well with the different perspectives assisting in better analysis and better feedback to the investigator to improve subsequent investigations.

Observable acts are described and then assigned to a "crew," which may be the flightdeck crew, the cabin crew, the maintenance crew, the airports crew, the dispatch crew, the management crew, or "other" for outside agencies. Once the observable act is described and the crew defined, the analysis team determines the human factor "code" to assign and determines if it was a positive or a negative contributor.

The possible codes are

1. External—expected
2. External—unexpected
3. External—latent
4. Crew—communications
5. Crew—intentional non-compliance
6. Crew—proficiency
7. Crew—procedural
8. Crew—operational decision

For example, on a landing gear failing to indicate down event, here are two of the observable events as recorded on the Human Factors Analysis Page:

**Crew Defined:**
Flight deck
**Description of Specific Threat/Error or Condition/Action:**
The crew confirmed the gear was extended and locked using the alternate lights.
**Code:** +7 (positive 7, crew—procedural)

**Crew Defined:**
Flight deck
**Description of Specific Threat/Error or Condition/Action:**
The crew changed the burnt out light bulb while in flight; this procedure is not in keeping with the elementary maintenance training they had received.
**Code:** - 7 (negative 7, crew—procedural)

## WestJet model

The WestJet model is based on the experience and lessons learned from the Jazz model, and from work done at WestJet both in our HF training and in the implementation of HF assessment in LOFT and simulator training. Considerations for determining the HF elements to assess were both accessibility and simplicity. A primary concern was that the information collected was not simply data for the sake of having data, but would be useful to the different departments when the information was passed on for corrective action.

As with the Jazz process, the WestJet HF classification team consists of at least three members to test assumptions, and ensure that any questions have been, or will be, clarified by the author of the safety report. This ensures that we are assessing the incident as it was experienced by the participants, and not through the assumptions of the investigators. Currently the classification team consists of the Director of Corporate Safety, the associated departments Safety Officer, and the Standards Pilot HF Training. As the week's companywide safety reports are all addressed in the same meeting, there are usually Safety Officers from different departments present, which provides a beneficial difference of perspective to the analysis.

The following is an outline of the HF elements as they appear on our HF assessment form along with the short description included to help the investigator test his/her assessment *(italic)*.

***Human Factors Classes***

***1. Skill based***

***1A. Absentminded, automatic***

Slip of habit, recognition failure, lose track of past actions, memory block.

***1B. Technique***

Unable or difficulties in performing a particular task.
If unable, due to lack of training or information, this would be a technical issue, not HF related. Cases where the individual has been trained, but is unable to properly perform the task, would be HF technique.

One of the fundamental concepts promoted in our HF training is that of the relationship between skill and error. The stronger or better developed a skill, the greater the potential that a habit pattern, or muscle memory, will result in an action that may be completely inappropriate for a given situation. These errors are most likely to occur when a repetitive or structured task (checklist, SOP) is misapplied or omitted altogether.The flip side of this coin, would be error that results from the lack of a skill—a proficiency issue, or misunderstanding the application of a procedure. The desire and intent to comply may exist, but the capabilities do not.

***2. Intentional non-compliance***

*Deviation from procedure, regulation, or written policy. Cutting corners.*
May be a norm in the operation, tolerated by supervisors, maybe even sanctioned.

This category is applied exclusively to those occasions where a crew is aware of, and understands, a given procedure but elects not to follow it.

***3. Operational decision*** *(No intentional non-compliance.)*

*Where the decision-makes find themselves in uncharted waters and must use a slow and effort- filled reasoning processes that may be affected by insufficient time or faulty logic. Decisions that result from deliberate, conscious thought. Was the choice a good or a bad one? Risk management.*

***3A. Threat/error management***

*A situation that is unique, for which there is no procedure or policy.*
*Error recovery is not a normal part of the written procedure. If the crew recognizes, "traps" an error, the decisions made regarding. the recovery would be an "operational decision."*

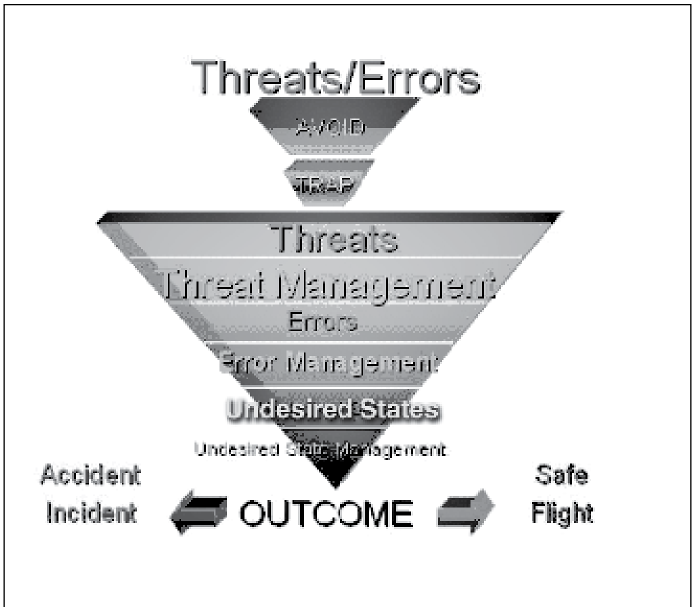
*Similarly, any identified threats not managed by procedures or policy would require an, and fall under, "operational decision."*

*A decision to deviate from the standard, or written, procedure, would be considered "intentional non-compliance,"* ***NOT*** *"operational decision."*

***3B. No decision made***

*No decision where one should have been made (failure to see/understand/identify threat).*

Within the context of threat/error management, the category "operational decision" relates to the crew's ability to identify and man-




age threats that arise in the operation. Given that no SOP can identify all contingencies or circumstance that a crew may encounter, this category allows us to examine the caliber and success of the decisions the crew make operationally. Where a "decision" is made to deviate from a standard operating procedure, the act would be categorized as "intentional non-compliance." The only exception would be if it was understood the deviation was made to manage a threat not considered or managed by the SOP—again, a situation that, through the interview, considers the crew's thought process rather than the assumptions and perspective of the investigator.

***4. Communication***

***4A. Utilization of other resources***

*Were other group people contacted or utilized?*

***4B. Quality of communication***

*Was the communication used clear, unambiguous, and understood? Was there clear acknowledgement? If trail balloons were used, was the meaning clearly understood or clarified, if required?*

Again, in our HF training, we discuss the use of "trial balloons" or the "hint and hope" style of indirect communication used in our polite society and as a technique used by less-senior crew to communicate through higher levels of rank. Was a critical communication not understood, clarified, or received? If there was no acknowledgement garnered by the sender resulting in missed communication, it would be categorized as "quality of communication."

The other consideration is whether the crew made use of other resources in determining its course of action. That might be other members of the crew/group, ATC, or OCC/Dispatch.

***5. Physiological***

***5A. Adverse mental states***

*Complacency, stress, distraction, task saturation.*

***5B. Adverse physiological states***

*Fatigue, illness, effects of medication, motion sickness.*

***5C. Physical or mental limitations***

*Visual limitations, overload, reaction time.*

***5D. Personal readiness***

*Rest, self-medication, diet.*

***5E. Physical environment***

*Temperature, noise, lighting, equipment interface.*

Initially the category "physiological" was dismissed from the form. However, as we began testing the process, it became apparent that workload, fatigue, and (especially in areas other than flight operations) physical environment were being cited as contributors by interviewees. This category was also of interest to the flight safety group as the airline has started operating longer flights, often with multiple crossings of up to four time zones. (This entire physiological section was taken directly from the work of Dr. Scott Shappell and Dr. Doug Wiegmann. Refer to their paper from 2004 ISASI in Australia.)

***6. Other***

The category "other" was included to allow for the eventuality that an issue might arise that does not match any of the other criteria. Should this category find frequent use, it would then bring into consideration a new category to track any recurring issues.

## Example situation utilizing the Jazz model

**Narrative**

After a normal takeoff at between 1,300 and 1,500 ft in the initial climb, the crew received a cargo hold smoke detector indication. The first officer was the flying pilot and the captain contacted the flight attendant and informed the flight attendant that there was indication of a fire in the back.

The flight attendant understood the concern to be regarding the aircraft engines and went into the cabin and checked out the windows looking at the rear of the engines.

The captain then declared an emergency with air traffic control (ATC) and the actions for returning to the departure airport were taken.

As the captain was talking with air traffic control passing the fuel and passenger loads, the flight attendant called the flight deck. The first officer took the call from the flight attendant, who informed the first officer that there were no smoke or flames visible but it was difficult to be sure because of the aircraft being in cloud. Though the first officer thought the comment was odd, it was not questioned.

After completion of the transmission to air traffic control the captain was advised by the first officer that the flight attendant said there was no sign of smoke. The flight deck crew agreed it was unlikely there was a fire but planned to land and confirm. The captain then made an announcement to the passengers advising them of the return to the departure airport and that further information would be given upon landing. The flight attendant resumed her seat for what she perceived to be an abnormal landing.

The landing was completed without difficulty and the flight deck crew advised air traffic control that they would proceed onto the taxiway to confirm the situation. The engines were left running while the first officer left the flight deck and proceeded to the cargo hold to check conditions. While the first officer was checking the cargo hold, the fire department outside the aircraft asked for the engines to be feathered while they checked the exterior of the tail and opened the cargo hold to check. Everything was normal, and the first officer returned to the flight deck and the aircraft was taxied back to the terminal.

**Human Factors Analysis**

| Crew Defined | Description of Specific Threat/Error or Condition/Action in this Event | Code |
|---|---|---|
| O | The smoke warning light for the cargo compartment illuminated in the climb-out phase of flight. | -2 |
| F | The captain was the non-flying pilot and contacted the flight attendant and stated that there was an "indication of fire in the back." | -4 |
| I | The flight attendant believed that the fire was in the "back" of the engine and checked the back of both engines. | -4 |
| F | The flight deck crew declared an emergency and returned for landing. | +8 |
| F | The flight deck crew did not follow the Quick Reference Handbook for the general smoke procedures or for the smoke warning light. | -7 |
| I | The flight attendant reported to the flight deck that she was "unable to see fire but that it was difficult to tell since the aircraft was in cloud and it was difficult to see." | +4 |
| F | The first officer took the call from the flight attendant and noted that her comment regarding being in cloud was odd, but the first officer did not pass that information to the captain nor did he ask for clarification from the flight attendant. | -4 |
| F | The flight deck did not brief the flight attendant about the type of landing. | -7 |
| F | Once the aircraft stopped, the flight deck crew did not utilize the flight attendant to check the cargo hold, rather the first officer went to the hold himself without discussing or involving the flight attendant and returned to the flight deck without discussion or involving the flight attendant. | -6 |

## Example situation using the WestJet model

This example involves a crew that was faced with a runway change during taxi for takeoff in a busy airport. The process we use for entering takeoff data to the FMS is through an ACARS uplink, which is initiated by an ACARS request for data on up to three different runways.

As the crew was having difficulty receiving the ACARS uplink (technique), it elected to revert to the manual method, using the data provided in the flight release. This process was performed by the first officer and monitored by the captain as he taxied ahead in the line up for takeoff. In the process, the first officer made an error and derived speeds using their zero fuel weight rather than the GTW, a difference of 20,000 pounds. The captain (FP) missed the error during the data entry, but trapped it on takeoff when he recognized the abnormal performance on rotation and maintained a 10-degree pitch attitude till the aircraft flew away.

The ACARS takeoff data system is still in its first six months of operational use and as such is still quite new to the crews. There is an SOP bulletin regarding the systems use and common errors and includes guidance on managing a runway change. It states;

"The optimum time and place for a runway change is at the gate with the park brake set. This allows for the uninterrupted attention of both pilots through this crucial process. If it becomes necessary to perform a runway change after engine start or pushback, the crew should delay the FMC entries associated with the runway change until the aircraft can be stopped. This will allow for the uninterrupted attention of both pilots during the confirmation/verification process as well as mitigate the risk of taxiway/runway incursion."

The use of the word "should" rather than "shall" in the guidance regarding stopping to make the data entry required further interview with the crew to understand if they were in "non-compliance" or making an "operational decision" to continue taxi during the process.

**Department/Involved Parties**
Maintenance
Flight deck
Inflight crew
Airports customer service
Airports ops
Dispatch
Other

---

**WestJet Human Factors Assessment Tool**
Assessors: ______________________________

______________________________

______________________________

| Department/ Involved Parties | Observable Act | Human Factors Class | Impact (+/-) |
|---|---|---|---|
| Flt Deck | Did not stop to reprogram the FMS when runway changed (Possible norm at this airport) | 2 or 3A | - |
| Flt Deck | Manual T/O data entered without verification | 2 | - |
| Flt Deck | Manual T/O data entered without verification | 5A | - |
| Flt Deck | Runway change reprogramming not done as per SOP | 1B | - |
| Flt Deck | Wrong data from TLR entered into FMS | 1A | - |
| Flt Deck | General contributing factor—fatigue (circadian shift, loss of sleep, YHZ 0530 check in) | 5B | - |
| Flt Deck | Maintained maximum 10 degree pitch on T/O | 3A | + |
| Flt Deck | Pilots consulted F/As regarding abnormal T/O indications (i.e., tail strike) | 3A | + |
| Flt Deck | Pilots consulted F/As regarding abnormal T/O indications (i.e., tail strike) | 4A | + |
| Flt Deck | Adjusted target V2 bug to V2 + 15 after T/O | 3A | + |

## Difficulties, results, and surprises

The companies have found little difficulty in the tri-partied assessment group agreeing on the observable acts or on coding the acts; however, there was a great deal of difficulty on the extent to which single observable acts should be noted. For example, if a procedure with seven steps was done correctly for six but incorrectly on one, should each and every step be recorded or just "significant" steps. (This is still being resolved.)

Another difficulty is when an observable act falls in more than one human factors code area—should it be listed twice, for example, the communication of information and the procedure to communicate. (This is still being resolved.)

In both of the above difficulties, the inclination to solve the problem by increasing the amount of data recorded has to be balanced against the original requirements to keep the system as labor UNintensive as possible and to record only information that can reasonably be used by the operational and training departments.

As expected, the companies found the following results by adding human factors analysis to the database for events:

- improved technical investigation,
- greater interaction with the crews,
- improved feedback to crews,
- better data to support changes,
- labor intensive and resource needy process, and
- although the examples in this paper were flight operational in nature, the process works well in all areas of the safety management system (maintenance, ground operations, etc.).

Though not really a "surprise," the companies also found that

- little or "minor" events are more data rich as people will talk about the bad things when they are small easier than the *big* bad things (the higher profile the event, the more discomfort in talking about why something was done the way it was),
- proof of the effectiveness of major event training (consistent excellent handling of engine failure procedures etc.), and
- proof of the small events hiding much bigger problems than they first appear to be.

### The flightpath ahead

Air Canada Jazz and WestJet proved that two *highly competitive* airlines can work together productively on safety issues despite all the commercial pressures. They have shared information with one another and with other organizations.

Air Canada Jazz has entrenched the human factors analysis in their safety management system and will continue to improve the process and glean useful information to enhance safety. Air Canada Jazz proposes to look at the abnormal (non-serious) events in more detail as it has found those to be richest in information (example, two engine go-arounds, minor or inconclusive indication problems immediately after takeoff).

WestJet continues to test and gain experience using its HF analysis tool through the sharing and analyzing of safety reports brought forward by different members of the team. The system will not be a fully integrated part of the investigation process, though, until a new database has been selected and is brought on line as part of the safety management system at WestJet.

North Cariboo Air will be building on the results of these two companies and implementing the human factors analysis into its new safety management system and event investigation and follow-up program.

All three companies are open to sharing their knowledge and learning from other operators.

Another key concept in our HF and simulator training is that of threat error management. The WestJet TEM model promotes SOPs as a first defense to avoid and trap threats and errors. The need exists to identify threats and manage expected, unexpected, or latent threats before they can result in an outcome. Managing the undesired states that can result from unidentified threats or errors is necessary. ◆

# Safety Incident Classification Systems—Made Redundant by Text Mining Tools?

By Tom O'Kane

***Tom O'Kane** helped develop Operational Flight Data Monitoring at British Airways in the early 1970s. He was an avionic system design engineer and spent 4 years in Seattle as the British Airways representative at Boeing. He has held general management positions at British Airways in engineering, treasury, information management, aircraft operations, crew scheduling, and safety services, where he was Head of Air Safety and ran the BASIS business. Tom is now an aviation safety consultant specializing in safety management systems. Tom has an honors degree in electrical engineering (1971), a masters degree in computer systems engineering (1977), has completed the Executive Management Program at Harvard Business School (1988), and is a Fellow of the Royal Aeronautical Society (FRAeS).*

## 1. Introduction

As a fundamental part of their safety management system airline safety departments receive and review reports on safety incidents occurring within their organization. The most serious incidents will be investigated and recommendations made to prevent their reoccurrence. Those of a less-serious nature will be noted and stored in a database for possible future reference. To enable better analysis of the complete incident database, many airlines will manually classify safety incidents into predefined categories and assign risk levels to each one. This is carried out by using either their own in-house classification system or a system such as that incorporated in BASIS (British Airways Safety Information System). The capability to analyze the safety database is fundamental to effective safety management since it provides the means to identify areas of significant risk and monitor the effectiveness of corrective actions. The quality of incident classification and subsequent analysis is very dependent upon the expertise and memory of the airline safety officer. Larger airlines will receive many thousands of reports a year and achieving consistent classification between safety officers is difficult. Classification and risk assessment is an extra task that must be performed by the safety officers though the administrative burden can be reduced if the classification system is well-designed and supported by the appropriate software.

One of the most interesting developments in information management is the increased availability of "data mining" and "text mining" analysis tools. A definition of data mining is "the process of discovering hidden patterns and relationships in data." Text mining involves the application of data mining techniques to narrative or textual information. Might the application of text mining techniques to safety incident reports have the potential to improve safety management by (i) reducing the burden of current analysis and (ii) discovering previously unknown patterns and relationships? Could we feed raw unprocessed reports into the safety database and let the text mining tools identify areas for concern and provide the regular reports required by line management and safety review boards?

This paper investigates the relevance of classification systems in a world where such powerful text and data mining tools exist. It concentrates on flight safety reports but the thoughts apply equally to other safety incident reporting areas such as airworthiness/maintenance, cabin safety, ground handling, and occupational health and safety. It draws on the six proof-of-concept technology demonstration reports sponsored by GAIN (Global Aviation Information Network) and detailed in the references section.

As such, some of the subject matter presented is derived from these reports. Permission to reprint is given by GAIN.

This paper also briefly looks at the application of data mining techniques to Operational Flight Data Monitoring (OFDM) or Flight Operations Quality Assurance (FOQA) as it is known in the U.S.A. OFDM data are inherently "structured" in contrast to the free text narrative found in most safety incident reports.

The paper is not an explanation of text mining techniques and algorithms, as excellent in-depth descriptions of these can be found in the referenced GAIN reports.

## 2. Classification systems

An airline's flight operations manual will specify safety incidents that should be reported by the flight crew. All reports will be routed to the Flight Safety Department, which will determine the level of investigation required depending on the seriousness of the incident. Some investigations will require significant effort while other incidents will only be recorded in the air safety report (ASR) database. A safety tool like BASIS or AQD (Aviation Quality Database) will help manage single-incident investigations and record the outcome and recommended corrective actions. A typical process for managing an individual incident is show in Appendix A.

### 2.1. Use of classification systems

Many large airlines receive in excess of 150 air safety reports a week. Only a minority of these will require any investigation, but each report contains an element of valuable safety information and should be included in the ASR database. Each air safety report will consist of specific or "structured" information, such as aircraft registration, phase-of-flight, etc., as well as a freeform description of the safety event. The purpose of a classification system is to provide additional structured information about the incidents so that the database can be analyzed effectively thereby enhancing safety management. The classification system is not necessary for the management of individual incidents but is required to ensure that the safety information in each incident is available and used in safety analysis and not "lost" in the database. While important safety lessons can be learned from the investigation of serious indi-

vidual incidents, proper analysis of the total incident database provides meaningful trend analysis and information filtering. This allows flight safety officers to identify areas of significant risk and to track the long-term effectiveness of corrective actions. Specifically, analysis of the safety database can
i) identify safety issues that require action.
ii) show areas of highest risk so that resources can be applied most effectively.
iii) provide regular management reports (showing safety trends, etc.) to both senior line management and to review or oversight boards such as a Board Safety Review Committee.
iv) provide feedback and communication on safety issues to "interested groups," such as flight crew, engineers, and mechanics.

### 2.2. Attributes

The primary requirement of a classification system is that it should describe *what* happened. It should also have the following attributes:

- It must be easy to use and understand and not impose a high workload on the person carrying out the data input and classification. For example, the ADREP 2000 system developed by ICAO for recording and structuring information on aircraft accidents is valuable for accidents but would impose an impossible workload on flight safety officers if it were to be used for all incidents.
- Classification will be carried out by a number of people so the system needs to be designed to ensure consistency of input. This consistency requirement is *important* for an individual airline but is *crucial* if data from different airlines are to be analyzed in a combined database.
- It must strike the right balance. If classification is too detailed, every incident will be individual or only part of a small group. If it is too broad, it will not be possible to draw meaningful conclusions from the analysis.
- It must recognize that all the information may not necessarily be available when an incident is classified, usually when the ASR is received. For minor incidents, many airlines will only carry out a single pass classification.
- It must cover the full range of incident types and issues so that all relevant information can be classified, and it must be structured in such a way that it provides meaningful results that can be acted upon, i.e., it must avoid the *"interesting but what do I do with this"* result.
- It must offer a *precise* selection of incidents for display or trending. A filter of a classified database should display *every* relevant incident and *only* relevant incidents. It must avoid the retrieval of irrelevant information "false positives" and, perhaps more importantly, not exclude relevant information "false negatives."
- The system should cater to the expert user who needs to put together sophisticated filters and queries while also being easy to use by the occasional user with more basic requirements.
- A quick response to queries is highly desirable in any software system; therefore, the structure of the classification system should not make this difficult for the software developer to achieve.

### 2.3. Risk

Closely associated with the classification system is the need to provide a means of assessing the risk of an individual incident. A popular solution is to set up a two-dimensional matrix with severity on the y axis and frequency of reoccurrence on the x axis. Cells can then be assigned a risk with A being the highest and E the lowest. See Figure 2.1.

**Frequency**

| Severity | | | | | |
|---|---|---|---|---|---|
| | A | | | | |
| | B | B | A | | |
| | C | C | C | B | |
| | D | D | D | C | |
| | E | E | E | E | D |

***Figure 2.1***

Variations on this theme are possible depending on individual airline needs. Three examples of risk assessment matrices from AVSiS, BASIS, and AQD are shown in Appendix C. It is also possible to employ more sophisticated methods such as decision charts that ask questions such as "Was there injury or loss of life," "Could another single failure have led to the loss of the airplane." These are only usually employed where the degree of investigation between a B and C risk, for example, is significantly different. British Airways Engineering uses such a decision-making process to classify airworthiness incidents.

Another technique is to risk assess the event causes as opposed to the actual events. This provides extremely valuable information as to which root causes are causing the greatest risk and helps prioritize fixes.

Risk assessment of incidents adds further structured data and provides the opportunity to analyze the database on the basis of risk rather than the number of incidents of a particular type.

### 2.4. BASIS descriptor system

The BASIS Classification System is designed to summarize
i) What informed the flight crew of the existence of a problem or threat (*Event Descriptor*), e.g., engine oil pressure.
ii) What the *Immediate Effect* was of the incident or the aircraft/systems/occupants/crew actions, e.g., engine shutdown, altitude deviation, passenger restraint, etc.
iii) What the Operational Effect was, e.g., return to stand, diversion.

This is intended to help define incidents in a clearer manner in order to enable better analysis of the problems and their effects on the airplane and the airline operation. The Descriptor Classification System classifies "what" happened, i.e., the event(s) and not the "why" or causes. Causes are dealt with by a separate factors list (see later).

*Event Descriptors* describe "what happened" and specify a real, apparent, or potential safety occurrence that is normally the trigger for an Immediate Effect. A Descriptor is not necessarily the incident cause. Each Event Descriptor is unique and is found in the drop-down list of only one Event Type.

*Event Types* are sensible groupings of Event Descriptors. They are divided into two subsets, Operational and Technical. Operational Event Types are those involving procedural, human factor, organizational, or environmental issues. Technical Event Types are used only for significant technical defects or for identifying damage. They are organized by ATA chapter. Each Event Type has a unique associated drop-down list of Event Descriptors. An incident can be classified using one or more Event Types.

The Operational and Immediate Effects do not have a hierarchal relationship between each other or with the Event Type. Appendix B shows the list of Event Types used in the BASIS classification system and also the Event Descriptors available for Event Types airport management through to documentation/data. The list of Operational Effects and Immediate Effects is given also.

Factors or causes are used to describe the causal aspects of an incident. They should be kept separate from the incident description as they may not be known until any incident investigation is complete and can often be mistakenly reported by the flight crew.

It is also worth noting that the classified portions of safety reports in different languages could be combined and analyzed in a common database provided that the same classification system is used.

### 2.5. Drawbacks

No classification system is going to be perfect. The need for a system that is relevant, quick, and easy to use will inevitably lead to compromises in the design. A well-designed system will still be subject to inconsistency of classification, and it is highly preferable that an expert user carries out the classification. As not all the information may be available at the time the air safety report is received, it may be necessary to update the classification at a later stage when the incident investigation is closed. However, if classification is carried out at the same time as the decision is made about the level of investigation required for an air safety report, it can be completed in under a minute by a flight safety officer using one of the three main safety incident reporting systems—BASIS, AQD, or AVSiS. The "coordinator" referenced in Appendix A is usually the flight safety officer.

## 3. Text mining and its application to flight safety reports

Text mining tools are designed to analyze freeform text using automated algorithms to identify specific concepts and ideas looking for hidden patterns and relationships. Emphasis is placed on automated learning as the mining tools find patterns without a person asking the initial queries. However, subject matter expertise from a person is always needed to review the results.

### 3.1. Techniques

The techniques used in text and data mining can include the following:

- Classification—Predicting a category for an example.
- Clustering—Partitioning data with similar characteristics into a number of groups or clusters.
- Association Rules—Detects significant associations between objects.
- Decision Trees—Derives decision boundaries to partition data according to particular characteristics.
- Anomaly Detection—Identifying unusual examples.

The processes used to prepare safety databases for analysis, together with various analysis algorithm, used are well-explained in the GAIN reports (see references) so no attempt is made to repeat them here. The reports also explain the various issues that arose due to the techniques used. It is worth addressing three of these as they highlight the problems associated with text mining, particularly on freeform text.

### 3.2. Lemmatization and stemming

English is an inflectional language where a single word (or lemma) may be written in several inflected forms. For example, the verb "to talk" may appear in reports as "talk," "talks," "talked," or "talking." While a native speaker has no difficulty in establishing the correspondence between plural and singular forms of the same noun or between inflected forms of the same verb, computers will typically treat all such word forms as single entities. To alleviate the problems that may arise from such a situation, various techniques have been used to aggregate inflected forms into a common lemma or root and thus reduce the total number of linguistic units to process. Text analysis software can use two different techniques: stemming and lemmatization.

#### 3.2.1. Stemming

Stemming is a well-known technique of form reduction by which a common suffix and sometimes a prefix are stripped from the original word form. For example, a stemming algorithm will remove the final "s" from the word form "areas." It will also successfully treat "believe," "believing," "believes," and "believed" as a single linguistic unit by transforming all those words into the root word "believe." The problem is that it will reduce words with different meanings such as "negligible" and "negligent" and "ignore" and "ignorant" to the same root. The problem for aviation is apparent when "terminal" and "terminated" are both reduced to "termin."

#### 3.2.2. Lemmatization

Lemmatization is another form reduction process by which inflected forms are reduced to their canonical form. For example, verb forms are reduced to their infinitive and inflected forms of nouns will be reduced to their singular form. One benefit of lemmatization over stemming is that it relies on a lexicon and thus always returns valid words. However, this approach leaves the possibility that lemmatization, while potentially valid from a linguistic point of view, may be semantically incorrect. A good example is the substitution of the word "ground" used as a noun with the infinitive verb "grind." In the majority of cases, this will be clearly wrong when applied to flight safety reports. Another example is "smoking" being reduced to "smoke." "Smoking" in a flight safety report is most likely to refer to the act of smoking tobacco whereas "smoke" is probably used in the context of "smoke and fumes."

#### 3.3.3. Dictionaries and thesaurus

The problems with coming up with an aviation dictionary, particularly one that contains all the commonly used abbreviations, are well-documented in the reports. Text mining commonly tries to remove certain words that add little to the overall meaning, for example "to" and "at." However, in aviation these are used as abbreviations for "takeoff" and "autothrottle." All these issues are solvable but require a huge amount of work. It would really be useful if there were a common shared aviation dictionary that could be used by all text mining tools, as this would substantially reduce the costs of each company developing its own.

An important aspect in the construction of dictionaries is their validation. Validation problems are caused by words like "stress," which will have different meanings in different contexts.

"He was under a lot of stress."
"No excessive stress was placed on the aircraft."
"They further stressed that it was a good decision."

Techniques to deal with this issue will depend on the relative criticality between missing "false negatives," i.e., excluding relevant items and returning "false positives," i.e., including incorrect items. One technique uses a rule of thumb involving a threshold whereby an item is kept in a category if at least a certain percentage of hits

(80% say) are "true positives." However in some situations, missing a critical case has far worse consequences than retrieving irrelevant reports so the threshold might be reduced to say 50%.

A simple analogy for the issues in text mining is the use of a spellchecker. To what extent would you be inclined to let spell checker autocorrect? Personally, I want to see all the items the spellchecker highlights and then decide. A large majority of highlighted items are spelling errors but the remainder are words or abbreviations I wish to keep, and the suggested replacements are totally incorrect.

The Polyvista website www.polyvista.com has a short paper *"Know" and "Don't Know": The Building Blocks of Knowledge.* It uses the familiar "Know"/ "Don't Know" matrix (See Figure 3.1) to describe the various states of knowledge.

| | |
|---|---|
| State 2<br>Know What you<br>Don't Know | State 4<br>Don't Know What you<br>Don't Know |
| State 1<br>Know What you<br>Know | State 3<br>Don't Know What<br>you Know |

***Figure 3.1***

The interesting state here is Don't Know what you Don't Know. For those involved in aviation safety management, this is an uncomfortable place to be. Airlines using OFDM or FOQA are making a conscious effort to address this area with respect to the operation of their aircraft. An expert analyst using a well-designed classification system can only analyze the safety database with directed queries about what s/he knows or suspects and cannot easily see the problems in State 4. This is the area where the use of text and data mining has the greatest potential. Analysis of both structured and free text or data can reveal interesting issues that were previously unrecognized.

The IATA STEADES Report (Reference 3) identifies the potential of text mining tools to validate the classification of incidents (Event types and Descriptors) received from the various airline contributors to STEADES. It also identifies the "ability to combine both structured and unstructured data in the same analysis model."

Most airlines have separate databases for air safety reports, airworthiness incidents, audit results, and flight data monitoring events. There is little or no capability available at present to carry out analyses across these databases and look at the whole picture. Text and data mining tools have real potential to help in this area.

## 4. Data mining and its application to operational flight data monitoring

Event detection is the primary tool in most OFDM systems. Events are detected when certain aircraft parameters exceed predetermined thresholds. Analysis of the database of events typically revolves around event types and location. No classification system similar to that applied to air safety reports is used, as OFDM, by its very nature, consists only of structured data. In addition to event detection, some systems also record the maximum and minimum values of a number of parameters for every flight, e.g., "maximum pitch rate at takeoff." The resulting database is called Flight Data Measurements at British Airways and is referred to as "snapshot parameters" in some other systems.

Data mining tools applied to the structured event and "snapshot parameter" data will detect items that were already known from using existing analysis tools. In addition, they can detect interesting patterns and relationships at what could be called a "second level down" that are not at all obvious from the use of existing tools. These exist in the "Don't Know What you Don't Know" state described earlier. The tools are also adept at detecting date-related changes and so could be used to monitor the effect of procedure changes, for example. Once the models are set up, they are quick and easy to use and can be more efficient than some of the existing processes and provide reliable quantitative information.

The tools are not a replacement for existing FDM software and are best applied to the structured output from event detection and "snapshot parameter" software. There seems little point in applying them to the raw parameter data associated with events.

Reference 5, "Application of Smiths Aerospace Data Mining Algorithms to British Airways 777 and 747 FDM Data," and Reference 6, "Application of Insightful Corporations Data Mining Algorithms to FOQA Data at JetBlue Airways," give comprehensive accounts of the potential for data mining to aid in the safety analysis of flight data monitoring databases.

## 5. Improving safety management

Based on the information presented in the previous sections, I believe that it is reasonable to propose the following:

### 5.1. Classification systems are good for

i) filtering and trend analysis.
ii) identifying safety issues by Event Type or risk.
iii) producing management reports where month-to-month comparisons and increases or decreases in numbers are important. Using structured data are the most reliable way of generating accurate statistics.
iv) providing feedback and communication to flight crew and engineers who by their nature like quantitative measures.
v) enabling airlines to share safety incidents and contribute safety incident information to programs such as IATA STEADES (Safety Trend Evaluation, Analysis and Data Exchange System).

### 5.2. Traditional analysis of classified databases is not good for

i) discovering new safety related issues.
ii) generating additional safety information from the freeform text.
iii) running automated queries and reducing analyst workload.
iv) working across different databases.

### 5.3. Text mining systems are good for

i) analyzing freeform text.
ii) looking for unknown safety issues.
iii) running automated queries on structured data.
iv) reducing analyst workload (when applied to structured data).
v) looking at information across different databases.

### 5.4. Text mining systems applied to freeform text are not so good at

i) producing quantitative measures.
ii) running filters and trends.

iii) producing management reports (for action) and factual reports for review and oversight committees.
iv) facilitating the sharing of safety incident data.

**5.5. Flight data are by their very nature fully structured**. The results of the Smiths Aerospace and British Airways Proof-of-Concept Technology Demonstration show the potential for mining techniques to identify unknown issues and produce quantitative information when applied to structured data.

The GAIN report on the Role of Analytical Tools in Airline Flight Safety Management (Reference 7) quotes William Hewlett, the co-founder of Hewlett-Packard, "You can't manage what you cannot measure." It goes on to state, "As implied by the quote attributed to William Hewlett, without a structured approach to measuring each aspect of an organization's activities, managers are forced to resort to intuition and guesswork, unable to determine whether the situation is getting better or worse and whether decisions and actions have the intended effect. This is particularly critical in the case of airline flight safety."

What is required is reliable, quantitative information together with the ability to identify unknown issues. A well-designed classification system, supported by an incident reporting system such as AQD, BASIS, or AVSiS, and combined with text mining capability, can provide this. These tools, used together, can also reduce the administrative burden on the flight safety officer, freeing up time for analysis of results

Are classification systems made redundant by text mining tools? No. On the contrary, they provide the structured data that will enable these tools to work effectively.

In the future, incident reporting systems will be enhanced to provide data mining capability and/or text and data mining tools will be developed to provide safety incident management functionality. In addition, text mining tools need to be developed so that they can be applied across an airlines' separate safety databases, carrying out analysis that is not currently possible.

## 6. Summary

Safety incident classification systems were developed to help manage the flight safety reports that are typically generated by airlines as part of their safety management system. They provide the means for effective analysis for the flight safety incident database in order to identify areas of significant risk and to track the long-term effectiveness of corrective actions. However, there is an administrative burden involved, and the manual classification of incidents reduces the time available to the flight safety officer for investigation and analysis. The system relies on intelligent queries by the user in order to provide useful results. However, an expert analyst using a well-designed classification system can only analyze the safety database with directed queries about what s/he knows or suspects and cannot easily discover "unknown" problems.

Text and data mining tools are designed to analyze freeform text using automated algorithms to identify hidden patterns and relationships. Emphasis is placed on automated learning as the mining tools find patterns without a person asking the initial queries. However, subject matter expertise from a person is always needed to review the results. The tools can identify relationships and associations but are not good at providing reliable quantitative results. They work best when applied to structured data such as that generated by an incident classification system.

A well-designed classification system, supported by an incident reporting system and combined with text/data mining capability, can provide the optimum results from database analysis, i.e., reliable quantitative information together with the ability to identify unknown issues. This will help determine the areas of greatest risk to the operation and improve the effectiveness of the safety management system. ◆

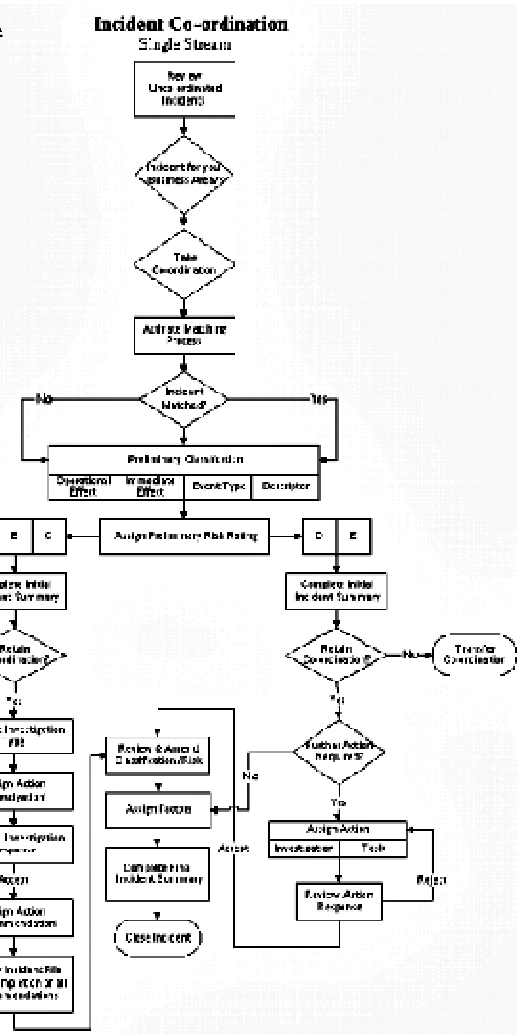
## References


1. Application of Aviation Safety Data Mining Workbench at American Airlines, November 2003.
2. Application of PolyAnalyst to Flight safety Data at Southwest Airlines, January 2004.
3. New Capabilities of PolyAnalyst Text and Data Mining Applied to STEADES Data at the International Air Transport Association (IATA), October 2004.
4. Application of Provalis Research Corp.'s Statistical Content Analysis Text Mining to Airline Safety Reports, February 2005.
5. Application of Smiths Aerospace Data Mining Algorithms to British Airways 777 and 747 FDM Data, December 2004.
6. Application of Insightful Corporations Data Mining Algorithms to FOQA Data at JetBlue Airways, December 2004.
7. Role of Analytical Tools in Airline Flight Safety Management, June 2003.


## Notes

1. The views expressed in this paper are mine and are not necessarily those given in the above references.
2. The BASIS business and software tools were acquired in 2005 by Mercator, the information technology affiliate of Emirates Airlines. BASIS is now also known as SENTINEL.

## APPENDIX A



## APPENDIX B

### Appendix: List of BASIS Descriptors

| Operational Effects | Immediate Effects | Event Type |
|---|---|---|
| Air Turnback | Abnormal Landing | Airport Management |
| Aircraft Unfit for Service | Aircraft Systems Inhibited | ATM |
| Ambulance/Paramedic | Altitude Deviation | Birdstrike |
| Cancellation | Avoidance Manoeuvre | Cabin Management |
| Delay | Damage - Ground Equipment/Vehicle | Configuration Warnings |
| Diversion | Damage - Major | Documentation/Data |
| Extra Security Checks | Damage - Minor | EGPWS/GPWS |
| Ferry Flight | Damage - Other Aircraft | Environmental |
| Fire Services | Emergency Checklist | Fire/Sparks/Smoke/Fumes |
| Maintenance Action | Emergency Declaration - Mayday | Flight Management |
| Police/Security Services | Emergency Declaration - PAN | Maintenance |
| Return To Stand | Emergency Descent | Other Aircraft |
| | Emergency Evacuation | Passenger |
| | Engine Operated at Reduced Power | Ramp/Terminal Management |
| | Engine Rundown | Security |
| | Engine Shutdown | TCAS |
| | Fire Extinguisher - Portable Used | Weather |
| | Fire Extinguisher System Activated | Air Cond & Press'n |
| | Flight Path Deviation - Lateral | APU |
| | Fuel Imbalance | Autoflight |
| | Fuel Jettison | Cabin Equipment |
| | Fuel Low State | Communication Systems |
| | Fuel Spillage | Doors |
| | Go Around | Electrics |
| | Incapacitation - Cabin Crew | Engine |
| | Incapacitation - Flight Crew | Fire Protection/Detection |
| | Medical Procedure On-Board | Flight Controls |
| | Other Automatic Systems | Fuel |
| | Oxygen - Flying Crew | Hydraulics |
| | Oxygen - Passengers | Ice/Rain Protection |
| | Passenger Caution | Instruments |
| | Passenger Off-Loaded | Landing Gear |
| | Passenger Restraint | Lighting |
| | Rapid Disembarkation | Navigation Systems |
| | RAT Deployment | Oxygen Equipment |
| | RTO - High Speed | Pneumatics |
| | RTO - Low Speed | Propellers |
| | Smoke Detector Activated | Safety/Emergency Equipment |
| | Stall Warning | Structures |
| | Stall/Alpha Protection | Water/Waste |
| | Stand by System Used | Windows |
| | Temporary Loss of Control | |

#### Event Descriptors (Environmental)

**Airport Management**
Airport Closed
Airport Congestion
Approach/Landing Aids
Bird/Animal Control
FOD (Runway/Taxiway)
Marshalling
Parking Guidance Control
Runway/Taxiway - Contamination
Runway/Taxiway - Lighting
Runway/Taxiway - Markings
Runway/Taxiway - Surface Conditions
Runway/Taxiway Incursion by Ground Vehicle

**ATM**
Airprox
ATC Congestion
ATC Coordination with Other ATC
ATC English Not Spoken
ATC English Poor
Barometric Information Error
Callsign Confusion
Comms with ATC Lost
Confusing ATC Instructions
Excessive Hold Delays
Inadequate Separation
Jet Blast - Encountered
Jet Blast - Generated
LAHSO/SIMO
Landing Clearance Not Received
Landing Clearance with Runway in Use
Late ATC Clearance
Met Info/Briefing
Military Influence
Poor Instructions or Vectoring
Take Off Clearance Cancelled
Take Off Clearance with Runway in Use
Wake Turbulence - Encountered
Wake Turbulence - Generated

**Birdstrike**
Multiple Birdstrike - Damage
Multiple Birdstrike - No Damage
Single Birdstrike - Damage
Single Birdstrike - No Damage

**Cabin Management**
Cabin Baggage
Cabin Crew - Illness
Cabin Crew - Injury
Cabin Crew Procedures
Cabin Not Secure
Flight/Cabin Crew Comms
Inadvertent Slide Activation

**Configuration Warnings**
Configuration - Flaps
Configuration - Gear
Configuration - Speedbrake
Configuration - Trim
Configuration - False Warning

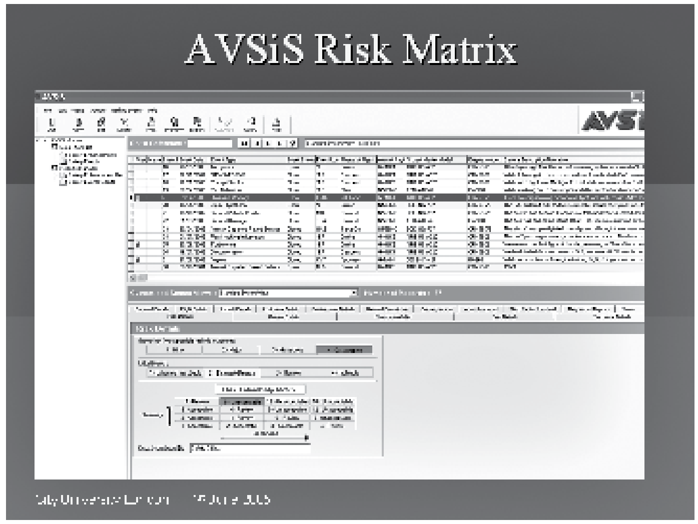
**Documentation/Data**
Airport/Aerodrome Booklet
Aircraft Library
Checklist Discrepancy
Flight Plan
FMS/INAV Data
Fuel Plan
Loadsheet Error
Loadsheet Late
Meteorological Data
Navigation Charts
NOTAM
Related AIS
Other Operational Data

**EGPWS/GPWS**
False EGPWS/GPWS Warning
Hard EGPWS/GPWS Warning
Nuisance EGPWS/GPWS Warning
Soft EGPWS/GPWS Warning
Windshear Warning

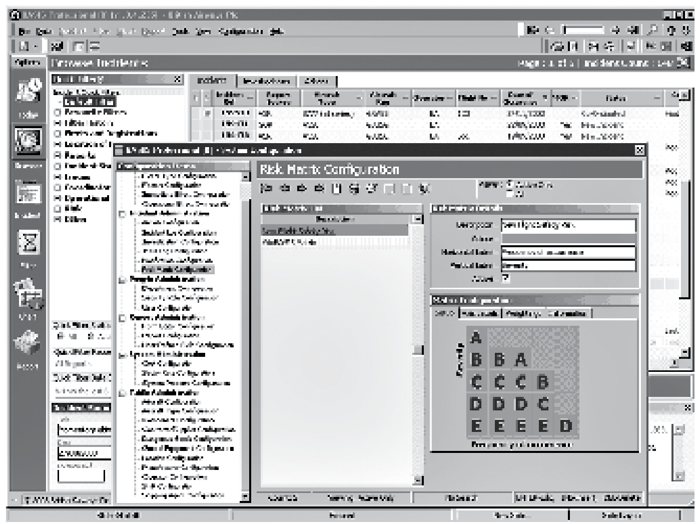
**Environmental**
Airborne Object
Aircraft Strike
Earthquake
Flood
Insect
Missile Launch
Suicide
Volcanic Ash
War Zone
Weather Balloon

**Fire/Sparks/Smoke/Fumes**
Fire - Engine Tailpipe
Fire - Fuel
Fire - Wheel/Brake
Fire/Smoke - APU
Fire/Smoke - Engine
Fire/Smoke - Oven
Fire/Sparks - Cabin
Fire/Sparks - Flight Deck
Fire/Sparks - Hold
Fire/Sparks - Toilet
Fire/Sparks/Smoke - IFE
Overheat - APU
Overheat - Engine
Overheat - Wheel/Brake
Overheat - Wing/Body
Smoke/Fumes - Cabin
Smoke/Fumes - Flight Deck
Smoke/Fumes - Hold
Smoke/Fumes - Toilet

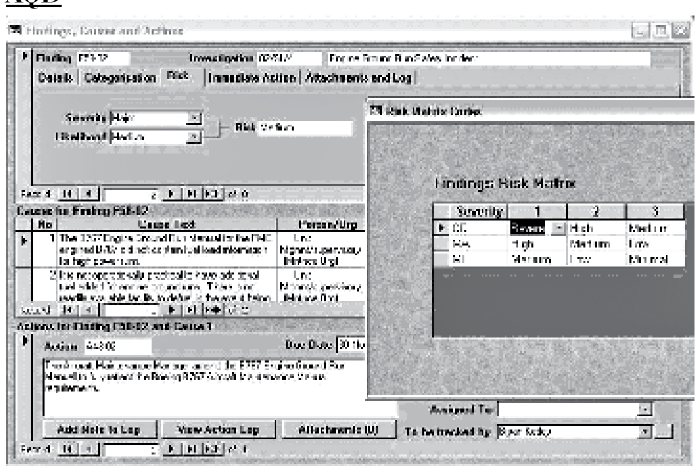
## APPENDIX C




## BASIS




## AQD



# Update: Finding Wreckage Under Water

By John P. Fish (CP131), Vice-President, American Underwater Search and Survey (AUSS), and John W. Purvis (WO3002), Partner, Safety Services International (SSI)

*__John Perry Fish__ is Vice-President of AUSS, an oceanographic company based in Cape Cod, Mass., U.S.A. An oceanographer specializing in acoustic and optimal remote sensing, he is recognized as one of the foremost experts in active sonar data interpretation. His work has taken him to 26 countries, and he has participated in air safety investigations since 1985. He has effected or managed more than 325 at-sea search-and-recovery operations. Senior author of two textbooks on sonar, he teaches survey techniques to commercial, Navy, and other government clients and has authored numerous articles in scientific and technical journals.*

*__John Purvis__ is an internationally recognized expert in large aircraft accident investigations. He has been in the aviation field for nearly 50 years. The last 17 years of his long Boeing career were spent heading its commercial airplane investigative team. He and Kevin Darcy are partners in an aviation safety consulting business, Safety Services International (SSI). He is currently instructing at the Southern California Safety Institute and is a member of its Advisory Board. He holds ISASI's prestigious Jerome F. Lederer Award for outstanding contributions to the industry. He is an ISASI Fellow, AIAA Distinguished Lecturer, professional engineer, and a pilot.*

## Introduction

In a majority of airplane accidents, the wreckage provides clues to the investigators who have the ability to euphemistically "kick tin" as they put the pieces of the accident puzzle together. But there are other accidents where the process begins with the complexities of searching for the tin itself. This paper explores the history and updates the processes and techniques of under water search and survey.

Our method will involve the introduction of a historical craft as a teaching tool. Not an aircraft, however, but a seacraft called the *Wyoming*. The *Wyoming*, the world's largest wooden sailing vessel, was designed to transport merchandise and goods along the Eastern seaboard. The six-masted schooner went down in 1924 during a perfect storm off the coast of Cape Cod. After decades of fruitless searching for her by a number of search firms, American Underwater Search and Survey (AUSS) found her in 2003. The techniques and processes used will be the centerpiece of this paper and will be readily adapted to the process for finding airplane wreckage underwater.

## A brief history of the *Wyoming*

The *Wyoming* was built in 1909, the finest, most modern sailing ship of its kind. (See Figure 1.) She was built in the heyday of maritime transportation. At the same time, just a few states away, the Wright Brothers were offering the possibility of another dramatic mode of transportation. The aviation industry was just taking its first baby steps. (See Figure 2.)

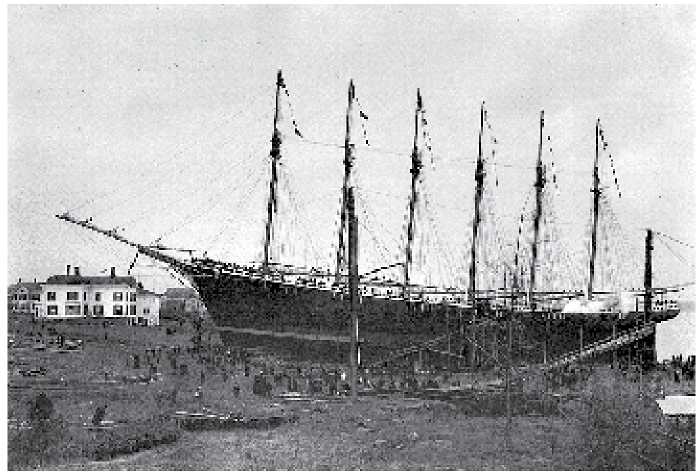


***Figure 1. With her boilers fired and with dignitaries on board, the largest wooden sailing ship ever built prepares to thrill the gathering crowd on launching day in 1909. (Courtesy Capt. Douglas Lee)***

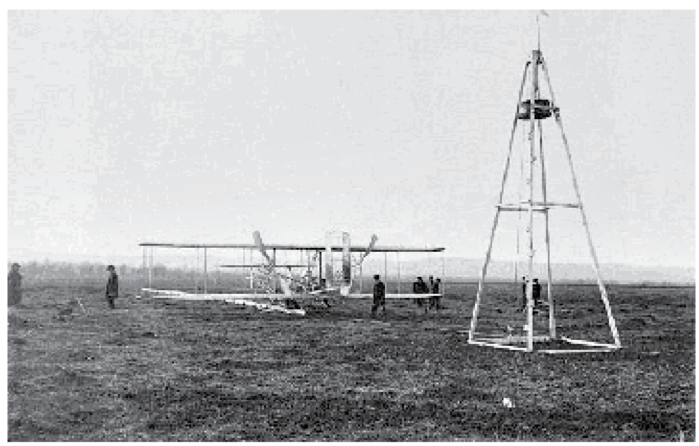


***Figure 2. In 1909, when the*** **Wyoming** ***was on its way to being constructed from massive long leaf yellow pine timbers, the Wright Brothers used lightweight materials for their new aircraft. The tower in this picture is a derrick with weights used to launch their airplane on demonstration flights. (Courtesy Library of Congress)***

The *Wyoming* was a crowning achievement in the construction of wooden sailing vessels. She measured 329 feet at the water line with an additional 100 feet overall, including rigging. Fifty feet wide, she drew 30 feet. No expense was spared, and her hull construction was unique. It was known that using more than a single piece of wood for keels caused damage in storms when the forward and aft sections could be left unsupported and sag below midships, a condition called "hogging." But 300-foot-tall trees weren't available, so three 100-foot trees made up the backbone. Hundreds of iron straps were built into the hull to strengthen it against hogging. This large amount of ferrous metal proved fortuitous for the search team, which would comb the ocean floor for her remains and one day, find her.

During her 14 years at sea, the *Wyoming* set the record for carrying the greatest load on a single voyage, 6,000 tons of coal from Virginia ports to the northeast.

She was carrying a load of coal on March 10, 1924, when she set out from Norfolk in the company of the five-master *Cora F. Cressey*. As the weather deteriorated, the ships kept each other in sight. The wind was blowing out of the northeast at 25-30 knots, and they anchored in shoal waters to ride out the storm. Gale-force winds around midnight found the vessels 5 miles apart. The *Cressey* weighed anchor and with shortened sail, clawed her way east into deeper water to battle the storm at sea. She showed up 3 days later in Boston, a mere 60 miles distant, with her sails shredded and leaking badly, but essentially in one piece. All on the *Cressey* survived.

No one knows what happened to the *Wyoming*. There are many opinions, and the feeling that the ship was so well built that she could not have gone down on her own. None of the 13 crewmen lived to tell the tale. Unlike most all of today's air crash investigations, the exact causal factors were never determined.

### Recovery techniques straightforward

Historically, actually locating submerged debris from an aircraft accident over water has been the most daunting of tasks. Once located, recovery operations use techniques that have been in place for thousands of years—along with a few recent developments in robotics. Despite the advances during the last decade in robotic technology, the "sling and pick" salvage method is still used today.

During the mid 1970s, hyperbaric experimentation led to man's ability to descend to depths exceeding 2,000 feet without pressure protection and breathing a mixture of exotic gases. However, the tried-and-proven recovery techniques that have been in use over time are essentially straightforward.

### Evolving sonar technology

In circumstances where accident wreckage came to rest under water, investigators were often left with little evidence. Initially they could only surmise the causal factors. Cases in point: KAL Flight 858 in 1987 over the Andaman Sea and ATI 870 near Ustica Island, Italy, in 1980.

About the time of the crash of KAL 007 and the loss of an Air India 747 in the Irish Sea, aeronautical search sonar systems had entered an adolescent phase where, although effective, had limitations.

In the case of KAL 007, the waters to be searched were shallow, but the search area was extremely large. The U.S. Navy alone scoured 250 square miles in the search. In the case of the Indian Air crash, falling debris had been tracked accurately by radar, but the water was significantly deeper.

These two cases are examples that helped to point out the limitations of the search systems available at the time. In those

***Figure 3. The heart of imaging sonars are transducers mounted on a hydrodynamically streamlined structure often called a "towfish." Note the relocation pinger on the aft end of the silver towfish (arrow). This is very similar to those attached to DFDRs and CVRs. In the event the tow cable is severed by fishbite or an obstruction, the pinger transmits a signal allowing it to be located and recovered.***

days, sonar systems were primarily analog devices. For shallow operations, the tow cables were short, but wide-area search operations required multiple systems be employed to cover large areas in a short time. Deep-water aeronautical search operations required more advanced technology. The great distances in deep sonar operations required data amplifiers to boost analog signals for transmission over long cables.

The sonar search systems of the 1980s and 90s, lauded for their cutting-edge technology, are already obsolete. Much of this is due to the advancement of computer networking. Only a few years ago, search sonar displayed data on a single screen connected to one system. The navigations systems displayed their data on a separate screen connected to a separate system. All of these instruments had independent processors and, although data were correlated within the systems, the operator had to scan a variety of displays to get the required visual information.

Fast forward to today's era of modern technology. Since the new century began, manufacturers of aeronautical subsea search systems have refined the instrumentation to the point where all the needed information is available on one integrated display. That information, now networked, is available at any location aboard ship. The skipper of the vessel, perhaps a hundred feet away and four stories up, can simultaneously observe the same data as that are being displayed in the sonar "shack" on deck.

Further, all the navigational parameters, crucial for proper search efficacy, are now available to the sonar operator as well as the captain. This is important in that the search supervisor and sonar operator need to know whether the ship is on the proper track during search operations.

### Applications to aviation

With the development of ocean exploration—initially in the late 1970s for mineral-rich crustal deposits and in the 1980s for petroleum reserves beneath the sea—remote sensing in the sub-

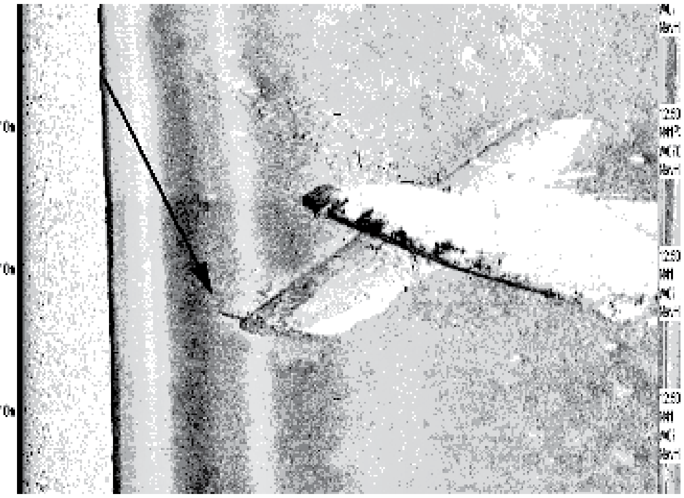


***Figure 4. New high-frequency digital sonar systems create very accurate images of submerged objects such as aeronautical debris from an accident site. After an SB2C Curtis Helldiver was bellied in with an engine fire in 1947, the pilot escaped and was rescued. The aircraft sank in the ocean. In this modern high-resolution sonograph, note the pitot tube (arrow) mounted on the left wing.***

merged environment made great strides. These included developments in accurate acoustic imaging systems as well.

Today, digital sonar systems, like the ones used to image the remains of the great *Wyoming*, can provide the air safety investigator with tools that can be used in deep water over long tow cables such as required during the search for deep-water debris fields. (See Figure 3.) As well, they have low noise characteristics that allow longer ranges in shallow-water environments such as required in the search at sites like KAL 007 in 1983 and TWA 800 lost in 1996.

These sonars can now provide the exploration team with remarkably high-resolution images at great ranges, thus allowing the location of objects of interest at a much more rapid rate than ever before. These new developments in digital sonars and computer processors translate to advances for aeronautical component search operations, allowing us to reap these benefits as well.

Another tool that is beneficial at certain submerged debris sites is the cesium vapor magnetometer. It evolved in the late 1980s and attracts targets containing ferrous metals. These extremely sensitive instruments can detect objects as small as a steel paper clip with a minimal level of electronic or magnetic noise.

## GPS a major leap

Another major leap in search technology occurred in 1978 with the launch of the first GPS satellite equipped with an atomic clock. By 1993, there were 24 such satellites circling the earth. Before GPS navigation, at-sea positioning had significant shortcomings.

We recall a search for a Marine A-4 Skyhawk lost in the sea. When we located the wreckage, all the main and backup navigation systems went down simultaneously. A navigation system called LORAN was being used at the time. The accident site image on the sonar was clear, and we could successfully repeat the imaging passes on the site. By radio, we informed the Navy that we had located the wreckage. They then asked the embarrassing question, "What is the wreck's location?" There was an uncomfortable silence on our end as we had no answer for them. Our technicians scrambled to reinitialize the nav systems as we replied to the Navy, "Please stand by one."

Those familiar with any type of search operation realize that there is a problem with finding something but not knowing its geodetic position or having some sort of positional reference for it. If you departed the target's location, you were required to search for it all over again. Now, with GPS, surface navigation is straightforward and highly reliable.

The application for these remote-sensing systems is quite varied but can be applied to any type of search or survey task. Although much of this technology is used in general seabed survey such as in the oil and gas industry and fisheries and environmental studies, one of the best applications is target search operations.

Aircraft debris still represents a challenging task for subsea search, particularly if the aircraft consists of a "debris field" rather than a largely intact aircraft. The smaller and more fragmented aeronautical components in search data appear to closely resemble objects in the natural environment such as patches of gravel, rocks, and other irregularities on the sea floor.

Modern shipwrecks are more often a subject of search operations for interests such as insurance, environmental, or forensic concerns. These recent losses, which often consist of largely intact structures or complex targets that are simply broken in half, can be located using acoustic imaging technology with a minimal amount of optical confirmation. These "targets" of search present themselves with predictable shapes and sizes and can be detected at very long sonar ranges (measured in hundreds or thousand of meters away from the search sensors). Older wrecks and smaller targets such as aeronautical debris fields do not provide such a luxury.

Historic shipwrecks present a different scenario. These vessels typically deteriorate over time due to corrosion, physical ocean processes, biodegradation, and other destructive forces of the sea. This has the net effect of making them difficult to locate. The general rule during undersea search operations is that the larger the target, the more easily it is detected by instrumentation and thus recognized by search personnel.

## At-sea beta testing finds *Wyoming*

During the evolution of remote sensing instrumentation used in aircraft accident investigations, some engineers developed software or instrumentation that seemed innovative in the lab but when used at sea in actual real-life situations proved impractical. This is a repeated problem with system and software developers who live in the lab and seldom go to sea.

As a result, at-sea testing was—and still is—one of the most crucial components of engineering and design of subsea search instrumentation.

American Underwater Search and Survey (AUSS) is fortunate to be part of a beta test team for at-sea testing. Together with others, the company has been able to form a beta test team utilized by a variety of system manufacturers. We are proud to have been a part of this team over the past three decades as the technology of subsea remote sensing was making significant advances.

It was decided that, when at-sea testing was to be done, it made sense to deploy the systems in areas that were not only topographically feature rich, but also had the potential to make dis-

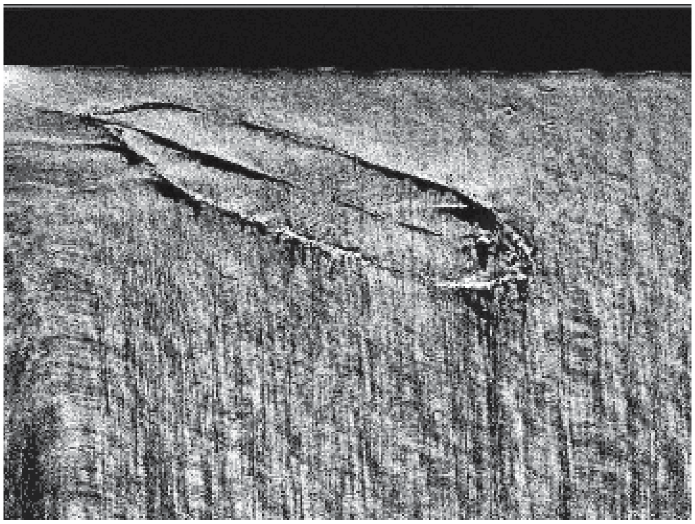


***Figure 5. This sonograph shows the remains of the once-great* Wyoming, *her hull forever entombed in a sandy grave. The upper decks have deteriorated from ocean forces, shipworms, and storms, leaving only the inner keel and timbers at the turn of the bilge protruding from the sediments of the North Atlantic Ocean.***

coveries that might solve past maritime questions or mysteries. The search for the *Wyoming* fit the bill.

In earlier searches for the *Wyoming* in the late 1970s and early 1980s, AUSS tested such systems in the area where historical records indicated that the *Wyoming* had met her fate. During the equipment tests, search patterns were laid out over large areas of seabed. Nothing showed up in the sonar data that indicated a wooden wreck the size of the behemoth *Wyoming*.

Over a period of 25 years of at-sea equipment tests, ship after ship, and even an intact Helldiver, were located in the area. (See Figure 4, page 76.) They included smaller schooners carrying stone, coal, and even one carrying marble dust. None of them proved to be the *Wyoming*. The search sonar even located William K Vanderbilt's personal 285-foot yacht *Alva*, lost in 1892 in a collision in the fog. Although richly appointed, she did not satisfy the scientists' desire to locate the remains of the largest wooden sailing ship ever built.

Then, in 2003, while testing a cesium vapor magnetometer, the search team came across an anomaly that could not be explained as anything other than a major ferrous deposit on the seafloor. Immediately our scientific team knew that the magnetic signature was too large to be a big ship anchor, yet too small to be an entire steel ship. Once it was pinpointed with the magnetic instruments, an imaging sonar was deployed. Interestingly enough—several miles from where the ship was reported to have sunk—the final resting place of the *Wyoming* had been found. (See Figure 5.)

It is expected that the reason for the error in historical documents was due to the lack of sophisticated navigational instrumentation of the day. The ship, now deteriorated to the bilge, lies half buried in the shifting sands of Cape Cod. Her remains still contain timbers of immense size including 14" x 14" x 20" long leaf yellow pine, a species of wood no longer growing to this size. Further research by the discovery team may lead to clues to the cause of the demise of the huge ship. Like tin-kickers, the *Wyoming* team will examine the site for clues over the coming underwater seasons.

## Summary

Although historic shipwrecks and modern aircraft debris have dissimilar parentage, they share the same characteristics for small-part search operations. They both benefit from recent developments over the past decade and make subsea target location ever faster and more efficient.

## Keys to a successful search and survey

1. Be on site as soon as possible.
2. Have good preliminary data (tides, winds, radar, radio transmissions from the airplane, eyewitness reports, etc.).
3. Surface debris location vs. the time when it was found and the capability to plot this information and "hindcast" its drift.
4. The latest and best equipment and a means to mobilize it quickly.
5. The best expertise; the best people to operate the equipment and, more importantly, having the understanding and experience to interpret the data in real time.
6. As always, the factors least under your control: good weather and calm seas. ◆

# Similarities and Differences in the Characteristics of Fatal General Aviation Accidents in Several Countries

By Robert Matthews, Ph.D., Office of Accident Investigation, U.S. FAA

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This paper reviews fatal accidents in general aviation (GA) and limited-capacity commercial aircraft from several countries to identify basic similarities and differences in safety trends and issues. The intent of this paper is to address non-airline operations. However, each country uses slightly different definitions and somewhat different regulatory structures for general aviation, air taxis, and other small commercial operators, and each country treats some categories of aircraft differently. As a result, precise comparisons of subsets such as "GA" or "air taxis" across countries are not possible because the terms do not include consistent populations from one country to another.

Therefore, rather than struggle with fine distinctions, this paper addresses GA, air taxis, and limited-capacity commercial operators as a single group of "non-airline operators," with the exclusion of micro-planes, ultralights, and small gliders. Some small differences are still likely across national populations, but nearly all activity captured by this single, broad grouping will be fundamentally comparable.[1]

Part One of the paper briefly summarizes trends in accident statistics from Australia, Canada, and the United States, as these countries have high volumes of non-airline civil aviation activity. Part Two reviews publicly available accident reports from those same three countries, plus the United Kingdom to identify some similarities and differences in issues and characteristics. Due to differences in aviation volumes, fatal accidents in the United States are reviewed only for 2002 through 2004 while fatal accidents in other countries are reviewed from 1999 through 2004. Part Two supplements this data with a small number of fatal accidents from New Zealand. Part Three then addresses some major changes that are under way in the field. Data in Part Three mostly are limited to the United States, primarily for the convenience of the author, but that data will be indicative of changes that are under way or that are about to get under way in other countries as well.

## Part One: General trends in fatal accidents and activity

Aviation safety professionals recognize that fatal accident rates

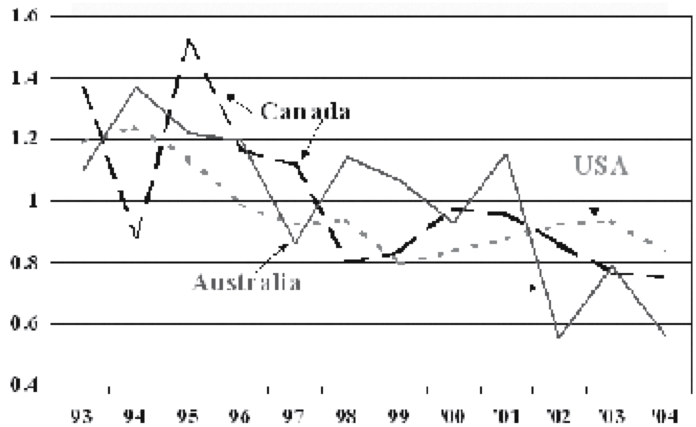


***Figure 1: Non-Fatal Accident Rates in Three Countries, Indexed to 1993-2004 Averages.***

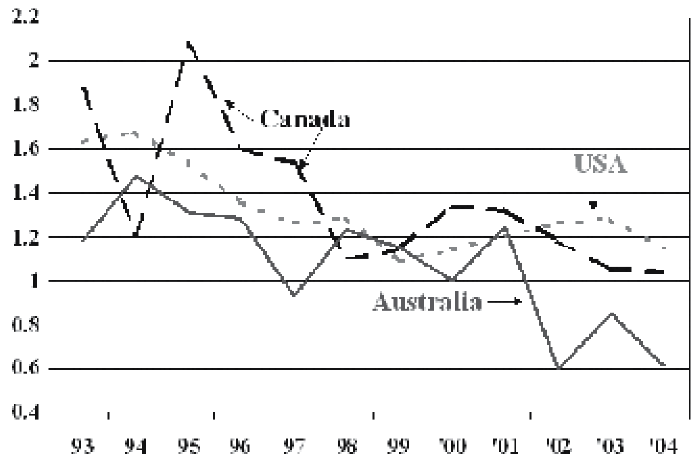


***Figure 2: Non-Fatal Accident Rates in Three Countries, 1993-2004.***

continue to improve in airline transport throughout the world. Especially in the rich OECD countries, major airline accidents are becoming increasingly rare events. Among non-airline operators, fatal accidents are hardly a rare event and the trend line has not been as dramatic as with airline transport. Nevertheless, non-airline operators have a positive story to tell.

Figure 1 presents indices of non-airline fatal accident rates in Australia, Canada, and the U.S.A. from 1993 through 2004 to illustrate the direction and relative magnitude of change in non-airline fatal accident rates in each country. Data are indexed to the 12-year fatal accident rate within the respective countries, based on each country's internal accident experience. This is a useful comparison because the three countries share some basic characteristics such as large land masses, coastal population centers, and high rates of private aircraft ownership and operation.

The figure shows that fatal accident rates are improving in all three countries, but at somewhat different paces. Allowing for some annual variation, the rate of improvement has been greatest in Australia, followed by Canada. The figure also shows that the rate of improvement in the U.S.A. has been strong, but not as strong as in Australia and Canada. In fact, after sharp and sustained improvement throughout the 1990s, accident rates for non-airline operators increased in the U.S.A. for several years after 1999. However, rates resumed their downward trend in 2003 and 2004. Preliminary data for the first 7 months of 2005 indicate that improvements will continue in all three countries this year.

Figure 2, page 78, shows actual fatal accident rates for non-airline operations in the three countries. For the 4 years from 1998 through 2001, the three countries had very similar fatal accident rates

Generally, though, Australia has consistently had lower fatal accident rates than either Canada or the U.S.A., and the margin of difference has accelerated in the past several years.

The trend lines for Canada and the U.S.A. intersect several times but their 12-year averages are identical to two decimal places, at 1.37 fatal accidents per 100,000 flight hours. As discussed below, much of the difference but not all the difference between Australia's rate and those in North America can be explained by basic factors, such as who is flying, topography, and climate.

Despite some differences among the countries, the bottom line is a good story: fatal accident rates in non-airline aviation are steadily improving in all three countries with large civil aviation systems. Given the relatively large systems in each of these countries, plus some supplemental information from the U.K. and New Zealand, the data indicate steady safety improvement in non-airline aviation in much of the world.

As the remainder of this paper will illustrate, the differences in fatal accident rates among the three countries are not random. Fundamental factors help to explain the relatively high rates in Canada and the U.S.A. Those factors can be so fundamental that, once their effects are considered, they might even flatter safety performance in Canada and the U.S.A.

## Part Two: Similarities and differences in the characteristics of fatal accidents

Part Two examines core similarities in non-airline fatal accidents in Australia, Canada, the U.K., and the U.S.A., explains some of the differences in national rates, and identifies some common areas of concern among the four countries. Part Two is based on a combination of publicly available summary data from Australia, Canada, and the U.S.A., plus a detailed review of fatal accident reports from those countries, the United Kingdom and New Zealand. Data here are organized according to the country in which the operator was based (not on aircraft registration or location of an accident).

## Who is flying: Differences in the purpose of flight

The demographics of non-airline aviation go a long way to explain some of the differences in national rates. For example, as Table 1 shows, 72% of fatal accidents in the U.S.A. involve personal flight and non-commercial business flight compared to a range of 35% in Canada to 42% in the U.K.[2] Note that the percentage in the U.K. normally would be a bit higher, but it is suppressed in the study period (1999-2004) by a random spike in accidents related to air shows and air show practice. Nevertheless, Table 1 indicates that personal-business flight is a much larger share of total flight activity in the United States than elsewhere.

***Table 1. Selected Flight Activity as a Percentage of Non-Airline Fatal Accident Aircraft in Four Countries***

| ACTIVITY | AUS | CAN | U.K. | U.S.A. |
|---|---|---|---|---|
| Personal and Non-Commercial Business | 36.7 | 35.4 | 41.9 | 71.5 |
| Instruction | 13.3 | 10.1 | 10.8 | 7.2 |
| Charters and Small Commuters | 14.7 | 24.4 | 5.4 | 4.1 |
| Charter Aircraft Positioning | 5.6 | 4.0 | 2.7 | 2.0 |
| Aerial Mustering and Application | 5.6 | 3.0 | 0 | 2.1 |
| Medical Evacuation and Ambulance | 2.2 | 1.0 | 1.4 | 1.9 |
| Off-shore Oil and Gas Operations | 0.0 | 0.0 | 1.4 | 1.2 |
| Air shows and Air show Practice | 1.1 | 0.0 | 8.1 | 1.1 |

When flight instruction is added to personal and non-commercial business, those categories account for 49% of non-airline fatal accidents in Australia, Canada, and the U.K., combined, versus 79% in the U.S.A. Therefore, the other side of this coin indicates that commercial uses are much more prominent in non-airline aviation in Australia, Canada, and the U.K. than in the U.S.A.

The differences in types of flight activity substantially affect systemwide averages for pilot training, experience, and flight skills, and they help to explain a larger share of the U.S. fatal accident rate. More importantly, they indicate some differences in the populations that each country needs to target if it is to reduce still further the fatal accident rate.

## Accident fleets

The various national accident fleets reflect the demographics of non-airline aviation. In the U.S.A., where personal flight is a very large share of total activity, home-built or amateur-built aircraft account for 16% of the accident fleet, versus 9% in Australia. In contrast, home-builts account for just 7% of the accident fleet in the U.K. and 4% in Canada.

Conversely, where personal flight accounts for smaller shares of total activity than in the U.S.A., various categories of commercial activity account for the difference in this zero-sum game, where each country's distributions must add to 100%. Reflecting the greater role of commercial pursuits, helicopters account for a much higher share of accident aircraft than in the U.S.A. Helicopters account for 26% of aircraft in fatal accidents in Canada, 24% in and nearly 19% in the U.K., for an average of 23.4% in the three countries. In contrast, helicopters account for just 9% of fatal accident aircraft in the U.S.A.

The net effect of these differences in the fleet partly offset each other. Amateur-built aircraft have considerably higher fatal accident rates than do production aircraft. Consequently, this partly inflates the fatal accident rate in the U.S.A., at least in relative terms. However, helicopters have higher fatal accident rates than do fixed-wing aircraft, partly as a function of different flight missions. As a result, this partly deflates the fatal accident rate in the U.S.A. in relative terms.

## Night flying and weather

Night flying and flying in weather, or instrument meteorological conditions (IMC), are two more basic factors that strongly influence fatal accident rates. Both environments significantly increases risk. Data from the U.S.A. indicate that fatal accident rates in-

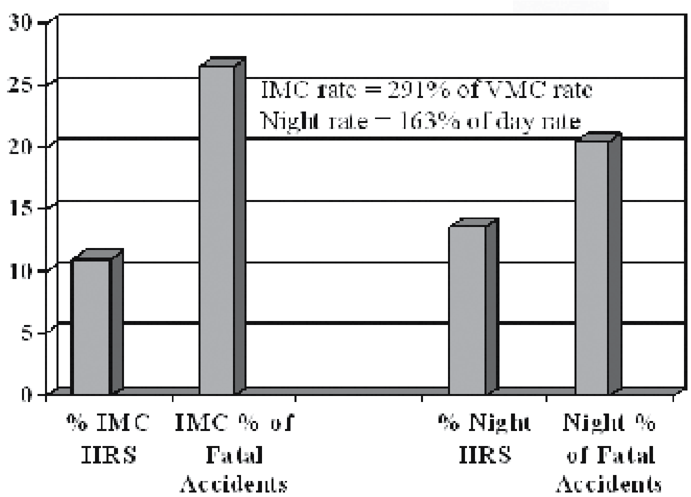


***Figure 3. Percent Flight Hours and Fatal Accidents in IMC and Night.***

crease by nearly two-thirds at night and triple in IMC, as illustrated in Figure 3.

Risk increases at night or in weather for obvious reasons, such as visibility. At night, pilots simply cannot clearly see what is beneath or ahead of them. This invites flying into terrain, vertigo, loss of control, etc. Pilots also may have difficulty seeing inside the cockpit, so night flying requires a high level of familiarity with the precise location of all instruments, switches, breakers, and knobs. Flying in IMC exposes a pilot to all the issues associated with night flying, regardless of time of day, and weather adds the risks of icing, snow, severe winds, lightning, etc.

As Table 2 shows, night flying and weather (IMC) influence aviation safety differently among the four countries. Night flying accounts for 13.1% of fatal accidents in Canada, 18.3% in Australia and 20.4% in the U.S.A., versus just 6.8% in the U.K. The very low percentage of night flying among fatal accidents in the U.K. clearly indicates the safety benefit that regulatory policies can provide, as regulatory policies on night flying are most restrictive in the U.K. among the four countries. However, the U.K. data also are affected by geographic orientation of the national land mass because some night-time fatal accidents in Australia, Canada, and the U.S.A. involve west-to-east flight in which pilots take off in daylight but reach their destinations after sunset. This certainly happens in the U.K. as well, but the geographic orientation of the country means that no domestic flights operate across multiple time zones.

However, time zones do not affect weather issues; at the risk of stating the blindingly obvious, climate affects weather-related accidents. The percentages of fatal accidents that occur in IMC are very comparable in Canada, the U.K., and the U.S.A., averaging 26.7% in the three countries. In contrast, just 14.9% of fatal accidents occur in IMC in Australia, where climate is a bit more forgiving for aviation in general.[3]

***Table 2. Percentage of Non-Airline Fatal Accidents at Night and in Weather***

| | % Night | % IMC |
|---|---|---|
| Australia | 18.3 | 14.9 |
| Canada | 13.1 | 29.3 |
| U.K. | 6.8 | 27.0 |
| U.S.A. | 20.4 | 26.5 |

When VFR flight is added to the mix of night flight and weather, the level of risk multiplies. Table 3 shows the percent of non-airline fatal accidents that involve VFR at night and VFR in IMC. VFR at night accounts for 17% of fatal accidents in Australia and 13% in the U.S.A. versus 10% in Canada and just 5% in the U.K. The Figure shows VFR into weather is most significant in Canada, followed by the U.K., accounting for one in five fatal accidents in the two countries combined. Comparable figures in Australia and the U.S.A. are somewhat lower, but still significant at 12% and 13%, respectively. Table 3 also shows that a small but meaningful number of pilots manage to combine all these risks by flying VFR in weather at night (an average of 4.3% of all fatal accidents among the four countries).

***Table 3. Percentage of Non-Airline Fatal Accidents VFR at Night and VFR in Weather***

| | VFR at Night | VFR in IMC | VFR in IMC at Night |
|---|---|---|---|
| Australia | 17.2 | 11.9 | 2.3 |
| Canada | 10.1 | 20.2 | 4.0 |
| U.K. | 5.4 | 17.6 | 4.1 |
| U.S.A. | 13.3 | 13.3 | 4.5 |

A comparison of Tables 2 and 3 indicates that a majority of fatal accidents that occur at night or in weather involves VFR flight. VFR into IMC often is characterized as "inadvertent VFR into IMC," which typically is explained by the lack of timely or accurate weather information or, more frequently, by poor flight planning. However, the texts of accident reports imply that at least a significant minority of these accidents involves conscious risk-taking by pilots.

## CFIT into high terrain

Controlled flight into high terrain accounts for 13% of fatal accidents and 16.2% of fatalities in Canada. Comparable figures in the U.S.A. are 11.5% of fatal accidents and 14.2% of fatalities. In contrast, CFIT into high terrain accounts for 5.4% of fatal accidents in the U.K. (all in Scotland) and just 1% of fatal accidents in Australia.

Topography also emphasizes the added risk of night flying or flying VFR in IMC. Both in Canada and the U.S.A., just over half of all CFIT accidents (53%) occur in IMC while 26.5% occur at night, most of which are VFR flights. Again, nearly 15% combine the risks by flying VFR at night in weather. In short, three of five fatal CFIT accidents into high terrain in North America involve night VFR, VFR into IMC, or both. CFIT alone explains much of the disproportionate risk of night VFR or VFR into weather.

Yet, again at the risk of stating the blindingly obvious, the presence of high terrain is one rather fundamental factor in CFIT into high terrain. Flat terrain can forgive some navigational or other errors, but mountainous terrain is less forgiving. The difference in CFIT experience between Australia and New Zealand illustrates the point. Australia's civil aviation system is five to six times the size of New Zealand's system, which is a safe system in its own right. Yet, with a much more mountainous environment, New Zealand had six fatal CFIT accidents into high terrain from 1999 through 2004 compared to just one in Australia. Similarly, in North America, pilots do not strike mountains in Kansas or Saskatchewan, but they do strike the three mountain chains that run north-to-south across the entire continent. In short, topography affects fatal accident rates.

### Other accident scenarios and broad factors

Table 4 shows the distribution of selected accident categories and some key factors. Since each country's accidents add up to 100%, the figure is a zero-sum gain in which a positive result must be offset by an apparently negative result and vice-versa. Consequently, the figure obscures the fact that fatal accident rates are improving in all four countries. Some high numbers may be misleading. With that caveat, the figure shows that many accident categories and factors account for comparable shares of fatal accidents in all four countries.

Again, night flying and IMC are important factors. For example, of the fatal loss-of-control accidents in the U.S.A. and Canada, 22% involve night flying versus just 8% in Australia and the U.K. The percentage of fatal loss-of-control accidents involving IMC ranges from one-third in the U.K. to 38% in the U.S.A. and just under half in Canada. To a large degree, these various shares reflect the overall significance of climate in the respective countries. Similar points apply to fatal accidents involving loss-of-control on takeoff and climbout or during approach and landing: night flying is least significant in the U.K. and IMC is least significant in Australia.

*Table 4. Percentage of Fatal Non-Airline Accidents Attributable to Selected Accident Categories and Factors*

| | AUS | CAN | U.K. | U.S.A. |
|---|---|---|---|---|
| CFIT into High Terrain | 1.1 | 13.0 | 5.4 | 11.5 |
| Mid-air Collisions | 3.4 | 3.0 | 5.4 | 1.8 |
| Undershoot, CFIT-LOW, and Other Approach and Landing | 17.2 | 12.1 | 13.5 | 21.5 |
| Loss of Control T/O—Climbout | 16.1 | 22.2 | 24.3 | 18.8 |
| Loss of Control in Flight | 20.7 | 13.1 | 12.2 | 18.3 |
| LOC Maneuver | 17.2 | 22.2 | 25.7 | 15.3 |
| Loss of Control in Emergency Maneuver | 5.7 | 5.1 | 1.4 | 4.8 |
| Wire Strike or CFIT Into Obstacles | 10.3 | 3.0 | 2.7 | 5.3 |
| System-Component Failure—Powerplant and Other | 24.1 | 17.2 | 14.9 | 15.1 |
| Fuel-Related | 10.3 | 8.1 | 2.7 | 6.6 |

In contrast to many accident scenarios, mid-air collisions and fatal loss-of-control accidents in low-level maneuvering seldom involve night flying or IMC.[4] The purposes for which low-level maneuvering normally is undertaken, such as sightseeing, aerial application, or observation, normally require good visibility.

Mid-air collisions, which are rare events in all four countries but highly visible when they occur, almost never involve either IMC or night flying. A recent review of 330 mid-air collisions, both fatal and non-fatal, over 22 years in the U.S.A. shows that the number of mid-airs has consistently decreased, but when mid-airs occur, their characteristics have remained remarkably stable. Most mid-airs involve VFR pilots in day VMC at low altitudes close to airports. Most impacts involve one aircraft overtaking another from behind or at quartering angles. When mid-airs oc-

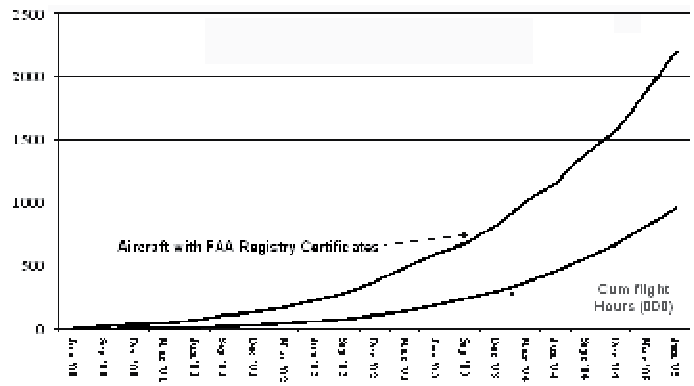


*Figure 4. New Aircraft: Active Fleet and Cumulative Exposure Cirrus SR 20, SR22, and DA-40.*

cur enroute, most involve formation flying in which pilots failed to plan their inflight procedures carefully. Air shows and practice for air shows are other relatively common environments for mid-airs. The few mid-airs identified in accident reports from Australia, Canada, and the U.K. show a similar set of characteristics.

### Two other contributing factors

In addition to night flying and weather, Table 4 shows that two other factors are stubbornly common explanations in fatal accidents. Fuel issues in this paper are limited to fuel management, fuel contamination, and simple fuel exhaustion; they do not include failures of fuel systems and their components. Yet, even with this limited definition, fuel-related issues are factors in a high of 10.3% of fatal accidents in Australia versus 8.1% in Canada and 6.6% in the U.S.A. In the U.K., fuel-related issues accounted for just 2.7% of accidents.

In most cases, fuel issues indicate poor preflight planning or very poor decision-making, and these weaknesses should be most common in systems with relatively high proportions of personal and recreation flight. However, they also reflect basic facts of geographic size and population density. For example, both Australia and Canada have huge expanses of land in which fueling options are very limited. This is true in large portions of the U.S.A. as well, but, on average, U.S. pilots will have more in-flight options than pilots will enjoy in Australia and Canada. In contrast, domestic flights in the U.K. are much less exposed to barren ground.

However, no such convenient factors help to explain the role of system-component failures in all four countries, ranging from 15% in Canada and the U.S.A. to 17% in the U.K. and a high of 24% in Australia. Much of the difference in Australia's relatively higher share of system-component failures is a simple function of arithmetic. Since some categories like CFIT and weather-related accidents are relatively minor or modest issues in Australia, a greater percentage of Australia's accidents remain to be explained. Given Australia's lower fatal accident rate, the rate of system-component failures as factors in fatal accidents, in fact, is quite comparable to those of the other three countries.

The more central point is that system-component failures, including engine failures, are primarily a surrogate for maintenance issues. Though design or production issues appear occasionally, the overwhelming share of these events involve maintenance that simply was not performed—poorly maintained aircraft.

Regardless of the precise accident scenario at issue, non-airline fatal accidents in all four countries disproportionately reflect the following issues.

• Pilot skills—even pilots who are competent under normal conditions may not have the skills to recover from mistakes or handle unexpectedly challenging conditions (an issue especially with personal and recreational flight).
• Pilot knowledge and judgment—some pilots involved in fatal accidents do not appear to have understood the increased risks associated with certain weather information (again, this is especially an issue with personal and recreational flight).
• Night flying—risk increases for IFR flight but even more so for VFR flight (especially with west-to-east flight).
• Weather.
• Fuel issues.
• Airworthiness issues (maintenance).
• Preflight planning, which helps to explain some of the issues noted above (did the pilot check weather or fuel supply, did the pilot plan a flightpath, did the pilot even have a clear destination in mind, etc.?).

### Summary of Part Two

Part Two explains some of the differences in fatal accident experiences among the four countries examined most closely, such as the role of topography, climate, and aviation demographics. Part Two also identifies some obvious issues that might be targets for improving safety, such as night VFR flying in the U.S.A., weather information and knowledge in all four countries, and maintenance. Despite some differences among the four countries and despite the continued existence of some obvious targets for improvement, the bottom line remains that trends are positive in all four countries. As discussed in Part Three, below, those positive trends not only should continue, but they should accelerate over the next decade or more.

### Part Three: Changes in non-airline aviation and future issues

For the first time in several decades, general aviation and smaller commercial segments of aviation are undergoing multiple and rapid changes that will profoundly influence safety over the next 10 to 15 years. Except perhaps for large corporate jets at the very top of the GA market and some improvement in engine reliability, technology in GA had stagnated for years. That state of affairs is finally changing, and fast. Suddenly the term "glass cockpit" is part of the GA vocabulary. Every established manufacturer now offers a glass cockpit of one degree or another.

In a relatively short period, general aviation and the smaller commercial fleet have incorporated satellite technology into the cockpit with precision navigation, multifunction displays, improved visual displays, data link, air-to-air monitoring, moving-map displays, overlays, onboard diagnostics, etc. Pilots not only will have more information in the cockpit, but the information will be better and will be more easily understood. The same equipment also will help more than a few pilots to correct mistakes. Though no aircraft can save us from all bad decisions, this equipment clearly will produce better safety.

The real news may lie in how quickly these new aircraft are entering the fleet and how quickly GNS-based navigation will become the norm. For example, the FAA in the U.S.A. has announced that it will soon begin to decommission ground-based navigational systems and that it will accelerate the decommissioning program over the following decade. That was unthinkable just several years ago due to the need to ensure safety in general aviation and smaller commercial operations. Today decommissioning not only is thinkable but it is under way.

Figure 4 illustrates how quickly the fleet change is occurring by showing the rate at which the Diamond-40 and Cirrus SR-20/SR-22 have penetrated the U.S. fleet. From zero in early 2000 to just 250 or so in mid-2002, the U.S. aircraft registry now shows 2,300 Cirrus and Diamond-40 aircraft. Combined, they are entering the fleet now at the pace of 100 to 125 per month. Add the new Cessna aircraft and other models, and we can foresee very rapid changes in the fleet.

So far, the U.S. aircraft registry indicates that about half of all Diamond-40 and Cirrus owners are individuals and half are small companies, while most glass-cockpit Cessna aircraft are owned by individuals and flight schools, as are most DA-40s. Given the prices for which such aircraft now sell, they are being purchased for real transport purposes, and they are being flown more intensively than most of the non-airline fleet. Cirrus, for example, reports that its aircraft are flying longer segments than the manufacturer had anticipated and are averaging 325 flight hours per month. Flight profiles are likely to include some net increase in night flying, but they also are likely to increase IFR flying regardless of time of day or weather conditions, and they clearly will offer more precision flying with more information in the cockpit.

Ironically, the very same aircraft that promise to expect improved safety also will introduce transitory risks of their own. Again, the historical experience of the air carriers can help put this into perspective. Each new generation of air carrier jets has produced accident rates that resemble an abbreviated "U" curve. Each new generation of jets enters service with lower initial accident rates than each preceding generation, and the learning curve is shorter for each new generation. Each generation then reaches a stable accident state more quickly, and that stable state is lower than was the case with older fleets. The early experience with technologically advanced aircraft (TAA) appear to be following a similar path.

The early accident experience with this new fleet implies that some pilots are more willing than others to assume high risks, perhaps in the belief that the aircraft will overcome any problems. Fatal accidents very early in the service history of the various new generation GA business aircraft include a disproportionate share of the usual suspects, such as knowingly flying VFR into weather, flying VFR at night, high-density altitudes, operating too close to high terrain, etc.

The point here is fairly straightforward: no matter how capable an aircraft may be, it cannot save us from every bad decision. However, as the various aircraft become more established in the fleet, that lesson penetrates the pilot population. Combined with some minor changes that may be made to the aircraft, the net benefits to safety then become more apparent. This already is under way with the Cirrus and Diamond-40. At first, their overall accident rates were about 25% higher than the rest of the fleet, though the fatal accident rate was comparable to the rest of the non-airline fleet. Their fatal accident rates have fallen well below rates, in general.

In fact, a shift to up-market aircraft has been under way for some time in corporate-executive aviation. Figure 5 shows recent fleet changes among corporate-executive jets. In the past decade,

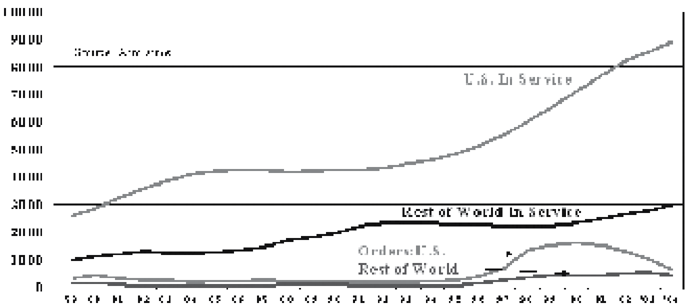


***Figure 5. Corrorate-Executive Jets in Service and Firm Orders U.S. and Rest of World (at end of year).***

the world's fleet of corporate jets has doubled. Though new orders have slowed, net growth continues. Much of the growth has come from so-called fractional ownership arrangements. Though that market has begun to slow down, it will remain a key player and on balance should improve an already impressive safety record among corporate operators.

Yet, the new micro-jets could create new risks in corporate aviation. With price tags as low as $1.25 million, micro-jets will challenge for some of the existing corporate market. On balance, though, micro-jets are more likely to expand the net corporate market. The net risk is that these new corporate operators are likely to have more modest corporate support structures for their aviation departments, little experience in dealing with professional pilots and sophisticated aircraft, and perhaps less-experienced crews.

### Other changes driven by the fleet

These and other changes to the fleet also will influence aviation safety. For example, the price of a new, normally equipped reciprocating aircraft today typically will range from US$250,000 to $500,000. Those prices push more and more pilots out of aviation. Though amateur-built aircraft can run the full price range, typically for $40,000 to $60,000 a pilot can acquire a very capable, high-performance aircraft. Though even those prices exclude many people, the price elasticity that exists between, say, US$50,000 and US$250,000 will continue to make amateur-builts an attractive market. On balance though, the net effect of higher production prices will be to exclude more and more potential private pilots. Somewhat perversely, this should improve fatal accident rates as the population of the least skilled group of pilots will decrease, thereby reducing flight hours among those pilots with the highest accident rates in general.

As for the remainder of the fleet, it will continue to age. The fact is that a large part of the fleet in all countries is very old and getting older. However, attrition will continue to reduce the size of the truly dated fleet, and, much as with all forms of transportation, the older aircraft that survive will accrue few flight hours per unit than newer, better equipped aircraft. The net effect, again, will be to reduce fatal accident rates.

### Conclusions

The most significant conclusions in this paper are (1) fatal accident rates are improving in all three countries in which rates were closely examined, and all indications are the same in the U.K. and (2) the rate of improvement should accelerate in all four countries over the next 10 to 15 years due largely to the introduction of new technology. Where significant differences exist in fatal accident rates, the paper has shown that much of the difference can be explained by basic environmental factors, such as climate and topography or by demographic factors, such as the relative size of personal or recreational flight segments.

The paper also shows that each country has some very obvious targets for efforts designed to improve safety in non-airline operations. For example, night flying is an obvious target in Australia, Canada, and the U.S.A. Flying in IMC is an obvious target in all countries, but climate makes IMC flight particularly important in Canada, the U.K., and the U.S.A. Similarly, terrain makes CFIT an obvious target in Canada and the U.S.A., as well as New Zealand.

In addition, basic decision-making and pilot knowledge may be an obvious target in all countries, especially in the U.S.A. where night VFR flight is a disproportionate issue. Similarly, VFR into IMC is an obvious target everywhere. These kinds of common issues may offer opportunities for cooperative efforts between or among governments and national aviation communities to understand these issues better and to develop effective strategies.

The paper also has shown that major and rapid change in non-airline aviation for the first time in several decades. These changes will produce major changes to safety by introducing new technology, new displays, more-precise navigation, etc. ◆

### Endnotes

1 Unless otherwise explicitly stated, this paper combines data as follows. In Australia, charters, agricultural operations, flying training, other aerial work, and private-business are combined. In Canada, commuters, air taxis, state operators, corporate operators, other aerial work, and private operators are combined. In the U.S.A., Part 91 operations, including corporate, personal, etc., plus FAR Part 133 operations (heavy lift), FAR Part 137 (aerial application), FAR 135 commuters and FAR 135 on-demand operations are combined. Despite some differences across national definitions among these various categories, their sums provide comparable populations.

2 To make the data as comparable as possible, purpose-of-flight here differs from some categories reported in official data in the three countries. For example, Australia and Canada distinguish between "non-commercial" business flights while "business" flight in the U.S.A. captures some commercial activity. Similarly, accidents involving medical evacuation or ambulance flights in the U.S.A. may be recorded under non-scheduled Part 135, conceptually comparable to air taxis or charters operations in Canada and Australia, or under FAR Part 91. Therefore, "charters" activity for the U.S.A. excludes medical flights and flights in support of off-shore energy operations.

3 These figures are based on weather conditions at the accident site, rather than "prevailing" weather conditions, as determined from the texts of accident reports.

4 "Maneuvering" in this paper identifies flights that are outside the normal regime, such as agricultural application, aerial mustering, firefighting, aerobatics, sightseeing, buzzing, low-level observation, etc.

# Wet (?) Runway Operations

By Capt. A. Ranganathan

*__Capt. A. Ranganathan__ is a B-737NG training captain with 19,000 hours. He have been working on the ALR India project for the last 5 years and compiled an "Adverse Weather Operations Training Kit," which is the standard training aid for all airline pilots in India. He is a specialist in "wet runway operations," and is employed by a new low-cost carrier SpiceJet, India. During his airline career, he has received two commendations: 1) Partial gear-up landing on a scheduled passenger flight with Indian Airlines in November 1987 and 2) Partial gear-up landing procedure while operating a scheduled passenger flight with SilkAir, Singapore in 1994.*

Air safety statistics during the last 30 years show an average of four to six runway overruns, or excursions, every year. However, since 2004 there has been a dramatic increase in the number of wet runway overruns/excursions. The average during the last 2 years is more than 10 per year. In majority of the cases, pilot error or human error has been identified as the cause. The month from July 2 to August 2 have brought into focus the importance of wet runway operations. Two hull losses involving the Bangladesh Biman DC-10 accident at Chittagong and the most recent Air France A340 accident at Toronto and the Air India 747-400 overrun in Mumbai should be eye openers for the subject. Do we take this subject seriously, only when there are lives lost? Are pilots really to blame, or is the system deficient for safe operation in wet conditions?

Several safety studies involving air accidents/incidents have identified that almost one in three approaches are not stabilized. Not all the unstabilized approaches result in a runway overrun or excursion. Most of these happen in runway conditions that are reported as "wet." In most of the cases, the landing before the accident has been normal. Have they been lucky, or have they made a stabilized or safe approach to landing? Are the pilots getting the correct information on the runway condition?

A recent paper presented by D. Paul Geisman of Boeing on wet runways has some interesting statements.

The first one is "Airplane braking coefficient is **not** tire to ground friction but instead it is the percentage of the total airplane weight on the wheels which is converted into an effective stopping force."

The second statement under the heading "runway friction and runway texture or how slippery is wet" claims that a wet runway results in less friction available to stop the airplane in an emergency. The question is how much is the runway friction reduced by the presence of moisture on the runway surface? This is a function of the material and techniques used to construct the runway.

Another interesting fact that comes out of the article is the fact that certification flights are conducted in controlled "dry" conditions, where the friction coefficient is taken as 4 mu and the wet runway criteria is extrapolated with a friction coefficient of 2 mu. Certification flights are not done in actual wet conditions!

Figures 1 and 2 show two different pictures of a dry runway. The rubber deposits on the runway in Figure 2 make it a potentially lethal surface in wet conditions.

A common factor in most of the wet runway overrun and excursion accidents is the fact that the actual condition of the runway is not reported to the pilots. ICAO Annex 3 requires the runway information to be provided:

ICAO Annex 3—Meteorological Service for International Air Navigation
4.12.7 Recommendation: *Information on the state of the runway, provided by the appropriate airport authority, should be included in reports in the METAR/SPECI code forms in accordance with regional air navigation agreement.*

This involves several agencies to coordinate for the information to be disseminated. Unfortunately, a real-time report on the actual runway condition is not likely because of this multi-agency function.

There is no clear-cut definition of a "wet" runway in FAA rules, and while there are mentions of different category of runway conditions like "wet," "damp," etc., in JAA rules the subject has several grey areas. The only information that a pilot gets is based on

*Figure 1*

*Figure 2*

*Figure 3*

*Figure 4*

the assumption that the water depth is less than 3 mm when the runway is reported wet. The air traffic controllers rarely report "contaminated" or "slippery" conditions. The wet runway condition becomes more critical in heavy rain and in cross wind. Even for grooved and sloped runways, the water depth can be more than 15 mm during the period of heavy rain.

Most of the runways, worldwide, are not grooved. The rubber deposits on the runways can be as much as 8 mm, depending on the number of landings and the period between runway surface cleaning. The next two photos (Figures 3 and 4) show the visual perception from the cockpit.

They show the effect of the rain on rubber patches on the runway, which seems to disperse the water at varying depths. During a landing in heavy rain, these patches can play a major part in whether the aircraft manages to stay on the runway surface. When no flight tests are done in "actual" wet conditions, can the data available be accurate to decide on whom the blame rests in case of an overrun?

Training manuals of different manufacturers are strangely silent on "wet runway" operations, this in spite of so many overruns during the past 30 years. To quote:

Shoot a firm touch down and select MAX REV as soon as MLG is on ground—Reference: A320 instructor support issued by Airbus Industrie

Similar instructions are there in the flight crew training manuals issued by Boeing for various aircraft types.

These photos (Figures 5 and 6) show the effect of reversers on the water depth in front of the main landing gear wheels. High-definition films taken in heavy rain conditions show clearly that the effect of the reverser flow appears to push the water in front of the wheels. While reversers are definitely a bonus for stopping on wet runways, the use of maximum reversers could result in a hydroplaning wheel from making contact with the runway surface.

Take the most recent wet runway accidents. The common factors in all of them seem to be

1. heavy rain,
2. crosswind/tailwind conditions,
3. runway condition reported wet (not flooded or contaminated?), and
4. max. reversers used.

Are we justified in blaming the flight crew, even if the approach and landing were not carried out in stabilized conditions? Did they have the correct information to carry out a safe landing?

The rules and definitions for wet runway operations must be clearly defined. Training manuals should place more emphasis on the correct landing techniques in wet runway conditions, taking into account that the correct information may not be available to the flying crew. The manufacturers of aircrafts should consider a minor change in reverser flow, to prevent water accumulation in front of the wheels. A 10 to 15% loss of reverser action will definitely go a long way in reducing the number of overrun and excursion accidents taking place on wet runways. Finally, safety investigators should look at wet runway accidents in a different perspective. Is it a system error, or do we still continue to call them "human errors?" ◆

*Figure 5*


*Figure 6*

# Turbulence Forecasting, Detection, And Reporting Technologies: Safety And Operational Benefits

By Christian Amaral

*Christian Amaral is the project pilot supporting the in-service evaluation of emerging turbulence technologies for Delta Air Lines Flight Operations. A commercial pilot with multiengine and instrument ratings, Amaral has studied at Mansfield College, Oxford University, and is a 2000 graduate of the College of the Holy Cross, where he earned a degree in history.*

## Introduction

The year is 2016. Areas of thunderstorms lace the eastern United States, all but halting the flow of air traffic throughout the National Airspace System. With more than one billion passengers served per year on U.S. flag carriers in domestic and international operations since 2015,[1] even days of good weather prove challenging at the FAA's air traffic command center. Armed with little more than weather avoidance guidelines developed in the 1950s, controllers restrict the flow of air traffic in the vicinity of thunderstorms, causing a daily backlog that is raising serious questions about the viability of commercial airplanes as reliable modes of transportation. All else being equal, the alternative goes something like the following: in order to maintain some semblance of schedule reliability, controllers abandon traditional methods governing weather avoidance, focusing instead on the core competency of keeping airplane A separated from airplane B. With more airplanes exposed to weather that had been deemed hazardous under the old system, needed growth in airspace capacity comes at the price of the remarkable gains made in weather-related aviation safety during the 20th century. For air carrier aircraft, this backslide comes primarily in the form of higher rates of turbulence-related incidents and accidents. Still, for the sake of a viable air transport infrastructure, it is deemed a worthwhile sacrifice.

To satisfy the ever-increasing need for airspace at an equivalent or higher level of safety, new tools will be required. By promising the ability to pinpoint areas of actual hazard within weather systems where today's air traffic decision-makers dare not tread, emerging technologies aimed at the forecasting, detection, and reporting of turbulence offer an important first step in delivering the necessary solutions. As part of a NASA-funded in-service evaluation at Delta Air Lines, experience with two of these technologies, which were developed by AeroTech Research, with additional key expertise from Rockwell Collins and ARINC, suggests a paradigm shift in the way weather hazards are viewed in aviation.

It should be kept in mind that the weather hazards being considered here are those that apply to commercial air carriers and not general aviation aircraft, as the challenges posed by various weather phenomena to these two groups differ significantly. Based on an analysis conducted in 2003 for the U.S. National Aviation Weather Program Mid-Course Assessment, turbulence stands among the final frontiers of weather hazards facing air carriers. Additionally, turbulence remains one of the most common elements in NTSB air carrier accidents.

## The turbulence challenge

The reasons that turbulence remains on our list of hazards facing air carriers are many. In the absence of anything better, current definitions of turbulence, including guidance embraced in the FAA's latest advisory circular on the topic, rely on individuals' subjective interpretations of a given encounter with rough air. For the same encounter, these experiences may vary widely depending on where an individual might be in the cabin, as well as the varied tolerance levels of those individuals.

Despite the flaws inherent in such human-based assessments, pilot reports (PIREPs) of turbulence are highly valued because they are so rare. At air carriers, chatter on air traffic control frequencies about ride quality at various altitudes often constitutes the extent of flight crews' awareness of turbulence, informing tactical decisions about where to fly, with little knowledge of what levels of turbulence may exist further along in the flightpath. Due to the high workload of both pilots and controllers, such information very seldom gets reported into the FAA database of PIREPs, which are available for preflight and inflight planning purposes. Moreover, because of the very high workloads facing crews operating through areas of thunderstorm activity, virtually no information exists on the presence of turbulence in the vicinity of such systems.

This, in part, has contributed to some flawed assumptions about the extent of significant turbulence in areas of convective activity. Lacking good information on what levels of turbulence that airliners sometimes experience in these environments, controllers, dispatchers, and pilots have relied on areas of high radar reflectivity to imply areas of potential hazard. But by definition, areas of high reflectivity mean only the presence of significant moisture, or high rates of precipitation. There are currently no reliable means of detecting hail, and areas of red on the radar screen may or may not pose a turbulence hazard. Meanwhile, severe or greater turbulence may be present in areas of little or no reflectivity near these same systems.

Most modern airborne weather radar systems have a mode to show areas of turbulence as an overlay to the radar reflectivity. Displayed in the color magenta, the system uses the motion of moisture particles detected in a radar sweep to indicate areas of potential turbulence hazard. More specifically, if the horizontal motion of moisture particles in a given area is 5 meters per second or greater, then magenta will be overlaid over any radar reflectivity in that area.

But because of what is *not* accounted for in the formula used to populate magenta on the radar screen, pilots generally have an indifferent or slightly negative view of the turbulence mode. That is because determining the horizontal motion of moisture particles is only a first step in assessing the potential turbulence hazard to a specific aircraft with certain aerodynamic characteristics traveling at a certain speed, at a certain altitude, and having a certain weight. Using the current turbulence mode, a pilot looking at a radar display on a Boeing 747 would be presented with exactly the same magenta hazard assessment as a pilot flying a Beechcraft King Air, despite the obvious differences in the responses of these aircraft to the same patch of turbulence. In addition, the baseline of 5 meters per second being used to define a turbulence hazard with magenta amounts to quite a high threshold under almost any condition. Pilots could easily experience turbulence outside areas of magenta that they might deem operationally significant or even severe.

### Enhanced turbulence detection radar

Developed by AeroTech Research and Rockwell Collins, an enhancement to the magenta function that accounts for all of the factors missing from the current turbulence mode is so far showing tremendous promise in the ongoing evaluation at Delta. Installed as a software upgrade to Rockwell Collins' WXR-2100 Multiscan radar on one Boeing 737-800, two thresholds of turbulence are being presented in two patterns of magenta, offering crews a truly scaled hazard assessment for their aircraft, adjusting automatically to all flight conditions. Since the aircraft is deployed in revenue operations, flight crews are naturally avoiding areas where magenta is depicted as much as possible. But when few options are available in busy terminal areas, instances that require penetration of these areas have also presented themselves. Using both accelerometer data and qualitative feedback, correlation between the levels of turbulence predicted by the magenta and the turbulence that was actually experienced in these instances has been very good. The function, which currently has a range of 25 nautical miles, gives crews 3 to 5 minutes either to deviate around areas of potential hazard or secure the cabin.

With solid validation of the system, something else is also apparent in the data, making a strong case for abolishing the popular connection between areas of high reflectivity and a turbulence hazard. Jumpseat observations relate how air traffic controllers sometimes clear the aircraft away from areas of yellow and red reflectivity where no magenta is apparent, only to steer it toward areas of nil or green returns containing a high presence of magenta. With wider equipage and the downlinking of this information to air traffic decision-makers on the ground, it is easy to see how such data could be used to make better use of the available airspace on bad weather days, helping crews to more safely negotiate areas of hazard while also identifying areas of opportunity in the vicinity of convective activity. Potential even exists for controllers to use this information in developing a throughput strategy that is selective based on hazard assessments for individual airframes. Perhaps, for example, a given area is acceptable for a Boeing 777 to transit, but hazardous to a regional jet, allowing at least some opening in a corridor of airspace that would otherwise be closed to all traffic.

### Turbulence Auto PIREP System (TAPS)

While the enhanced magenta function can only identify areas of turbulence associated with particulate matter, better technology aimed at the reporting of turbulence offers benefits in all environments. Developed by AeroTech Research, the Turbulence Auto PIREP System (TAPS) consists of an integrated software, datalink, and display infrastructure delivering scaleable, objective turbulence reports to a wide variety of aviation users in real time. Any time that turbulence causes an upset exceeding a certain g load during flight, TAPS software codes information from the accelerometer and other sensors already on the aircraft into a message that is then packaged and automatically sent to a groundstation via ACARS. With support from program partner ARINC, the report is processed at the groundstation and uploaded onto a version of ARINC's WebASD flight-following display currently available only to project participants. Software enabling reports is now installed on 120 Delta aircraft, including all 737-800s, 767-400s, and most 767-300ERs, and all Delta dispatchers and meteorologists currently have access to the display.

In dispatch, reports are being used for tactical hazard awareness and avoidance, and can also identify instances in which the airframe limitations may have been exceeded due to severe loads. Meteorologists are using the information in validating forecasts and forecast methods, as well as providing real-time guidance on what avoidance measures to take using their understanding of the atmospheric phenomenon causing the turbulence. Seeing a report of moderate turbulence in real-time, for example, they may use their bigger-picture perspective to notify crews about how to escape or avoid that turbulence.

Since TAPS reports are aircraft specific and scaleable to different airframes, subjective, pilot-based interpretations of turbulence no longer need to cloud airspace decisions. In the enroute environment, for example, dated reports of "bad rides" from smaller aircraft can effectively shut down certain flight levels based on other crews' misguided fear of experiencing the same level of turbulence. The use of such poor metrics leads to enormous operational inefficiencies, with pilots deciding to fly at less-economical altitudes based on little more than hearsay. In the vicinity of convection, TAPS reports could similarly be used to identify areas of opportunity in airspace that would otherwise be shut down. Since the connection between reflectivity and turbulence hazard appears tenuous at best, TAPS represents another potentially important safety tool to inform better operational decisions.

### Summary

In light of the airspace constraints currently on the horizon combined with the existing hazard of turbulence, we will require better tools to ensure that safety is maintained. Controllers forced to be more aggressive in routing traffic through areas of bad weather will need better information than ever before in pinpointing areas of hazard. Though other tools will also be needed, so far, these emerging turbulence technologies offer significant promise in doing just that. ◆

### Endnotes

1 Assumptions for this scenario are based on the FAA Air Traffic Forecast, 2005.

# Total Safety Management for Aircraft Maintenance Using Total Quality Management Approach

By Derrick Tang, Principal Consultant, Advent Management Consulting, Pte, Ltd.

***Derrick Tang** runs his own management consulting firm, providing consultancy and training in service quality, ISO-9001, business excellence model like the Singapore Quality Award, and safety management for the aviation industry. He is a national assessor for the Singapore Quality Award and a senior auditor for ISO-9001. Derrick has 18 years of working experience in aviation industry, in the areas of aircraft maintenance and management of aircraft maintenance operations. His working experiences include Licensed Aircraft Engineer with Singapore Airlines and Air Engineering Officer in the Republic of Singapore Air Force in positions ranging from operational function, staff function, and senior management position. His last appointment held was Head of the Quality Assurance Branch in the Republic of Singapore Air Force (RSAF), responsible for quality management and safety system for aircraft maintenance. He left the Republic of Singapore Air Force in July 2003 and last held the rank of lieutenant colonel.*


### Abstract
About 75% of aircraft accidents are caused by human factors. Of which, about 25% are due to maintenance human errors. In the recent years, this has been the focus and concern of the aviation industries, and many aircraft operators are maintaining close watch over human factors in aircraft maintenance. Numerous programs, initiatives, and training have been launched to train and raise the awareness of staff at all levels and functional areas of human factors in aircraft-maintenance-related activities—not only for aircraft maintenance personnel, but also management, engineers, technical records, ramp workers, supplies, etc. In short, the whole organization needs to be involved, and it is a cultural change for some. This paper outlines the use of the Total Quality Management (TQM) framework to manage aviation maintenance safety, and to reduce human factors in aircraft maintenance. It is not just a one-shot program, but a continuous process of inculcating the safety awareness during aircraft maintenance work and how human factors can affect work performances. This paper also discusses the possible measurements and returns of investment (ROI) of using the TQM framework in aviation safety.


**Keywords:** TQM, human factors, aircraft maintenance, safety

### 1. Introduction
In 1992, a 747-200 bound for JFK from Hong Kong was touching down in Narita, Japan, for an overnight layover, but the plane was stopped on a taxiway and the front of the engine was seen touching the ground. From the incident report, "The flight and landing roll-out were routine. Engine thrust reversing was normal on four engines until coming out of reverse at about 90 knots."

What caused this incident? The fuse pins that held the pylon diagonal brace sheared in the incident. The upper fuse pin was recovered intact; however, the two diagonal brace fuse pins and their retainers were not found. The aircraft involved in this incident had undergone a maintenance check at the airliner's heavy maintenance facility a month before and had flown 18 flights since check. Following the Narita incident, the missing set of retainers was found on a maintenance stand at a heavy maintenance facility.

While there are interests in bringing human factors principles into an organization, it is this type of incident that serves to catapult the human factors in technical operations to high priority. Alike the cockpit crew resource management (CRM), the development of maintenance resource management (MRM) is the result of a series of such incidents. Figure 1 outlines the evolution of MRM and incidents that have triggered it.

Maintenance resource management (MRM) is a total system approach, which optimizes the organization's resources to manage and control human factors in aircraft maintenance. The aviation industries widely adopted the MRM, which shares basic features with CRM, including addressing issues of communication and team coordination. However, the target audience for MRM is the maintenance crew, support personnel, inspectors, engineers, and managers, which is a more diverse group than cockpit crews.

### 2. Industry practices and experiences
The details of MRM program vary from organization to organization. However, the goals of any MRM program are the same, which are to improve work performance and safety, and are linked to traditional human factors topics such as equipment design,

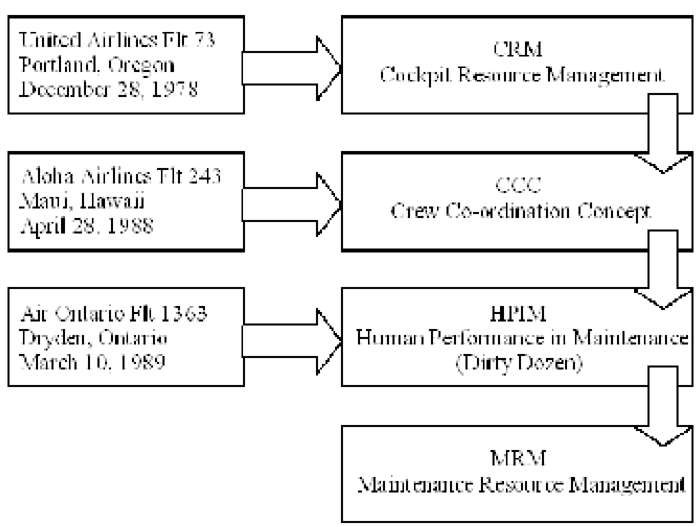


***Figure 1. Evolution of MRM and human factors training programs.***

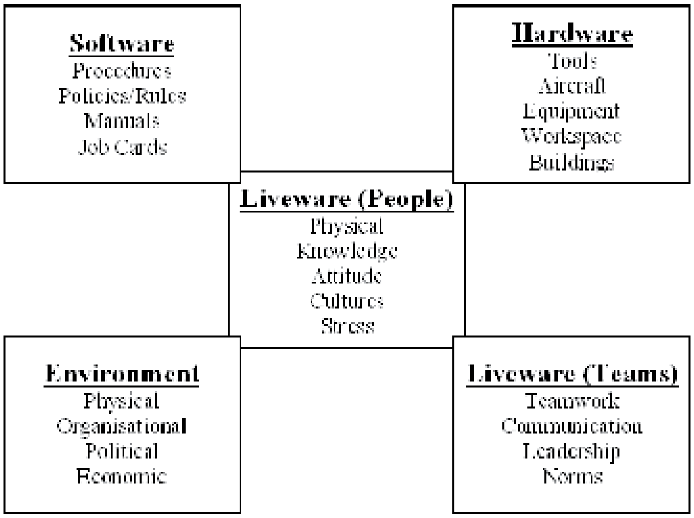


*Figure 2. SHELL model.*

human physiology, workload, and safety. Reductions in human errors are through improved coordination and teamwork.

Most major airlines develop their own organization-specific MRM program, as well as design human factors training courses for maintenance operations. The human factors training courses are typically based on the human performance in maintenance and the airline's own human-factors-related experiences and case studies. The trainings are being incorporated in their maintenance training schools. Some of the airlines with an MRM program are British Airways,

Singapore Airlines, Delta Air Lines, US Airways, United, Northwest, Southwest, American Airlines, etc. These companies are taking a system perspective by applying human factors and MRM principles at system, situation and workplace, tasks and activities, groups and teams, and individual levels, as shown in the SHELL model (see Figure 2).

The MRM and human factors training programs are not the only approaches to understand, identify, and provide solutions for maintenance errors. Maintenance error analysis program such as MEDA[1], AMMS[2], ASRS[3], and BASIS[4] are being developed and integrated into human factors training.

The MRM and human factors training programs create a common language within the organization, across departments and divisions. Even though, different company designs and implements a slightly different MRM and training program, there are notable common elements in their system approaches, and they are

- senior management support,
- use of system approach,
- education and training for all levels, from manager to maintenance staff,
- full participation in teamwork,
- data-collection tools, and
- continuous communication and feedback.

### 3. Need for total system approach

Corrections to human performance deficiencies often focus on individual remediation. Administering training, briefing, and sending notices to inform of the deficiencies are "quick fix," which may change behavior for a short time, but the underlying habit patterns of the individual, the department and the organization

**Table 1. Safety Management and Practices**

| Principles of TQM | Practices for Total Safety Management (TSM) |
|---|---|
| Leadership and Quality Culture | • Senior management creating a mission for safety in the company and gives personal support to the safety set up in the company.<br>• Safety policy and safety management principles.<br>• Safety culture—open reporting culture.<br>• Continuous communication and feedback.<br>• Human factors in maintenance program.<br>• Dirty dozen.<br>• Ground crew safety attitude survey. |
| Use of Information and Analysis | • Data-collection tools.<br>• Safety information system to share lessons learned from incidents.<br>• Analysis of human factors in maintenance using some form of the human error analysis tool to analyze causal factors (based on dirty dozen) of human errors, human error injury, cost of quality in terms of cost of rework and man day lost.<br>• Constant comparisons and benchmarking with other established airline operators on the performance in human factors in aircraft maintenance andprocesses as well as safety records. |
| Strategic Planning | • Strategic objectives are being set for safety programs.<br>• Goals and objectives are being set for both short-term, long-term, and stretch goals—like to maintain a zero accident record. |
| Human Resource Development and Management | • Full participation in teamwork.<br>• Education and training for all levels, from manager to maintenance staff.<br>• Human factors in aircraft maintenance training during trade refresher.<br>• Staff satisfaction survey in maintaining a safety working environment.<br>• Reward and recognition system for safety consciousness. |
| Management of Process Quality | • Use of system approach.<br>• Quality and management system based on ISO-9002.<br>• Surveillance, in-process-inspection, quality verification inspection, and self-check program within department and inter-departments.<br>• Risk assessment for hazardous or critical tasks.<br>• Task authorizations.<br>• Critical tasks checklists.<br>• Daily start-of-shift-brief and end-of-shift debrief by all departments.<br>• Shift hand-over management.<br>• Overtime management system. |
| Quality and Operational Results | • Safety as top line and bottom line.<br>• Safety index (SI) for departments.<br>• Cost of safety.<br>• Return of investment. |
| Customer Focus and Satisfaction | • Safe and reliable aircraft.<br>• Zero accident. |

may drive the behavior back to the original state, unless the underlying system is also fixed.

From the above-common elements of the MRM programs by successful airliners, it is obvious that MRM is not about addressing individual human factors of the maintenance crew or his/her manager alone, but the larger system of human factors concerning all levels involved in aircraft maintenance, working together to promote safety. As such, it is an integration of human factors and resource management into operations.

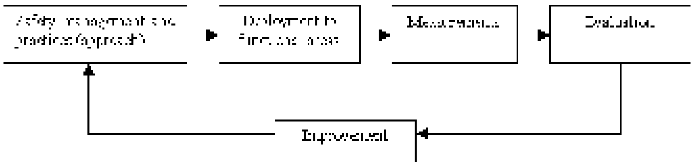

*Figure 3. Total Safety Management Cycle.*

So how do you integrate and translate the human performance principles into day-to-day maintenance operations? It will vary from organization to organization. I would like to suggest integrating the common elements of successful MRM program, adopted by the different companies, with the Total Quality Management (TQM) framework that is adopted by successful companies for business excellence. And we could call this framework Total Safety Management (TSM). One who is familiar with the TQM framework would be able to note the common elements in the MRM program with the core principles of the TQM framework.

## 4. Total Safety Management (TSM)

### 4.1. *Approach—safety management and practices*

Using the TQM framework, the safety management and practices can fit nicely to the Total Safety Maintenance (TSM) framework as shown in Table 1. To ensure that these safety management and practices are being deployed in all functional areas, the Total Safety Management Cycle as shown in Figure 3 could be adopted.

### 4.2. *Deployment—safety as top line and bottom line*

With safety management and practices, the challenge for most companies would be the deployment of these management and practices to ensure effectiveness and yield the correct results. Such safety management and practices should not be viewed as a program with an expiry date in mind, but rather be integrated into the day-to-day operational process. In short, these safety management and practices should not be a "one shot" affair. Different organization will have varying ways of integrating and translating into their day-to-day maintenance operations.

I believe that for the aviation industries, the buying in of these safety management and practices should not be too difficult a task, as passenger and air safety are paramount. Using safety indicators as the top line and bottom line (like in the profit and loss statement) for all departments and functional areas could be an outcome to gauge the effective deployment of the safety management and practices.

### 4.3. *Evaluation and improvement—do you have the correct safety culture?*

By adopting the Total Safety Management approach to manage human factors in aircraft maintenance will we achieve the correct safety culture? Surveys with ground crew and staff are one of the methods that are used to ascertain the safety consciousness and attitude in the company.

The survey results may show that you may have the safety culture, but does that mean that you have the desired safety culture? It is this culture that will be a hindrance to seek a further improvement of safety, because deep down both management and staff believe they are safe enough, when there are no accidents. Adopting the TQM approach for safety management means constant review and the introduction of safety improvements through the use of the improvement cycle as shown in Figure 3.

**Table 2. A Sample Checklist**

| Known ProblemAreas | Focus Areas |
|---|---|
| Management (Environment) | Systematic review of safety management program is important to identify problems that workforce faces and address the significant issues. |
| Workplace Environment (Environment) | Worksite review on a regular basis and noted shortfalls to be logged for remedial actions. The environment can include working conditions, weather, lighting, equipment, and transport required to support the tasks. |
| Tooling/ Equipment Availability (Hardware) | If tooling or equipment is unserviceable or unavailable, then temporary injunction to the task should be raised to warn that if task has to be completed during the shortfall then special precautions should be applied |
| Availability and Accessibility of Documents. (Software) | Relevant documents to carry out tasks should be available and readily accessible. |
| Hand Over of Work at Shift Change (Liveware—Teams) | Handover log should be a historical record of the day's work filled out as the day progressed and not a list raised at the end of the shift from memory. |
| Workload of Individuals (Liveware—People) | Workload is not the initiator of an incident but frequently is an escalation factor that allows the situation to deteriorate. Working hour limit should be imposed. |
| Supervisory Oversight (Liveware—Teams) | The supervisor (shift In-charge) should be doing the supervision of team, see shortfalls in resources, equipment, spares or tooling, maintain the shift log history, and establish priorities. Avoid using the supervisor as part of the team. The supervisor is part of the safety net for his team and should not be his own safety net. |
| Time Pressures (Liveware—People) | An escalation factor that can deteriorate the situation. Management overview of the mainte nance activities to identify insufficient time allocations and prioritizes. |
| Night Working (Environment) | Night management supervision and check on the quality of work, environment, and work practices. |
| Procedures (Software) | It is relevance of the procedures and compliance with them that really matters. Poor procedures lead to lack of respect for them and often encourage noncompliance. If procedures are to be effective, then they must be periodically reviewed and checked if they can actually be achieved as written, rather than needing interpretation for their intent. |
| Noncompliant Practice (Liveware—People) | Noncompliant to practice is often traced to maintenance work done from memory, especially routine tasks needed to monitor the compliance to practices periodically using similar approach to that used for pilots in the "line check." This process carried out by the supervisor will add the benefit of reviewing a procedure for relevance. |

The evaluation, feedback, and improvement are often our weak links. To strengthen this, a checklist can be developed for evaluation and control of human factors within the Total Safety Management framework using the applicable elements in the SHELL model adopted by the industry. Table 2 provides a sample checklist, which can be developed, based on known problem areas that could trigger human error incidents.

### 4.4. *Measurements—return of investment (ROI)*

In the Total Safety Management Cycle, illustrated in Figure 3, measurement is the means to determine the effectiveness of the deployment of the desired approach. In the case of Total Safety Management, the effectiveness of implementing the safety management and practices could be quantified by the cost avoidance of incidents or accidents.

Such cost avoidance could be termed as the return of investment (ROI) for the time and effort the company invested into implementing the Total Safety Management. It concerns the savings in the time and cost of carrying out investigations into incidents and accidents, which may have come about as a result of human errors in aircraft maintenance. In the worst scenarios, this would be the result of loss of lives in an aircraft accidents.

In the P/L statement sense, the investigation cost would be booked under expenses for engaging resources and equipment, and any damage whether direct or collateral would be booked under the write-down provision for equipment. Another aspect, which may not be apparent, is the diversion of fixed resources (i.e., manpower and assets) for the investigation. This would mean potential loss of revenue generated and economic benefit to the company. All these will definitely have impact on the bottom line of the company.

Based on the common consequences of human errors in aircraft maintenance, the following are some examples of safety indicators that could be used to measure such cost avoidance:

- Number of incidents or accidents resulting in damage to damage to aircraft.
- Number of incidents or accidents due to human maintenance errors.
- Number of incidents or accidents resulting in personnel injury.

With the occurrence of aircraft maintenance incident or accident, the following are some examples of quantifiable costs would be incurred during a normal operation:

- Cost of investigating the incidents or accidents.
- Cost of rework (as a results of damage).
- Cost of lost of usage of aircraft or equipment.
- Cost of aircraft or equipment (if beyond repair).
- Cost of fleet inspections or re-inspection (as a result of maintenance human error).
- Cost of lost of man-hours (due to injury).
- Cost of passenger transfer, food, and accommodation (for airliners).

Such costs, if quantified, could be factored for each incident or accident. With the implementation of the Total Safety Management, the objective is to reduce the number of aircraft incidents or accidents.

Hence, the return of investment (ROI) for the implementation of the Total Safety Management could simply be quantified by the cost avoidance for reduction of the number of related incidents or accidents, i.e., the safety indicators (e.g., the number of incidents or accidents resulting in damage to aircraft, number of incidents or accidents due to human maintenance errors, number of incidents or accidents resulting in personnel injury) compared with the cost of implementing the Total Safety Management in the company.

For the purpose of illustration, consider the investigation into the earlier example of the 747-200, which stopped on the taxiway of Narita Airport, with the front of the engine touching the ground. The cost investigation into such an incident, due to maintenance human errors, could be in the order of US$ 0.5 million and would likely be attributed by the following costs:

- Cost of investigation.
- Cost of aircraft recovery from the runway.
- Cost of lost of rework on affected engine and aircraft.
- Cost of fleet inspection for similar defects.
- Cost of lost of use of affected aircraft and fleet as a results of inspection.
- Cost of transferring passengers to another flight.

The cost avoidance of one such incident could be as much as or even more than running the Total Safety Management and training for the entire company, which could be in the order of US$0.2 to 0.3 million, which may vary from company to company, depending on size. These are the tangible cost avoidances.

Of course, for each incident such as this, the other intangible costs for the airlines concerned would be the image and the confidence level of its customers. This would translate in loss of revenue for a short period of time or even longer, if the case has serious adverse publicity.

In the review of the effectiveness of the Total Safety Management, the measures of these safety indicators and ROI (cost avoidance) would serve as a good feedback for further reviews needed, to ensure the approach and deployment are yielding the correct results.

## 5. Conclusion

The emphasis in safety has become very much an integral part of airline operators, and the investment in safety effort is to yield the must-sought-after accident-free safety record for as long as possible. This safety effort is never enough.

For some airlines operators, the present safety culture and mindset may have served them well, but the question remains, What happens when they have reached a point where there is nobody else ahead of them?

In my opinion, the challenge ahead is to take on a systemic approach to safety management that continuously reviews and aids the introduction of safety improvements to challenge ourselves in search of new markers in safety culture.

One such approach is to adopt the Total Safety Management Cycle, which is an adaptation of the improvement cycles of TQM to review and improve on the safety management and practices. ◆

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## Endnotes

1 MEDA: Boeing's Maintenance Error Decision Aid used by SIA.
2 Aurora Mishap Management System (AMMS) used by Northwest.
3 ASRS: Aviation Safety Reporting System, administered by NASA.
4 BASIS: British Airways Safety Information System.

# Maintenance Error Prediction Modeling

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## 1. Introduction

In June 2004, a Boeing 777 departed London Heathrow with 151 people on board. The aircraft was "tankering" fuel, and as such, had full wing tanks and a centre wing tank (CWT) over half full. Some months earlier the aircraft had undergone scheduled maintenance during which time the CWT purge door was removed. A very simple and repeatable maintenance error allowed the aircraft to return to service with the door not refitted. Nine contributory factors were indicated with the main causal factor being unrecorded work.

With the Harare-bound aircraft level on the ground, the CWT fuel was just below the open access door so no fuel leakage occurred that was visible. During the takeoff roll, the fuel surged rearwards and spilled out of the access hole. As no source of ignition was present, the escaping 2,500 kgs of fuel did not ignite; had it done so that the resulting fire would have been significant in intensity, considerably threatening the safety of the flight. This did not occur and the aircraft landed safely some 26 minutes later.

The principal problem is how to anticipate the likelihood of maintenance error, understand the consequential severity, provide suitable defenses to reduce the occurrence risk, and communicate this information to all users. Maintenance error is an immensely complex subject and the large number of maintenance tasks undertaken makes individual task analysis impractical and cost inefficient. This tends to focus the solution of the problem to the development of a model that can be applied generically to help identify potential risks and apportion suitable defenses.

## 2. Incident occurrence reporting systems

Several generic safety systems, such as ISO9001, total quality management (TQM), and six-sigma were reviewed, but each although valuable in their own right could not successfully increase the flight safety margin. With no effective generic quality-assurance system, the aviation industry has developed Critical Event Analysis, a process that examines system failures, be they through engineer self-disclosure or accident/incident investigation.

The primary focus of the evaluation in every case should be to prevent the critical (and similar) events from recurring. In the ideal situation all errors are reported, investigated and appropriate measures taken to prevent recurrence. Sadly, research tends to indicate this is not the case, and several obstacles to this exist. The CAA introduced Maintenance Error Management System (MEMS) in 2000 with the issue of AWN71, to try to overcome some of these obstacles and promote greater understanding of error investigation.

MEMS was introduced to complement, not supplant, the existing U.K. reporting mechanisms, which are Mandatory Occurrence Reporting (MOR) and Confidential Human Factors Incident Reporting Program (CHIRP) (CAA, 2000). The MOR scheme provides a legal requirement for licensed engineers to report all incidents (which has endangered an aircraft or its occupants) to the CAA within 72 hours (EASA Part-145, 2005). CHIRP, on the other hand, is an independent charity-based organization that allows free and confidential reporting of any incident or occurrence.

For any critical event analysis tool to be effective, it requires full and free flow of information. The MOR scheme, with its legal support, is well served and receives sufficient reports each month. Independent research revealed that engineering staff fully understood and complied with their legal reporting obligations, but demonstrated reluctance to report non-mandatory occurrences.

Such reluctance might indicate a mixture between fear and apathy, and although these elements are possibly present, the underlying reason suggested was lack of effective and visible change. Some of the engineering staff interviewed felt their self-disclosure would not lead to change but might result in punitive action so chose not to submit. Any control measure has to be transparently effective and well communicated, and this is where the application of critical incident evaluation appears limited. Many companies tend to use critical incident reports as a business measure, with continued 'quality' being a key performance indicator of many engineering staff. This need to demonstrate performance can in the short-term lead to report "answers" becoming more important than effective incident cures.

Even when effective controls are highlighted, poor communication of these can lead to recurrence of the error. The U.K. Air Accident Investigation Branch (AAIB) performs several comprehensive investigations each year. The reports are thorough and in general suggest suitable corrective actions, but the communication of the information is limited. MEMS can be applied effectively, but mistakes disclosed are often not communicated industry-wide.

### 2.1. Error classification and communication

Part of this reluctance to transfer information is due to corporate sensitivity to errors. To overcome this and provide the ability to analyze trends, several classification methodologies have emerged, for example, Rasmussen, Reason, Shappell, and Wiegmann have all extended work into system and latent failures.

Dr. William Rankin, Boeing's senior principal scientist for maintenance human factors, developed Maintenance Error Detection Aid (MEDA) in 1996, perhaps one of the best and most widely used classification tools currently available. MEDA is a tool that allows a consistent approach to be taken following an incident or accident. Analysis of MEDA results can indicate trends and areas where attention is required, which could be addressed through proactive design or cultural shifts.

These systems are good and add significant value but exhibit two distinct weaknesses. Firstly, the analysis is, in general, retrospective, or post event. Secondly, they do not identify specific maintenance tasks as potential problems, rather relying on complexity changes within a "system." All the schemes rely on senior management support, and with the increasing globalization of business, senior management slots are rotated fairly frequently. The most effective improvement schemes should be robust, in that they don't require executive support to survive. Such support would amplify the effects, rather than determine its survival.

This study complements these models and additionally offers a slightly different view. If MEDA data highlight a particular group of tasks as errant, a predictive model could be applied to evaluate the risk of failure in a specific maintenance task. This would allow MEDA information to be specifically targeted, allowing cultural initiatives to be fully exploited.

## 3. The predictive model

### 3.1. Basis for discussion

Two prediction tools are widely used in the aviation industry although not directly focused on maintenance error. These tools, FMEA and MSG-3, have proved very successful, so some adaptation of them would prove effective. Additionally as they are "old news" to many, the predictive model will be easier to welcome, understand, and support.

FMEA has been used successfully in the motor industry and has become an accepted standard (McDermott et al, 1996). Additionally it has seen effective use in aircraft manufacturing. FMEA uses subjective views and statistical process control data to establish risk. A risk factor is equal to the product of likelihood and severity. Figure 1 demonstrates the scales assigned to each (McDermott et. al., 1996. p. 34).

MSG-3 methodology offers a very comprehensive yet easy-to-follow process to ensure design for service criteria are met. MSG-3 in its form is not applicable to this study, but the widespread use of it and its acceptance would make a similar processed approach attractive.

MSG-3 relies on an expert system being asked a series of questions at differing levels. A simple flowchart allows the team to review progress and establish the next logical step to take. It is a method of taking highly valuable, subjective views and applying a consistent approach to each (Air Transport Association of America, Inc., 2002). The predictive model developed in this study uses a combination and adaptation of both.

| Likelihood of Occurrence | | Event Severity | |
|---|---|---|---|
| **Rating** | **Likelihood** | **Rating** | **Noticeable Effects** |
| 1 | Almost Impossible | 1 | None |
| 2 | Very Remote | 2 | Very Minor |
| 3 | Remote | 3 | Minor |
| 4 | Very Low | 4 | Very Low |
| 5 | Low | 5 | Low |
| 6 | Moderate | 6 | Moderate |
| 7 | Moderately High | 7 | High |
| 8 | High | 8 | Very High |
| 9 | Very High | 9 | Extremely High |
| 10 | Almost Certain | 10 | Dangerously High |

***Figure 1. Basic FMEA likelihood and severity tables.***

### 3.2. Likelihood of occurrence

The first stage of the model is analyzing the likelihood of occurrence. Whereas in a manufacturing situation there are large quantities of statistical process control data to determine failure rates, the very random nature of maintenance error makes such quantitative analysis impossible (Reason, 1990. pp. 3-5). To overcome this, an expert system (ES) of engineering staff is established, which can apply experienced, qualitative views. Developing a score from a subjective view is challenging even for trained professionals; the flowchart (see Figure 4) was developed to assist. It allows subjective information to be treated in a consistent manner.

Referring to Figure 4, the ES decide on an initial "feel" of likelihood and apply this as a level one question. The next stage is for the ES to evaluate the level two questions. These were developed following analysis of accident and incident reports. Reason (1990, p. 166) predicted the detection rates for different types of failure, with skill-based failure having an 86.1% chance of being discovered, whereas a rule-based failure has only 70.5% likelihood of detection. The level two questions of Figure 4 were devised to allow the ES to successfully weight their findings in sympathy with these studies.

Each of the guided questions evaluates the main organizational influences that increase or decrease the likelihood of the failure. For example, if the ES take a view that a task failure is probable, but then evaluate that there have been previous recorded occurrences and usually fairly strict time pressures are applicable, those two antecedents combine to suggest the likelihood is higher. The ES would then re-evaluate the task as almost certain and applying the same principals would probably return a likelihood score of two higher. This concurs to the fact that two defenses have essentially failed and so the likelihood is raised.

### 3.3. Defining severity of occurrence

The next stage is for the ES to assign a subjective view of the severity should the occurrence happen. Discussions with airline operation control staff revealed the most damaging failures in terms of cost and loss of customer confidence and a review of technical discrepancies of 2004 highlighted the lower severities scores. Figure 2 summarizes this information and demonstrates the severity rating to be assigned. The ES would assign the highest realistic severity.

The severity of the occurrence is perhaps the most significant part of the analysis for two reasons. Firstly, the severity cannot be altered regardless of the safety net applied, and secondly, a hull loss, which is unlikely, is more worrying than a very likely non-airworthiness event. To overcome this, the severity rating were weighted by a factor of two as demonstrated in Figure 2.

| Rating | Severity of Occurrence | Effect to Airline |
|---|---|---|
| 24 | Probable aircraft loss with single failure | Unacceptable loss |
| 22 | Possible aircraft loss with single failure. Or probable aircraft loss with two or more failures. Death | |
| 20 | Serious injury to passenger/ crew (includes ground crew) | Highly undesirable |
| 18 | Aircraft/equipment damage (serious in nature) | High cost penalty |
| 16 | Technical delay/loss of service customer satisfaction | Loss of external |
| 14 | Pilot dissatisfaction customer satisfaction, increased corporate fatigue | Loss of internal |
| 12 | Cabin crew dissatisfaction (or pressure on return to service date–base) | |
| 10 | Engineering dissatisfaction (or minor injury) | |
| 8 | Performance penalty | Minor cost penalty |
| 6 | Additional maintenance required | |
| 4 | Barely noticeable effects | Limited (if any) |
| 2 | Non-airworthiness/not noticeable | |

***Figure 2. Occurrence severity rating.***

### 3.4. Detection possibility

A missing engine, for example, would be spotted by anyone regardless of grade, training, or experience. But if we consider engine-mounting bolts being left unlocked, only a specific inspection would discover the error, and the inspector would have to be familiar with the task. It is possible to develop a scale of detection ranging from impossible to fly with the error to the latent failure. Figure 5, page 99, was developed to allow the ES to classify the possibility of detection. It should be noted that this figure is inverted to the previous figure regarding likelihood; this was considered appropriate as it leaves the most unlikely case on the right. The ES use the figure in the same manner as previously. The essential derivation rationale of Figure 5 was that as latent failures increase, the detection possibilities are reducing so the score should increase.

### 3.5. Risk factor analysis and communication

With the ES having established the likelihood, severity and detection based on their experience and guided questions; the next phase is to assign a risk factor. This is performed through the product of the three scores developed.

Risk factor = likelihood x severity x detection

Analysis of this formula and the scores was performed and revealed the model to be effective at identifying key events that must be captured. The analysis revealed that the highest risk factor was 6,144, and the lowest was 2. The sliding scale in between these extreme cases was established and key values were identified. A risk factor above 1,100 is at warning level, indicating insufficient control measures are currently applied. The higher up the scale, the more immediate the response needs to be. A factor below 550 was classed as standard and adequately covered under existing safety mechanisms. The events that fall between the two generally cause significant cost and so might need to be controlled, even though flight safety is not specifically at risk. Figure 3 summarizes this in the form of a "flight safety" thermometer.

A risk factor analysis can be applied both retrospectively following an incident and proactively if an engineer reports a specific task as exhibiting risk. Equally, MEDA analysis could indicate a group of tasks exhibit risk; applying the analysis following this enables targeting of these MEDA values.

An important element is onward communication of the data. O'Leary (2003, p. 165) discusses such communication, highlighting an example of how "go-around" (or rejected landing) problems could have been solved earlier had ATC and flight crew reports been collectively analyzed. Each maintenance task has a unique reference number assigned. This number, together with the risk data and appropriate defense, could be communicated to the manufacturer for inclusion in the leading section of each AMM task.

The U.K. flight safety committee and CHIRP are currently working to encourage the use of the MEMS section of CHIRP's website. Currently there are only five member organizations, and access to the site is restricted, but it is action in the right direction and would offer the right framework for such onward communication of risk factors and defenses (Rainbow, 2005).

### 3.6. Apportionment of appropriate defenses

After assigning the risk factor the ES should continue to assign a defense that is appropriate. In the case of standard risk factors, existing defense mechanisms will probably afford sufficient protection. In the more serious case of warning (and possibly moderate) risk factors, the expert system would decide the primary failure mode(s), either from investigation analysis or through reasoned consideration. In performing this analysis, it is important that the ES focus only on primary failure modes and apportion the analysis correctly. For example, if incorrect assembly is a result of poor maintenance manual instructions, the primary failure mode analysis must also include poor instructions, as it was the poor instructions that triggered the error.

Each of the primary failure modes is demonstrated in Figure

**WARNING:** Risk factors of this level indicate that flight safety is possibly endangered and additional safety nets would be highly recommended.

**MODERATE:** Risk factors of this level indicate that although flight safety is not specifically endangered, heavy financial penalties often exist for error, so organizations may opt for additional controls to reduce costs.

**STANDARD:** Risk factors of this level indicate that existing control measures are probably sufficient to recover the minor penalties incurred.

***Figure 3. Risk factor "thermometer" scale.***

6, page 100, and was derived from expanded criteria of MEDA/MEI. Technical report analysis further confirmed these failure modes to be the most likely causal factors. Developing this model further required evaluation of U.K. accident reports to discover the most likely antecedents of each of the classifications.

For example, with reference to Figure 6, consider the primary failure mode, incorrect, or incomplete assembly, which is the most likely failure mode. A functional check could guard against it, but is only valid if it suitably protects against task failure. Consideration has to be given not only to the functional check but also analysis of the maintenance manual reference to ensure any specified check is valid. Additionally the check needs to be linked to the appropriate task, in the manner appropriate to the organization. In a computer-driven maintenance environment, linked tasks are generated for the majority of maintenance tasks. Even with those considerations, an appropriate functional check is the most effective method of preventing incomplete/incorrect assembly.

If functional checks were not applicable, the next most suitable defense would be considered. Stage checks are a vital and valuable way of ensuring appropriate phase closure before proceeding to the next task (CAA, 2004). Omissions are the most common item that a stage check will detect, and omissions can be particularly problematic as they can have serious effects for other defenses "downstream" (Reason and Hobbs, 2003. p. 125). Stage checks are effective, but they can themselves become prone to omission either unintentionally or through a rule-based violation.

If the task breakdown schedule is incorrect, the maintenance task might be incorrectly sequenced, triggering an error. If the task is broken down correctly, it becomes in itself a checklist for completion. Although a checklist can be omitted or ignored, a certifiable task list requires the engineer to make conscious rule-based violation before omission. The limitation with task breakdown as a defense comes when ensuring the right level of breakdown is applied, and applied before an incident occurs. Reason (1990, p. 83) indicates that bad rules will be ignored through regular employment ("norms"). A task breakdown with too much detail will become clumsy. This will in time mean the mechanic may take an "illegal" approach to perform the task. Assuming no error occurs, this sort of "shortcut" will become accepted as suitable and so the task breakdown is negated. In establishing task breakdown, effective and workable stages are essential.

Final inspection pressures the ethos of instilling quality at every maintenance stage. Certainly it contradicts the TQM philosophy discussed earlier; however, a final inspection can provide a vital last chance at locating an error before flight. They are the very reason why predeparture checks are performed. A valid final inspection must capture the defect through the expected inspection method and be probable to apply. For example, if the proposed inspection requires the use of detailed equipment, it would be unrealistic to expect an engineer to perform this on a predeparture inspection. In reality the inspection would be bypassed and becomes an ineffective defense. The final inspection should be indicated as such and scheduled to fall at the latest practical time.

Equipment that is not designed for maintenance will drive access requirements to become a contributory factor. In the last 10 years, there has been a realization that "fit for purpose" is not sufficient design criteria, and more emphasis is being placed on continued airworthiness. If a task is simple to perform, it will usually be accomplished correctly. If a complex task is required to be performed, the very complexity can lead engineers to take shortcuts and commit rule-based violations (Reason and Hobbs, 2003. p. 122). The ES should review the access to determine if it is suitable.

Duplicate inspections have been the focus of a number of academic studies originated by the CAA. A duplicate inspection is a second independent inspection performed by a qualified engineer (EASA Part-145, 2005). The value of the inspection is established in its application; a correctly applied inspection will always be effective. That argument left unbalanced would imply the need to add such duplicate inspections to all tasks, but studies have revealed that too many inspections tend to lower their value (CAA CAP716, 2004. p. 3.5). In brief, confidential discussions, engineering staff believe three tiers of duplicate exist—flight control duplicates, which are treated very seriously; vital point duplicates, which receive a similar value, but not quite so much attention to detail; and the ETOPS or identicallity duplicate, which was in many cases not even performed. Adding additional inspections may lead the engineer, through "shared task responsibility," to subconsciously diminish responsibility for his part of the inspection. Hobbs and Williamson (1998, p. 17) demonstrated that more than 60% of professional engineers admitted to having not performed an inspection task, despite signing for it. In considering the duplicate as a valid defense, the ES must establish whether it would be performed, and at what level, before indicating its validity.

Environmental influences such as light, heat, and noise all add to the possibility of errors (Strauch, 2002. p. 83). Consideration should be given to the type of influence and the potential defense for it. This is complex as some tasks may have to be performed in poor environments, and this is a case where an additional defense might be required. For example, a task performed in a hangar might carry a standard risk factor, but the same task performed in an external environment may become a moderate risk factor.

The part the maintenance manual plays in accidents is often overlooked. Dury (1998), cited in Strauch (2002, p. 80) demonstrated that printed instructions often held mistakes or were poorly written. Chaparro and Groff (2001, p. 14) further demonstrated through research that 23% of engineering staff felt that poor instructions had resulted in unairworthy dispatch. More than 70%

felt that unclear instructions had at some stage contributed to incidents. This contrasts to the data indicating that only half of these errors are reported and corrected. This situation leads directly to other engineers being placed in the same compromising situation. In considering the impact the documentation plays, the ES should consider not only potentially misleading data, but also the accessibility and husbandry of such data.

The final step on each analysis is to consider what training program could be introduced to reduce, or remove, the risk. Care needs to be taken to understand that the program has to be effective as well as functional, otherwise the training will most probably not be carried out. Care also needs to be taken to ensure closure through training, perhaps by using post training analysis tools to evaluate program effectiveness. The analysis was continued for all the failure modes, and the results are summarized more effectively in the flowchart in Figure 6.

### 3.7. Triggers to action

The model has been proven to take roughly only 10 minutes to apply to each maintenance task. Accepting this fact, it is still unacceptable both from a commercial and flight safety perspective to undertake to evaluate every maintenance task. The cost would be prohibitive, and the overall effect might be to devalue the existing maintenance safety nets, which in most cases are effective. Three triggers to action were identified

- Retrospectively following incident or accident investigation, behaving similarly to other evaluation tools.
- Following engineer disclosure of potential errant task or "near miss."
- If MEDA evaluation highlights areas of concern, the model can be applied to all tasks in the sphere of concern to provide suitable predictive safety nets.

## 4. Implementation of the model

So far this study has evaluated the technical data and provided a solution that, through expert analysis, appears to work, in theory. The effectiveness of the model in reducing flight safety errors is only realized in the application.

### 4.1. Regulatory requirements

All maintenance organizations in Europe are required to work under the requirements laid out in EC regulation 2042/2003, Part-M, Subparts F and G, and also Part-145 (EASA Part-145, 2005). Although the requirements are complex, few specific requirements exist regarding error reporting. 145.A.45 requires that publication errors be submitted to the author as soon as possible, and 145.A.60 requires mandatory reporting of events that "seriously effect flight safety." No legal precedent for a predictive model is available; however, it is worth noting that Part-M, Subpart-G M.A.712, does indicate the safety management system requirements; and although these won't reduce maintenance error directly, appropriate application would control the overall level.

The reporting of incidents is only mandatory for particularly serious events and currently not extended to all occurrences. This was discussed in Chapter 2, together with the introduction of MEMS to overcome this problem. The acceptance of MEMS and its limitations were also discussed. Additionally it is noted that MEMS is only a U.K. initiative not pan-European, or even worldwide. With no legal precedent established for all errors to be reported, the correct culture is vital for the model to be successfully implemented.

### 4.2. A "just culture"

"Building a safety culture has been the objective of enlightened aviation organizations over the last two decades," (Learmont, 2005). In the past 20 years several texts have focused on the increased complexity of maintenance and the benefits and problems this brings. Additionally, several papers and conference documents have covered the subject and coupled with the EASA regulations adds weight to the breeding of a safety culture. Previous studies of just cultures have been summarized by Reason and Hobbs (2002).

Chaparro and Groff (2001, p. 2) wrote, "A human factors approach to maintenance error requires that causal attribution be extended beyond just the offending mechanic." They continue to discuss how error sources extend to management policy, organizational factors, communication, and corporate culture. Reason (1990, p. 188) develops Rasmussen's framework and discusses the stages of active and latent failures, often termed the "Swiss cheese" model. All of these studies highlight that the active failure by the tradesman is usually only the final act of several latent failures induced in the organization.

A "blame culture" is one where the investigation team or management absolve themselves of any latent failure blame by insisting the engineer is the error source. This quite understandably leads to a poor reporting atmosphere and one that positively discourages active self-disclosure of error. Fortunately, several key industry leaders have managed to reduce "blame culture" to a minimum (Newton, 2001).

Although in most cases the aviation industry has moved from a "blame culture," Reason and Hobbs (2002, pp. 148-155) state that a "just culture" is the next stage further removed. A "just culture" is one where all members of the organization feel trusted and valued, a corporate organizational culture that is inclusive and views errors as opportunities for development. It is a culture where action is taken when it is required and feedback of all information allows the workforce to feel they are working in a "just" environment. Clearly such a step is a difficult one for management to take in terms of allowing corporate nature to be determined by all employees, and if not carefully managed can interfere with corporate strategy.

A cultural survey of an organization demonstrated that the engineering staff is motivated to reduce error but feel reluctance to involve themselves more fully in a reporting process. A "just culture" may in fact be an elusive goal; however as open reporting is essential to the success of the predictive error model, leadership effort should aim towards creating a "just culture."

### 4.3. Motivational requirements

Several theories of motivation link high motivation with high output. A fairly well-publicized and applicable motivational model is Maslow's Theory of Hierarchal Needs. The impact of this in terms of implementation of the model is that employees would need to be above the social needs level to be able to successfully contribute to any improvement program. This level also aligns with Herzberg's growth factors in his Hygiene Model (Lawson, 2004). The more an employee will contribute depends on how high up the needs factors they are. A company cannot ensure its employees' self-esteem level; however, safety and social needs are the company's responsibility.

For the predictive model to be most effective, the management would have to ensure that basic safety criteria are met. Included within basic safety would be job security, so inclusion of workers in company matters would be encouraged, together with the additional assurances of no punitive action for non-criminal actions through self-disclosure. One method is to ensure workers of immunity, through an interface document laying down the company's intent not to take any punitive action, unless of course the error was through a criminal act. Norbjerg (2002, p. 153) describes a legally supported confidential reporting scheme introduced in Denmark. He continues to demonstrate that confidential reporting is better than anonymous reporting as it allows the investigation team to retrace steps and find out more information. The aim, therefore, is to increase the reporter's trust in the organization's objectives, rather than merely offering anonymous reporting systems.

Many companies are making use of "workers council" arrangements and including employees in the business future and this is precisely the right approach. Such works councils, although helpful in creating and fostering the right framework for the error model, are not the appropriate forum for investigations. If an organization has good intentions and supports this with demonstrable evidence, the motivation requirements for effective model implementation would be met.

### 4.4. Engineer involvement

One method of promoting trust and openness is to include engineering staff in investigations and error solution programs. Several have been pioneered in the U.S.A. Maintenance Safety Action Program (MSAP) is an adaptation of a program that was originally designed for flight deck crew, providing guarantees of immunity of self-disclosed errors. The scheme includes all parties and involves them in the investigation and application of defense discussions. Frontier Airlines has implemented the scheme and class the interested parties as the company, the FAA, and a union representative (Finnegan, *Aviation Today*, 2004).

The FAA issued Advisory Circular AC120-66B (FAA, 2002) to establish guidelines of safety action programs, with the main aim of encouraging the voluntary reporting and investigation of all errors. It provides legal immunity from punitive action for non-criminal disclosures, in much the same manner as the U.K.-led MEMS scheme does.

With engineering staff involved at all stages the scheme ensures openness, which in turn fosters active voluntary disclosure of information. Confidence in both the scheme and the organization's intentions is strengthened with each incident reported and appropriately dealt with. No evidence exists to suggest success, although the chief executive of Frontier is very encouraged by the results (Finnegan, 2004).

Taylor and Christensen (1998) cited by Patankar and Taylor (2004b, p. 137) first described round table discussions. They are in essence similar to the MSAP just discussed in that they include the FAA, union official, the reporter, and the maintenance manager.

As a roundtable discussion encompasses a more inclusive investigation and review board, it can achieve some advantage, although it would come with some financial burden, with the additional support staff required to operate the scheme. The U.K. industry is less unionized than the U.S.A. and the culture review suggests that U.K. engineering staff would prefer no union official present, but would feel encouraged by other qualified engineering staff present.

It is hypothesized that a team of perhaps a quality engineer, together with a maintenance manager and a licensed and practicing engineer, would provide a very competent investigation and review team. The team should also have the flexibility to co-opt additional experts such as technical or human factors, to help with specific problems or errors. The team basis should remain the same for each error, but varying the personnel from incident to incident would ensure a fresh and enthusiastic approach to each case, while further promoting confidence. The quality engineering staff would provide the consistency required. Application of the model is principally at the engineer and junior management level, so senior management support, although encouraged and welcomed, is not essential. The regulatory authority, instead of having direct involvement, could maintain an oversight through the normal approval mechanism, retaining the option to be more directly involved in significant events.

### 4..5. Leadership vs. consultation clashes

No matter how well intentioned the scheme and the people involved are, there will come a time when direction is required. A situation will arise where punitive action is required, but reluctance might be apparent from the review board. Confident leadership would be required in such situations to take the organization through to the next stage.

Vroom and Yettins (1973) established a normative model for leadership, looking at autocratic, consultative, and group leadership. Different styles are applicable at different times. Most of the time their model suggests consultation and group leadership are the best methods. The predictive model under discussion in this study suits consultative and group leadership. The problem of leadership arises when the company views decision quality as important, whereas the review team does not.

Regulatory authority involvement at this stage would not be helpful as it is unlikely to be heeded unless supported through mandate. Additionally, the company director, or senior manager, may have to perform an independent review of any punitive action and cannot be involved. It would seem sensible to remove an independent manager from the scheme, to allow him or her to take such leadership resolution decisions. In most companies, the quality manager reports directly to the managing director and is best placed to perform this role of scheme oversight

## 5. Extending and evaluating the predictive model

Fifty engineers were asked at random to complete anonymous reporting questionnaires. In keeping with the poor reporting culture highlighted earlier, only seven completed reports were returned, but each held significant information. All reports provided details of incidents that had actually happened but not reported, or incidents that the engineers felt could easily happen. The principal aim of the research was to gain information regarding live events to allow analysis of the model to be undertaken, no corrective action was to be applied, and the contents of the reports were withheld from the company. This was a complex choice and one that was required to allow the engineering staff

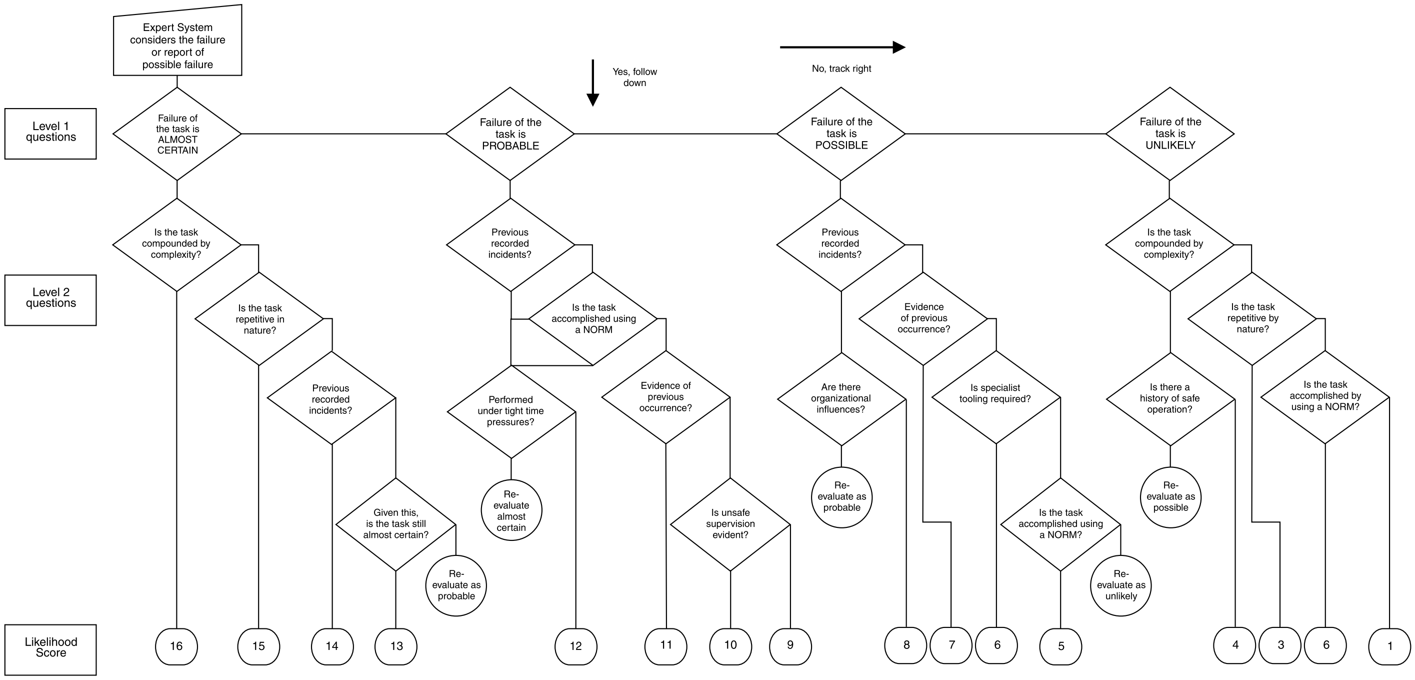


*Figure 4. Likelihood evaluation flowchart.*

the confidence to provide any information at all.

Other than printing, the data were handed to the ES for analysis without any classification. The ES had several directives in the analysis; initially they were asked to evaluate the validity of the data. Then they considered the primary failure mode(s) and applied the collected data to the model establishing a risk factor, and determining safety defenses to prevent recurrence. Finally they were asked to prove the validity of the model and indicate any improvements that could be applied, or even triggers for further research.

## 5.1. Model evaluation through submitted reports

The ES reviewed all the reports and, with the exception of one report, found all to be common and applicable reports. The errant report was deemed to be outside of the remit of the model as technically it wasn't a maintenance error, more a technical difference of opinion. All the remaining reports were evaluated independently by the ES and then discussed collectively. The ES discovered that they were adding significant value to the findings. Additionally discussions regarding the safety measures provoked debate, and, from this, more valuable solutions were found. This confirms the earlier theory that MSAP in the U.K. is achievable and an appropriate way of dealing with investigations.

The ES considered the numbers the model returned were in line with their "feel" for the risk. Disagreements were never considered at the outset, but they occurred and were handled by having an odd number of ES to allow a vote. Equally though, where a view was strongly held by only one member ,the model proved flexible enough to allow both failure modes to be traced and the same result was found. One of the reports provoked such a disagreement, with one member viewing the primary failure mode as inspection error and another viewing it as a ground incident. Both streams were followed and the final safety net assumed most applicable was communication increase, on which all agreed.

All the reports considered the onward communication to be applicable and valid. Several key failures of the Approved Maintenance Manual (AMM) were discovered during the evaluation, further confirming the need to be encouraging engineer involvement to allow active reporting and subsequent evaluation. One of the reports indicated a particularly serious situation, which was appropriately investigated and rectified.

## 5.2. Model validity discussion

The final section of the work with the ES was to determine if the model was valid and was, therefore, likely to be applied. Of the six reports that were evaluated, the ES returned a valid indication for all. Some weaknesses in the model were exposed during the evaluation. Industrywide communication is a good theory, but in reality would probably be prevented through inertia. This indicated the need to promote the model further and try to get broader industry understanding of the possibilities it holds. Also the ES were unsure of the figures provided for severity, although they commented that the color-coding and sliding-scale approach is logical. Mathematical analysis is beyond the deliverables of this project and so consideration of reevaluation at this stage was not given; however further research could be provoked. Finally the ES considered the model instructions were weak and these have subsequently been made more robust. Overall, the ES held a very complimentary view, and they urged that the model be presented to other industry stakeholders to allow increased interest and, ultimately, acceptance.

## 5.3. Summary of the predictive model

- Anonymous reporting schemes are discouraged—instead organizations foster trust in confidential reporting schemes, encouraging engineers to self-disclose errors or potential errors.
- Expert system established of a maintenance manager, an independent engineer, and a quality engineer. Discussions based on MSAP principles.
- Expert system defines likelihood, severity, and detection of error or prediction (disclosure) and calculates risk factor.

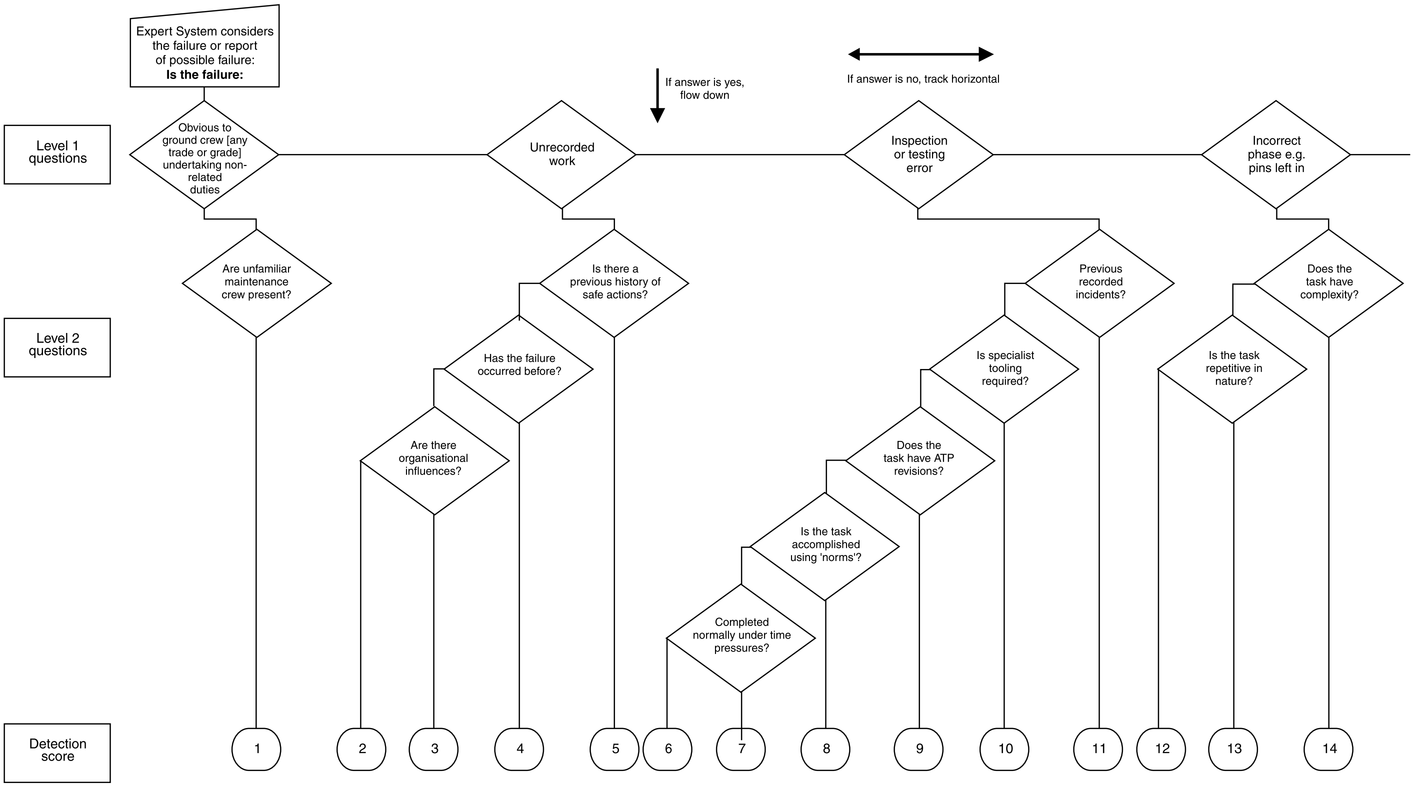


***Figure 5. Possibility of error detection before flight.***

- Risk factor evaluated as warning, moderate, or standard.
- Most probable failure mode(s) are defined by the expert system and the appropriate defenses applied when necessary, i.e., for warning and possibly moderate risk factors.
- Model reevaluated with appropriate safety mechanisms active, ensuring reduction of risk is satisfactory.
- Risk factor and defense communicated to manufacturer for inclusion at the AMM reference identified.

## 5.4. Further research

This study has reached its primary objective of establishing the validity of a predictive maintenance error model. Additional research is indicated and would be advisable before full implementation is considered, as follows:

- Increased mathematical analysis of the severity scores.
- Extended evaluation of the model to cover light aircraft, helicopters, and differing environments.
- Implementation and culture studies of detail at a number of differing companies to establish applicability.
- Finally, industrywide implementation evaluation is recommended and this document shall be shared with industry action groups through the Royal Aeronautical Society, the CAA, the AAIB, and others as seen fit.

## 6. Conclusions

This research was tasked to discover if a predictive model for reducing specific cases of maintenance error is possible. Primarily it was provoked in response to a serious, but very repeatable, lapse that almost cost the lives of a full commercial transport aircraft, although at the outset it was understood the overall aim was to provide a more wide-reaching defense mechanism.

Initially previous work in the manner of established systems was considered, evaluating the ability at reducing cases of maintenance-induced error. Three key quality standards were evaluated—ISO 9001:2000, TQM, and six-sigma, all of which were unable to reduce specific cases of error. It was noted that each could improve culture to enable other more specific tools to be used effectively, and, consequently, all of the three systems had value, albeit limited.

The industry's primary tool, critical event analysis, was then discussed. The discussion expanded into classification systems such as MEDA and SHEL, examining their effectiveness. All these tools were considered very valuable, although all were applied retrospectively, i.e., waited for the incident or accident to occur then reacted.

The study then continued to develop the predictive model, based on FMEA techniques but utilizing the common framework of MSG-3. These tools were chosen deliberately as they are simple-to-apply tools, and both have been in use in the industry for several years, making acceptance of the scheme that much easier. The model considered likelihood and severity of failure and assigned scores to these using an expert system guided through a table (Figure 4) developed from previous work of Reason et al. The expert system comprising a serving line engineer, a manager, and a quality representative allowed a balanced view to be achieved. A risk factor was established and methods of communication discussed. The model considered the primary failure mode(s) and applied logical solutions to apportion the appropriate defense mechanism (Figure 6). Finally, the three trigger levels for action were discussed.

Successful application of the model was considered vital to useful implementation, and although worldwide safety culture is on the increase, the study discussed the culture necessary for the model to be successfully implemented. Regulatory requirements were examined, where it was discovered that no legal precedent

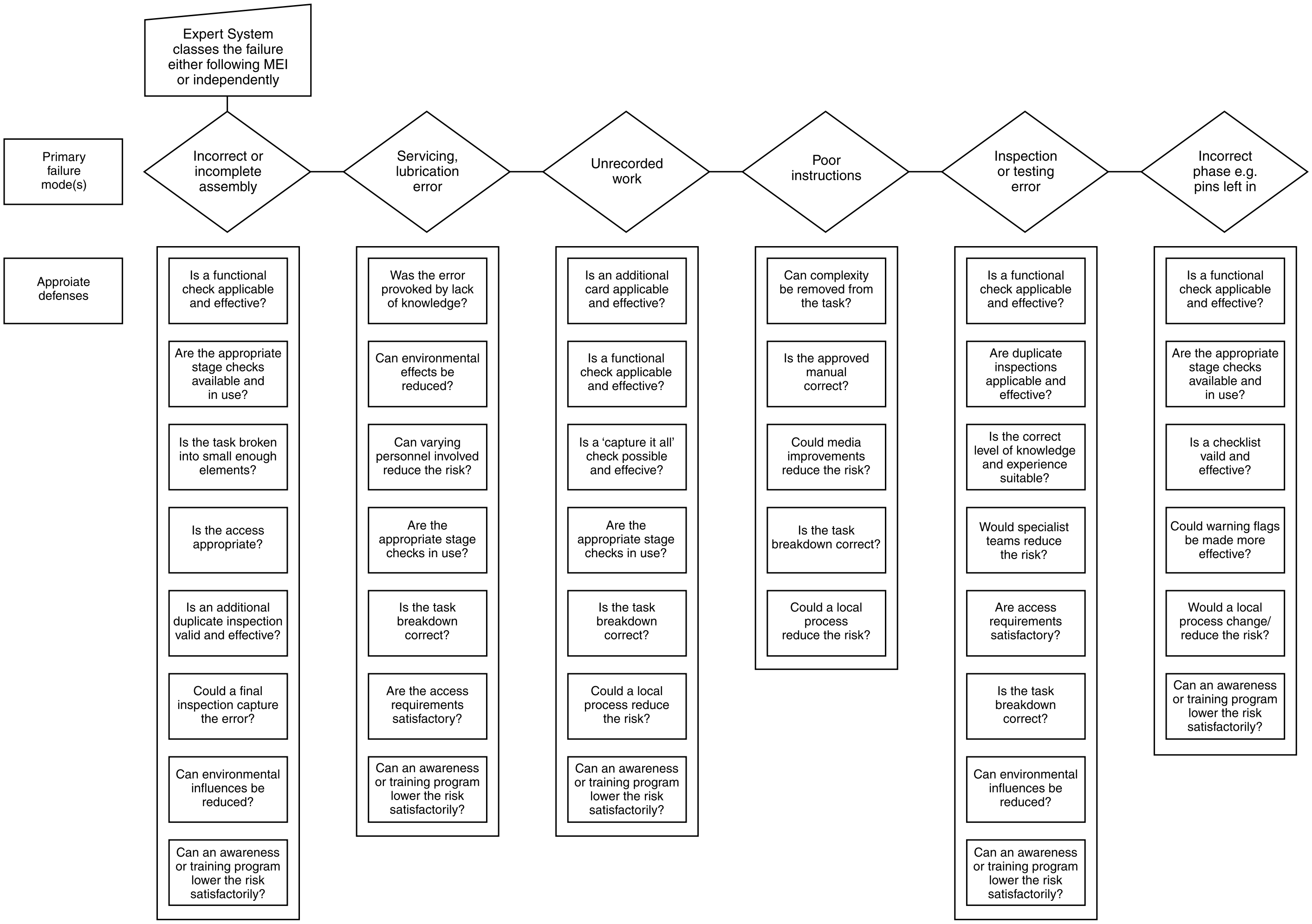


***Figure 6. Apportionment of appropriate defenses.***

is available for such a model, although schemes such as CHIRP and MEMS distinctly guide the way. A "just culture" and the inclusion of engineers through roundtable discussions or MSAP was considered of great importance and is most definitely recommended for any organization.

Following successful discussion of the model and the application of it, the study continued to highlight its application ability and equally important the weaknesses of it. The model was proven through the use of several experts performing analysis on events that had never been reported to the organization's quality department. In each case, the model proved effective at accurately identifying and reducing the risk factor. This coupled with the onward communication of defense mechanisms would play a significant role in improving flight safety through reduction of maintenance error. The weaknesses of the model were established to allow interested parties to further the work.

The primary deliverable of this study was to discover and develop a predictive model aimed at reducing maintenance error. Although some further work has been indicated, the primary objective has been met. Throughout the project, no rise in error rate has been detected, and the engineering staff directly involved are showing great enthusiasm for it. ◆

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# System Identification Techniques Applied to Aircraft Accident Investigation

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**Abstract**

This paper deals with aerodynamic parameters identification techniques applied to aircraft accident or incident investigations. The objective of the technique is to identify degradation on aerodynamic characteristics of a possible aircraft inflight loss of control. This characteristics impairment arises mostly from wing and tail surface contamination. However, the proposed aerodynamic parameters identification technique may also estimate control surfaces power deterioration and inversions. In this approach, the FDR data are analyzed through a system identification algorithm that provides the aerodynamic parameter estimates, enabling comparison with aircraft project characteristics. The research resources for this work are provided by both ITA and EMBRAER, which developed the system identification tools and stand on air safety improvement and accident investigation application of this technology. This paper presents some features of aerodynamic parameter estimation techniques and their relationship with aircraft accident analysis. The efficiency of this approach is shown and the main advantages become clear through analysis of a simulated inflight icing event.

**Keywords:** accident investigation, aerodynamic parameter estimation, system identification, output-error

## 1. Introduction

Aeronautical accidents and incidents happen and the safety indices are different from country to country, mainly due to the flight safety culture, which governs the aeronautical activities. These events are the results of a sequence of operational, human, material, and organizational contribution factors. In order to satisfy the objectives of an aeronautical accident or incident investigation, the contribution factors, after identification, must be neutralized and then new occurrences should be prevented.

Nowadays, in order to provide conditions to establish investigation processes, continuous investigation techniques advances are required. This way, the same technology advances that have been introduced to the aeronautical industry providing conditions to development and manufacturing new aircraft families can be applied and facilitate the aeronautical investigation activities.

In this work, the application of system identification techniques to the resolution of aircraft flight mechanics problems during aeronautical investigation is proposed. The main idea is to apply an aerodynamic parametric estimation algorithm to identify aircraft aerodynamic characteristics degradation experienced in flight. The necessary conditions are the knowledge of the aircraft project characteristics, i.e., aerodynamic, geometry, mass, and inertia, and the existence of the FDR data, containing the aircraft flight response and the flight control inputs.

The aerodynamic parametric estimation from flight data has been mainly used as an aircraft development and certification tool. Several works have been dealing with flight test data collected during specific flight test maneuvers performed in order to estimate aircraft aerodynamic parameters for data banks, flight simulation, product development, envelope expansion, flight data acquisition system calibration, and other applications (1-7). This work, however, concerns the application of system identification techniques, in particular the aerodynamic parametric estimation, for estimation of aircraft aerodynamic characteristics degradation during aeronautical accidents or incidents.

The approach used is the output-error (8), combined with the maximum likelihood criteria (9) and the Gauss-Newton optimization algorithm. This approach accounts for measurements noise only, which can be a strong disadvantage when dealing with FDR data submitted to atmospheric turbulence. It is important to point out, however, that the main objective of this work is to introduce the advantages of the system identification techniques applied during aeronautical accidents or incidents investigations, taking into account that other more sophisticated system identification techniques, such as filter-error methods or filtering approaches, could be applied as well.

In the following sections, the parametric estimation method is described with special attention to the output-error approach and to the Gauss-Newton algorithm. In addition, in Section 2, the six-degree-of-freedom aircraft dynamic model and the aerodynamic model are presented. A flight simulation considering aircraft aerodynamic characteristics degradation due to ice accumulation is presented in Section 3, providing data to aerodynamic parametric estimation analysis followed by a results discussion and some concluding remarks. Some advantages of the application of these techniques will become clear compared to previous investigation efforts in analysis of flight mechanics through FDR data.

## 2. Aerodynamic parametric estimation

2.1. The output-error approach. (See Figure 1.)

The output-error is one of the most used estimation methods in aircraft identification and aerodynamic parameter estimation. The basic concept of the output-error approach is to compare the aircraft flight response with the mathematical model response submitted to the same control input and then compose a cost function to be minimized as a function of the aerodynamic parameters of interest. The structure of the model is considered to be known, and the identification procedure consists just in determining the parameter vector . Therefore, the cost function to be minimized involves the so-called prediction error:

$$e(i,\hat{\Theta}) = y_m(i) - \hat{y}(i,\hat{\Theta}) \tag{1}$$

where $e(i,\hat{\Theta})$ is the prediction error based on the actual estimate of $\Theta$, which is $\hat{\Theta}$.

This work proposes the output-error approach for the estimation of aerodynamic characteristics degradation during aeronautical accidents or incidents, as shown in Equation 1. This problem can be formulated as a time varying one, in which some aerodynamic coefficients become a function of time. To estimate the time variation of the parameters of interest, the output-error can be applied for discrete time segments of the flight data under investigation.

Concerning the necessity of aircraft aerodynamic characteristics degradation analysis during aeronautical accident or incident investigation, the output-error can be performed through the data recorded on the FDR. The data contain the control inputs and the aircraft flight response variables considered on the six-degree-of-freedom aircraft dynamic model. In addition, it is necessary that the aircraft project information about the aerodynamic data bank and about the dynamic model structure be known and sufficient to compare the FDR data with simulated data over all flight envelope of interest.

2.2. Maximum likelihood criteria

The maximum likelihood (ML) criteria are used to compose the output-error cost function. The basic idea is to provide a weighted cost function concerning the measurement noise level of each measurement variable. Consider a dynamic model identifiable with output response denoted by , which is a function of the model parameters vector $\Theta$. Suppose that $p(y_m \mid \Theta)$ is the Gaussian probability density function of the random variable . $p(y_m \mid \Theta)$ is known as the likelihood functional (10), that is a measure of the probability of the observation $y_m$ for a given parameter vector $\Theta$. The maximum likelihood estimation (MLE), therefore, is the estimation of that maximizes this functional. The ML functional can be defined as:

$$p\left(y_m \mid \hat{\Theta}\right) = \left[(2\pi)^{-\frac{q}{2}}|R|^{-\frac{1}{2}}\right]^N \exp\left\{\sum_{i=1}^{N} -\frac{1}{2}\left[e(i,\hat{\Theta})\right]^T R^{-1}\left[e(i,\hat{\Theta})\right]\right\} \tag{2}$$

whose maximization, under some assumptions, is equivalent to the minimization of

$$J\left(\hat{\Theta}\right) = \frac{1}{2}\sum_{i=1}^{N}\left[e(i,\hat{\Theta})\right]^T R^{-1}\left[e(i,\hat{\Theta})\right] \tag{3}$$

Equation (3) represents the output-error approach under the MLE criteria cost function. For aerodynamic parameter estimation, the objective is to minimize (3) as a function of the parameters of interest. Concerning the aerodynamic degradation analysis for aeronautical accident or incident investigation, the objective is to minimize Equation (3), adjusting the aerodynamic parameters of interest from the aerodynamic data bank values to the values that provide the best fit of the aircraft response data recorded on FDR. This approach provides information to identify aerodynamic degradation during flight incidents or accidents.

2.3. Gauss-Newton optimization

The Gauss-Newton optimization assumes that there are suitable a priori values for the parameter vector $\Theta$ (11). For the aerodynamic degradation analysis during aeronautical investigation, these values must be provided by the aircraft aerodynamic data bank and, in general, should be close to the parameter values estimated after the aircraft aerodynamic characteristics changes. In this algorithm, the new updated estimates are obtained by applying

$$\hat{\Theta}_{k+1} = \hat{\Theta}_k + \Delta\hat{\Theta} \tag{4}$$

where the subscript denotes the algorithm $k^{th}$ iteration and

$$\Delta\hat{\Theta} = -M^{-1}G \tag{5}$$

In Equation (5), $M$ denotes the Fisher's Information Matrix, which can be approximated by

$$M = \frac{\partial^2 J}{\partial\hat{\Theta}^2} \approx \sum_{i=1}^{N}\left(\frac{\partial\hat{y}(i,\hat{\Theta})}{\partial\hat{\Theta}}\right)^T R^{-1}\left(\frac{\partial\hat{y}(i,\hat{\Theta})}{\partial\hat{\Theta}}\right) \tag{6}$$

and $G$ denotes the gradient vector, that is given by

$$G = \frac{\partial J}{\partial\hat{\Theta}} = \sum_{i=1}^{N}\left(\frac{\partial\hat{y}(i,\hat{\Theta})}{\partial\hat{\Theta}}\right)^T R^{-1}\left[e(i,\hat{\Theta})\right] \tag{7}$$

It is important to point out that the ML estimation is asymptotically bias free and efficient (10-13). The Fisher's Information Matrix provides good approximation of the parameter estimation error covariance. In other words, applying the ML estimator and computing the information matrix, a statistical assessment of the parameter estimation reliability can be done.

In (5), (6), (14), the authors, proposed, in general, that the dynamic aircraft flight response must be as much as possible excited in order to provide good parametric estimation. Concerning the dynamic flight environment normally preceding aeronautical accidents and incidents, it is supposed that the FDR data provide sufficient information content for reliable parametric estimations.

2.4. Aircraft dynamic and aerodynamic models

The state-space six-degree-of-freedom dynamic model that describes the aircraft motion, and which is proposed to be used in the output-error algorithm, can be given by (19-21)

$$\dot{p} = \frac{-(-I_y I_z + I_z^2 + I_{xz}^2)qr + I_z(I_{xz}pq + \bar{q}SbC_l) + I_{xz}((I_x - I_y)pq + \bar{q}SbC_n}{I_x I_z - I_{xz}^2} \tag{8}$$

$$\dot{q} = \frac{\left(-I_x + I_z\right)pr + I_{xz}(-p^2 + r^2) + \bar{q}Sl_sC_m}{I_y} \tag{9}$$

$$\dot{r} = \frac{I_{xz}(I_{xz}pq - (I_x - I_y + I_z)qr + \bar{q}SbC_l) + I_x((I_x - I_y)pq + \bar{q}SbC_n)}{I_x I_z - I_{xz}^2} \tag{10}$$

$$\dot{\phi} = p + \tan\theta\left(q\sin\phi + r\cos\phi\right) \tag{11}$$

$$\dot{\theta} = q\cos\phi - r\sin\phi \tag{12}$$

$$\dot{\psi} = \frac{q\sin\phi + r\cos\phi}{\cos\theta} \tag{13}$$

$$\begin{aligned}\dot{\alpha} &= -\frac{\bar{q}S}{mV_{tas}\cos\beta}C_L + q - \tan\beta\left(p\cos\alpha + r\sin\alpha\right) \\ &+ \frac{g}{V_{tas}\cos\beta}\left(\cos\phi\cos\theta\cos\alpha + \sin\theta\sin\alpha\right) - \frac{T\sin\alpha}{mV_{tas}\cos\beta}\end{aligned} \tag{14}$$

$$\begin{aligned}\dot{\beta} &= \frac{\bar{q}S}{mV_{tas}}C_{Y_{WIND}} + p\sin\alpha - r\cos\alpha + \frac{g}{V_{tas}}\cos\beta\sin\phi\cos\theta \\ &+ \frac{\sin\beta}{V_{tas}}\left(g\cos\alpha\sin\theta - g\sin\alpha\cos\phi\cos\theta + \frac{T}{m}\cos\alpha\right)\end{aligned} \tag{15}$$

$$\begin{aligned}\dot{V}_{tas} &= g\left(\cos\phi\cos\theta\sin\alpha\cos\beta + \sin\phi\cos\theta\sin\beta - \sin\theta\cos\alpha\cos\beta\right) \\ &+ \frac{T}{m}\cos\alpha\cos\beta - \frac{\bar{q}S}{m}C_{D_{WIND}}\end{aligned} \tag{16}$$

$$\dot{h} = u\sin\theta - v\cos\theta\sin\phi - w\cos\theta\cos\phi \tag{17}$$

where

$$C_{D_{WIND}} = C_D\cos\beta - C_Y\sin\beta \tag{18}$$

$$\tag{19}$$

In addition to the state variables, the linear accelerations , $A_y$, and $A_z$ are used as observations variables.

The aerodynamic stability and control derivatives, which establishes the aerodynamic characteristics of the aircraft, are linked to the dynamic model, Equations (8) to (17), through the following aerodynamic model:

$$\tag{20}$$

$$C_L = C_{L_0} + C_{L_\alpha}\alpha + C_{L_q}\frac{ql_\mu}{V_0} + C_{L_{\dot{\alpha}}}\frac{\dot{\alpha}l_\mu}{V_0} + C_{L_{\delta e}}\delta_e + C_{L_{\delta ih}}\delta_{ih} + C_{L_{\delta F}}\delta_F \tag{21}$$

$$C_m = C_{m_0} + C_{m_\alpha}\alpha + C_{m_q}\frac{ql_\mu}{V_0} + C_{m_{\dot{\alpha}}}\frac{\dot{\alpha}l_\mu}{V_0} + C_{m_{\delta e}}\delta_e + C_{m_{\delta ih}}\delta_{ih} + C_{m_{\delta F}}\delta_F \tag{22}$$

$$C_Y = C_{Y_0} + C_{Y_\beta}\beta + C_{Y_p}\frac{pl_S}{V_0} + C_{Y_r}\frac{rl_S}{V_0} + C_{Y_{\delta a}}\delta_a + C_{Y_{\delta r}}\delta_r \tag{23}$$

$$C_l = C_{l_0} + C_{l_\beta}\beta + C_{l_p}\frac{pl_S}{V_0} + C_{l_r}\frac{rl_S}{V_0} + C_{l_{\delta a}}\delta_a + C_{l_{\delta r}}\delta_r \tag{24}$$

$$C_n = C_{n_0} + C_{n_\beta}\beta + C_{n_p}\frac{pl_S}{V_0} + C_{n_r}\frac{rl_S}{V_0} + C_{n_{\delta a}}\delta_a + C_{n_{\delta r}}\delta_r \tag{25}$$

Any of the aerodynamic parameters appearing in Equations (20) to (25) can be analyzed and degradation estimated during FDR data analysis for aeronautical accident or incident investigations. In addition, other control aerodynamic derivatives could be included in order to account for different flight control surfaces.

### 3. Flight simulation and parametric estimation results

In order to introduce some results and some practical features of the system identification techniques proposed for aircraft aerodynamic degradation analysis during aeronautical accidents or incidents investigation, a simulated flight was performed. In this flight, some of the main aspects of previous experienced accidents caused by icing contamination regarding aircraft aerodynamic degradation were considered (15)(16).

The aircraft geometry, mass, inertia characteristics, and the aerodynamic data bank used for simulation are from a medium-sized turboprop airplane. The simulation started at 7,000 ft (pressure altitude) maintaining 250 KIAS and heading of 070 degrees with autopilot engaged (Figure 2). Just prior to start descent to 5,000 ft at 00:00:50, the ice accumulation was introduced to the aircraft aerodynamic characteristics. Then, as the airplane descended through 6,400 ft maintaining a heading of 135 degrees, the airspeed was reduced to 200 KIAS. After 40 seconds, at 00:02:20, passing through 5,600 ft, the airspeed was reduced to 150 KIAS. At 00:02:45, a turn right was done to 190 degrees. Some seconds after, the pressure altitude of 5,000 ft was reached and maintained. At 00:03:34, a left turn to 090 degrees was commanded. Finally, at 00:03:40, the aircraft gradually lost the capability to maintain 5,000 ft and 150 KIAS due to the aerodynamic modification introduced in order to represent ice accumulation.

According to the literature about aircraft icing contamination effects on aerodynamic characteristics and some aircraft accident investigation reports (15-18), the icing contamination was intro-

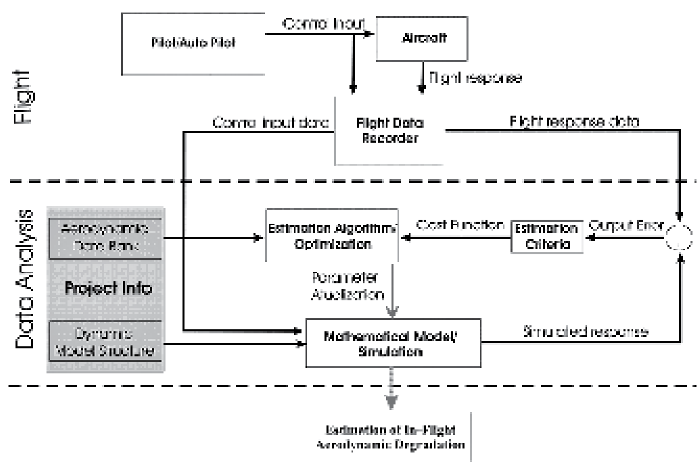


***Figure 1. The output-error approach for flight data recorder data analysis.***

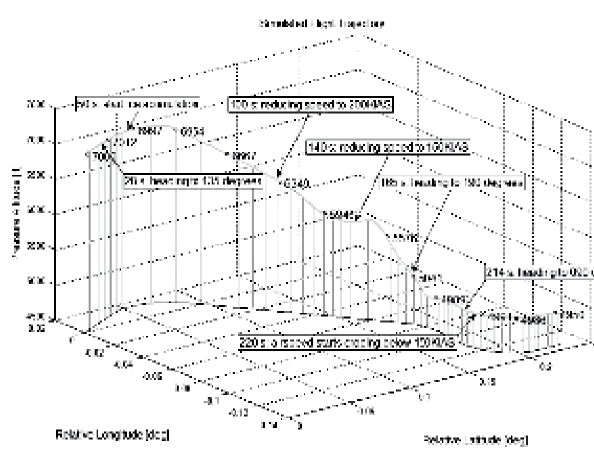


***Figure 2. Flight trajectory.***

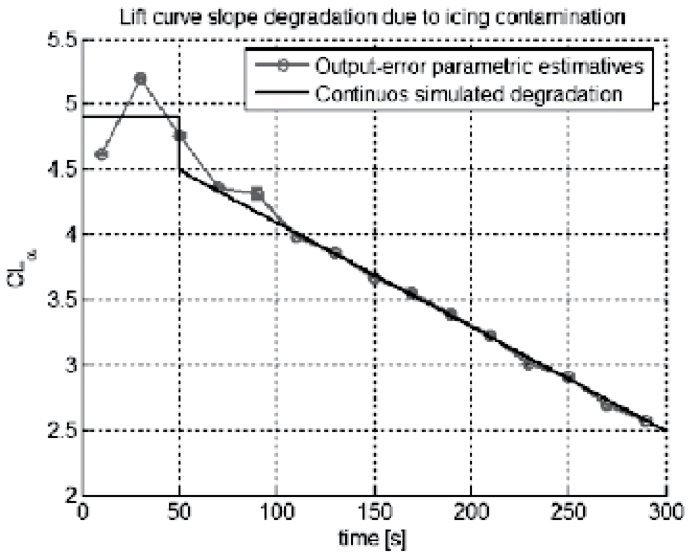


*Figure 3. Applied and estimated degradation on lift curve slope due to ice accumulation.*

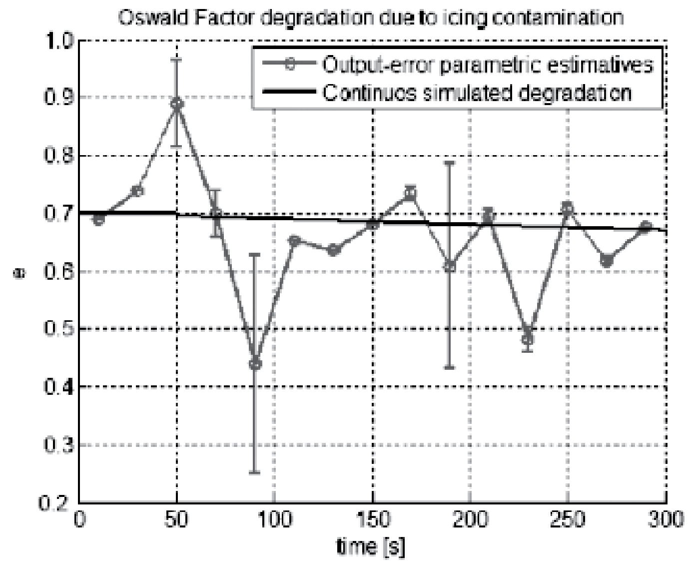


*Figure 5. Applied and estimated degradation on Oswald Factor due to ice accumulation.*

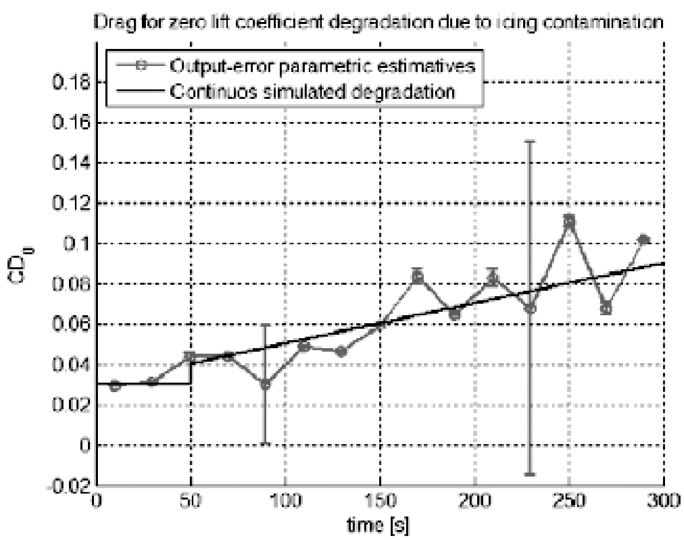


*Figure 4. Applied and estimated degradation on drag for zero-lift coefficient due to ice accumulation.*

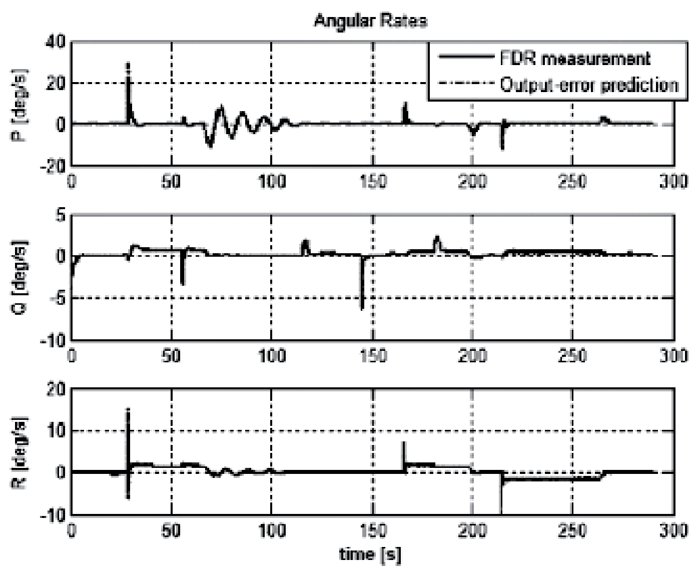


*Figure 6. Simulated FDR data and output-error prediction of angular rates.*

duced, cumulatively, as a function of time. The main aerodynamic coefficients affected were the lift curve slope, the drag for zero lift coefficient, and the Oswald Factor.

The flight data were recorded and introduced to the output-error aerodynamic parametric estimation approach in order to obtain the estimation of the lift curve slope, the drag for zero-lift coefficient, and the Oswald Factor for the different instants of the flight.

According to Figures 3, 4, and 5, the estimation algorithm provided good assessment of the aerodynamic changes introduced on simulation to represent the aircraft icing accumulation. For the drag for zero-lift coefficient and Oswald Factor estimation, the error bounds are significantly large in some instants. This can happen if the dynamic response of the aircraft during the flight segments is poor and provides low information content to estimation.

As can be seen, the variation of the aerodynamic coefficients was linearly time dependent. The values for lift curve slope and the Oswald Factor decrease, while the value for the drag for zero-lift coefficient increases due to surface icing accumulation. The estimation time history for these parameters confirms the tendency on aerodynamics changes introduced in simulation to represent inflight icing encounter.

In Figures 6, 7, 8, and 9, the output-error prediction curves for the angular rates, flow variables, attitude variables, and linear accelerations are compared to the FDR-simulated data. It is important to point out that these results show that the aerodynamic changes estimated through the output-error approach can provide good approximation of the icing contaminated aircraft dynamics.

## 4. Concluding remarks

Some system identification concepts are presented, with special attention to the output-error approach, the maximum likelihood estimation criteria, and the Gauss-Newton optimization algorithm. These concepts represent an aerodynamic parametric estimation approach, which provides conditions to identify inflight

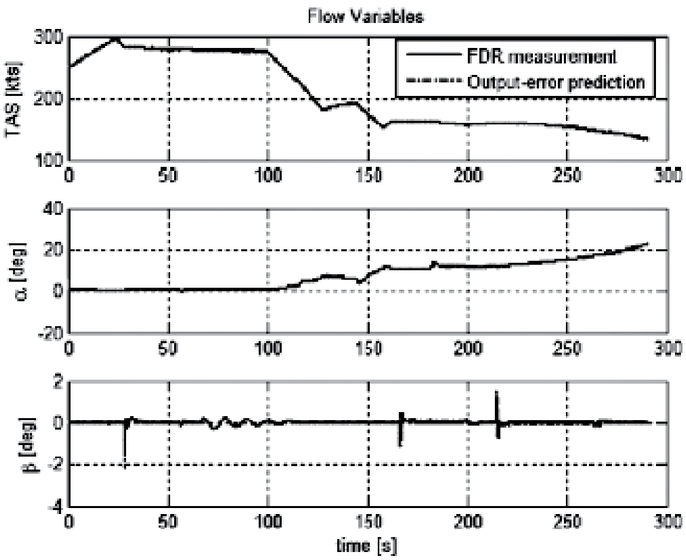


*Figure 7. Simulated FDR data and output-error prediction of flow variables.*

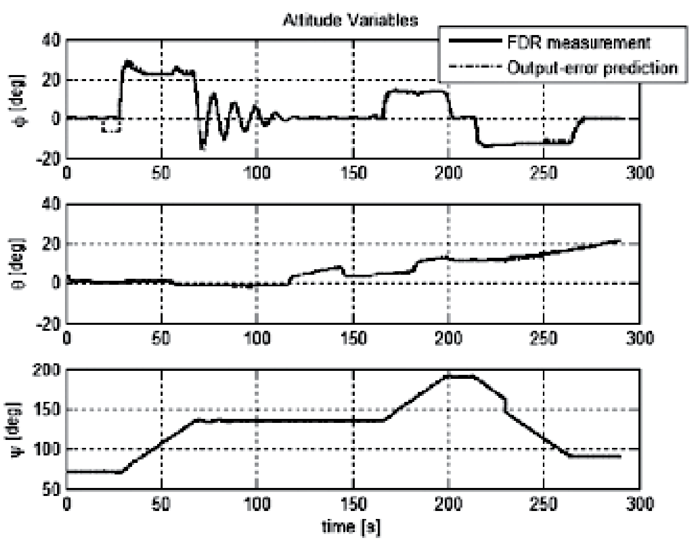


*Figure 8. Simulated FDR data and output-error prediction of attitude variables.*

aerodynamic changes encounter from FDR data.

The main conclusion that must be taken from this study is that the aerodynamic parametric estimation techniques can be widely applied to flight mechanics and aerodynamic degradation analyses during aeronautical accidents or incidents investigation. Compared to recent investigation efforts, these techniques can represent a very efficient methodology, providing tools in order to reduce workload and time expenditure in the investigation campaigns.

In addition, it is important to point out that the next steps on the research of system identification techniques applied for aeronautical investigation are the real FDR data analysis of experienced events and the application of more sophisticated techniques, such as filter-error or filtering approaches, in order to account also for process noise, which is represented mainly by atmospheric turbulence normally encountered in flight. Additionally, the details concerning identifiability under closed loop

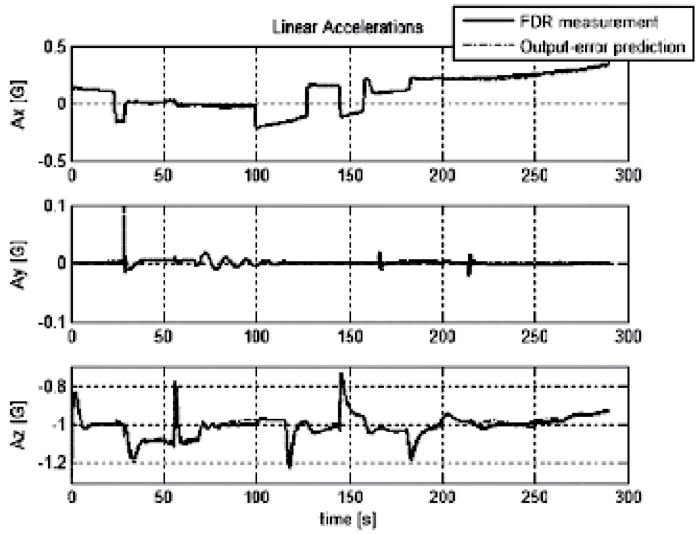


*Figure 9. Simulated FDR data and output-error prediction of linear accelerations.*

operations must be addressed. ◆

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# Runway Awareness and Advisory System (RAAS)

By Capt. Jody Todd, Technical Pilot—Business Jet Programs, Customer and Product Support

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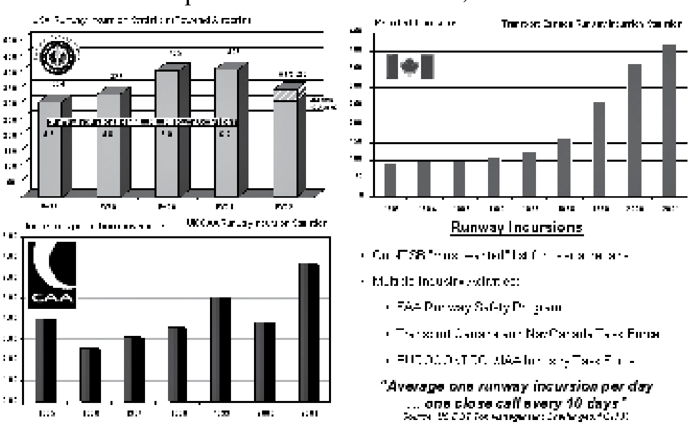
## 1. Introduction

Regulatory authority studies and aviation statistics conclusively highlight airport area operation incidents—and specifically runway incursions—as a growing safety concern. In addition to deploying awareness/prevention programs, the aviation industry sought a practical runway awareness and advisory product that addresses the root cause of problem in a cost-effective, near-term manner.



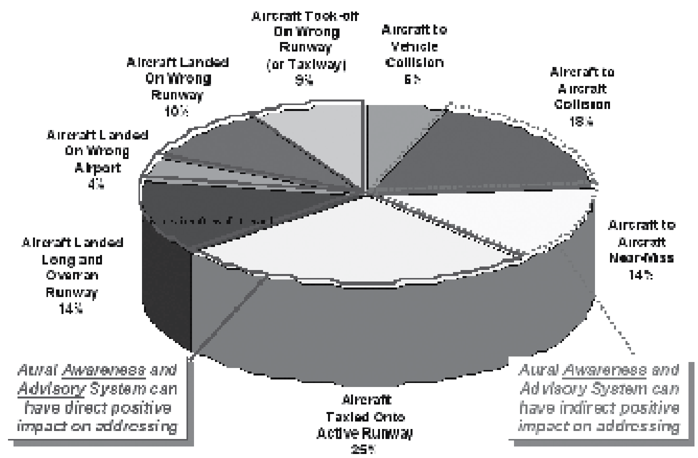

Honeywell responded, first conceptualizing and prototyping, then demonstrating and developing an operational solution based on

- the analysis of actual events and scenarios,
- a clear understanding of the airport area environment and operation,
- extensive end-user surveys, feedback, and aircraft and simulator trials, and
- sound human factors principles.

The result, the Honeywell Runway Awareness and Advisory System (RAAS), represents a significant safety advancement for aircraft equipped with the Enhanced Ground Proximity Warning System (EGPWS). The RAAS is an aircraft operation safety offering separate from the terrain awareness and warning and other functionality available in the EGPWS. However, to facilitate cost-effective and straightforward deployment, the RAAS can be hosted in any MK V or VII EGPWS computer updated with the prerequisite software and database. Therefore, the RAAS is offered as a key-enabled, database-configured, software-based capability on a per-unit basis.

## 2. RAAS description

The Honeywell RAAS provides flight crews increased situational awareness and advisories related to aircraft operations in and around runway areas, significantly lowering the probability of runway incursions as it complements the terrain/obstacle awareness and warning provided by the EGPWS during flight. While doing this, a major design goal is to provide maximum functionality with minimum impact to existing aircraft installation and unit hardware. Assuming GPS position1 is already provided to the EGPWS, the RAAS provides its aural advisories utilizing the existing aircraft wiring and installation. It is implemented via a software/enable process for the EGPWS without hardware modification to the unit.




The RAAS uses GPS data and an expanded EGPWS runway database (with validated runway descriptions2) to provide the aural advisories that supplement flight crew awareness of position and operations in the vicinity of runways and airports. It does so automatically without input from the flight crew. Other EGPWS functionality is unaffected by the addition of the RAAS.

It uses existing EGPWS voice and audio technology to produce its advisories, with the messages heard over the same aircraft audio systems that provide the EGPWS audio alerts in the cockpit. The audio volume settings, controlled by the EGPWS, have been adjusted based upon the expected flight operation for each advisory.

The RAAS aural advisories can be grouped into three categories

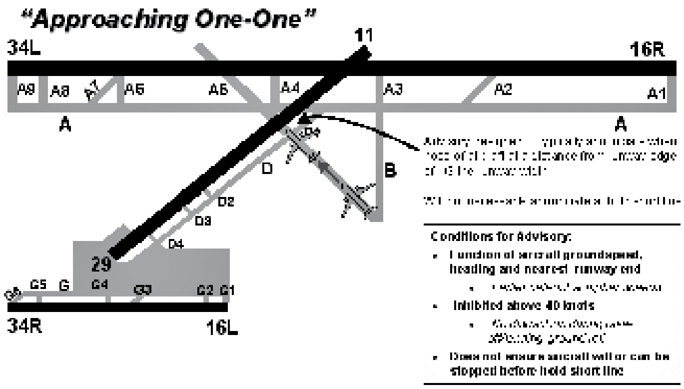
1. ***Routine***: messages heard during typical operations,
2. ***Semi-Routine***: messages heard during certain operations depending on aircraft type, runway length, and specific conditions, and
3. ***Non-Routine***: messages heard when increased awareness is warranted.

### 2.1. RAAS routine advisories

The RAAS provides three routine advisories, aural messages that flight crews hear routinely as they operate aircraft under typical airport area conditions. Focusing on runway incursion prevention, these messages are intended to provide increased situation awareness during operations in and around runways.

#### 2.1.1. Approaching runway—on-ground advisory

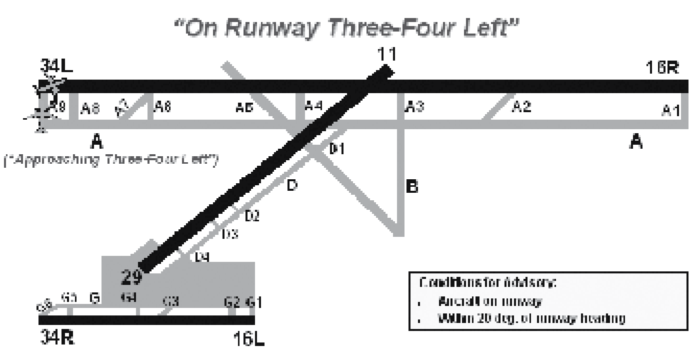
The RAAS-equipped aircraft provides a flight crew with an aural advisory as it approaches a runway during taxi operations. The message consists of "approaching" followed by the runway identifier, for example, "*Approaching One One.*" The advisory is annunciated once each time the aircraft approaches a runway. It is enabled when the aircraft ground speed is less than 40 knots.




The logic that triggers this advisory uses aircraft closure speed and closure angle to advance the generation of the advisory. The RAAS uses the runway identifier for the end of the runway that is closest to the aircraft's position.

#### 2.1.2. On runway—on-ground advisory

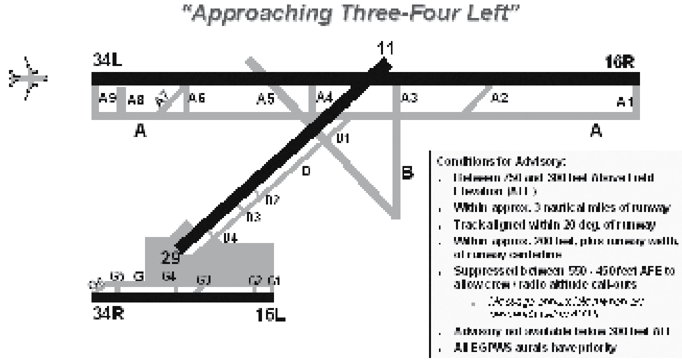
The RAAS-equipped aircraft provides a flight crew with an aural advisory when it enters a runway with a ground speed of less than 40 knots and a heading within ±20 degrees of the runway heading. The message consists of "on runway" followed by the runway identifier, for example, "*On Runway Three Four Left.*" This advisory is annunciated once each time the aircraft enters a runway.




#### 2.1.3. Approaching runway—in-air advisory

The RAAS-equipped aircraft provides a flight crew with an aural advisory when it is airborne and approaching a runway. The message consists of "approaching" followed by the runway identifier, for example, "*Approaching Three Four Left.*" It is enabled when

- aircraft is between 750 and 300 feet above runway elevation,
- aircraft is within approximately 3 miles of the runway,
- aircraft track is aligned with the runway within ±20 degrees, and
- aircraft position is within 200 feet+runway width of runway centerline.




Any EGPWS aurals, including altitude callouts, have priority over this advisory. The advisory is inhibited between 450 and 550 feet above runway elevation to allow any 500-foot altitude callouts and/or crew procedures. The advisory can be configured to be OFF.

Should the RAAS be unable to annunciate the advisory before the aircraft descends below 300 feet above runway elevation, the advisory will not be given. This could occur during a steep, fast approach with altitude callouts taking priority.

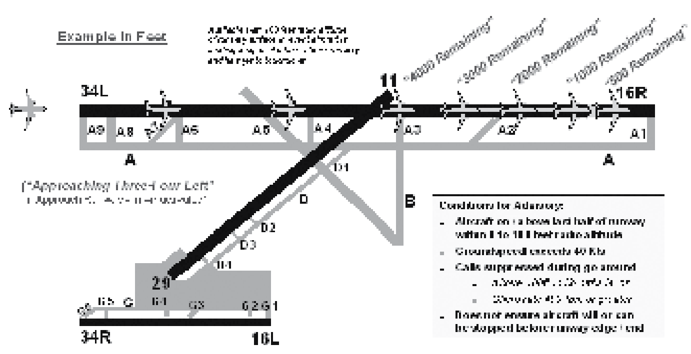
The advisory is annunciated once for each runway alignment. If the aircraft is flying the ILS on one runway and then executes a short final side-step to a parallel runway, the flight crew would hear two approaching runway advisory messages, one for the original runway and another as the aircraft aligns with the parallel runway.

### 2.2. RAAS semi-routine advisories

The RAAS provides two semi-routine advisories, aural messages that flight crews hear during some operations depending on aircraft type, runway length, and specific conditions (e.g., location on runway, ground speed).

#### 2.2.1. Distance remaining—landing and roll-out advisory

The RAAS-equipped aircraft provides a flight crew with aural advisories advising the distance remaining on a runway when the aircraft is on or over a runway and the ground speed is above 40 knots. The feature is configured to provide distance-remaining advisories for the last half of a runway. It can also be configured to be OFF.




For operators using feet as the unit of length, the advisories are generated at whole thousand-foot intervals, with the last possible advisory occurring at 500 feet. For example, an aircraft landing on a 9,000-foot runway would receive the following advisories: "*Four Thousand Remaining,*" "*Three Thousand Remaining,*" "*Two*

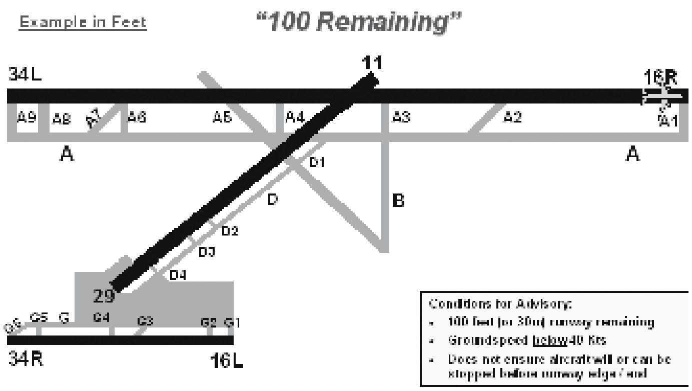
*Thousand Remaining,*" "*One Thousand Remaining,*" and "*Five Hundred Remaining.*"

For operators selecting meters as the unit of length, the advisories are generated at multiples of 300 meters, with the last possible advisory occurring at 100 meters. For example, an aircraft landing on a 2,700-meter runway would receive the following advisories: "*Twelve Hundred Remaining,*" "*Nine Hundred Remaining,*" "*Six Hundred Remaining,*" "*Three Hundred Remaining,*" and "*One Hundred Remaining.*"

The advisories terminate when the ground speed drops below 40 knots. If the aircraft elects to go-around after triggering the distance remaining advisories and the ground speed remains above 40 knots, the advisories continue at the appropriate distances along the runway or until the aircraft climbs more than 100 feet above runway elevation.

### 2.2.2. Runway end advisory

The RAAS-equipped aircraft provides a flight crew with an aural advisory when it is aligned on a runway, approaches within 100 feet (30 meters) of the end of the runway, and the ground speed is below 40 knots. The message consists of "*one hundred remaining*" for units of feet or "*thirty remaining*" for units of meters. The advisory can be very useful in poor visibility conditions by providing the flight crew an attention cue to look for the runway exit. It can also be configured to be OFF.



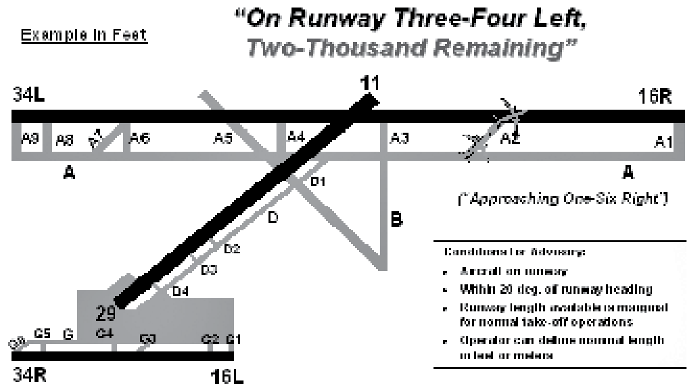

### 2.3. RAAS non-normal advisories

The RAAS provides five non-routine advisories, aural messages that flight crews hear during specific situations not normally encountered in routine operations. Some of these advisories contain distance information whose unit of measure can be configured as feet or meters.

### 2.3.1. Insufficient runway length—on-ground advisory

The MK V and MK VII EGPWS make use of aircraft type information selected when the system was initially installed. The RAAS makes use of this information in determining what lengths of runways are appropriate for the particular aircraft type.

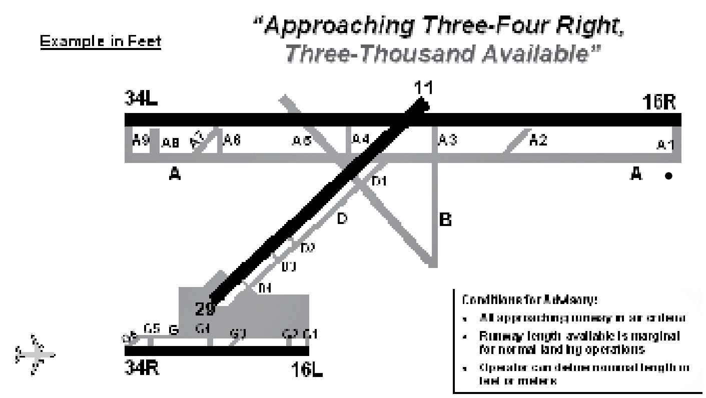
When the RAAS-equipped aircraft enters a runway that could be considered too short for the aircraft type, the system provides the flight crew a modified on-runway advisory. Specifically, after the normal on-runway-plus-runway-identifier aural, the RAAS annunciates the remaining runway length in a unit of measure that can be configured as feet or meters. An example of this advisory is "*On Runway Three Four Left, Two Thousand Remaining.*" It can also be configured to be OFF.




### 2.3.2. Approaching short runway—in-air advisory

The MK V and MK VII EGPWS make use of aircraft type information selected when the system was initially installed. The RAAS makes use of this information in determining what lengths of runways are appropriate for the particular aircraft type.

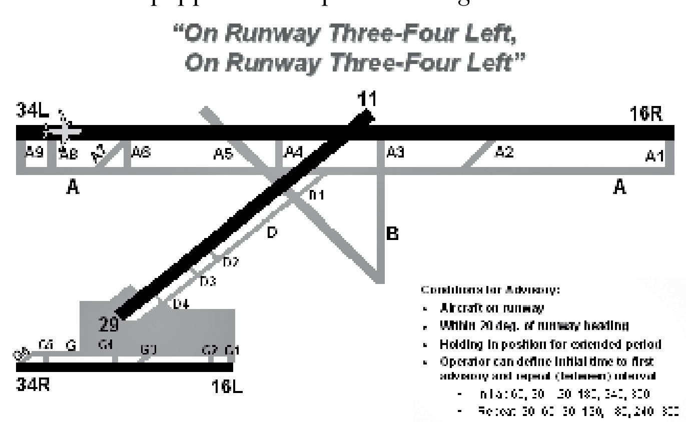
When the RAAS-equipped aircraft approaches a runway that could be considered too short for the aircraft type, the system provides the flight crew a modified approaching runway advisory. Specifically, after the normal approaching-runway-plus-runway-identifier aural, the RAAS annunciates the available runway length in a unit of measure that can be configured as feet or meters. An example of this advisory is "*Runway Three Four Right Ahead, Three Thousand Available.*" It can also be configured to be OFF.




It is possible that this advisory could be heard in conjunction with the normal approaching runway advisory if a side-step approach to a parallel runway is used.

### 2.3.3. Extended holding on runway advisory

The RAAS-equipped aircraft provides a flight crew an aural advi-



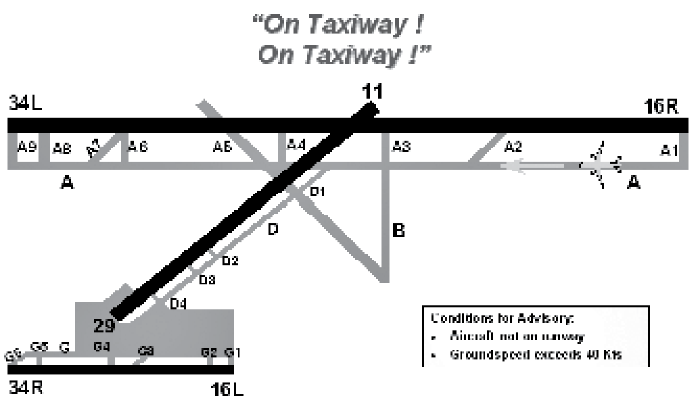
sory when it has entered a runway, aligned with the runway heading, and not moved more then 50 feet for a period of time that can be configured for 60, 90, 120, 180, 240, or 300 seconds. When this limit is met, the RAAS annunciates twice the message combination of "on runway" and runway identifier.

The interval between when the aural pair is first annunciated and when the pair is repeated can be configured for 30, 60, 90, 120, 180, 240, or 300 seconds. This feature can also be configured to be OFF.

The intent of this advisory is remind the flight crew that it has been have been sitting on an active runway for an extended period of time and perhaps should call airport traffic control and/or reevaluate the situation.

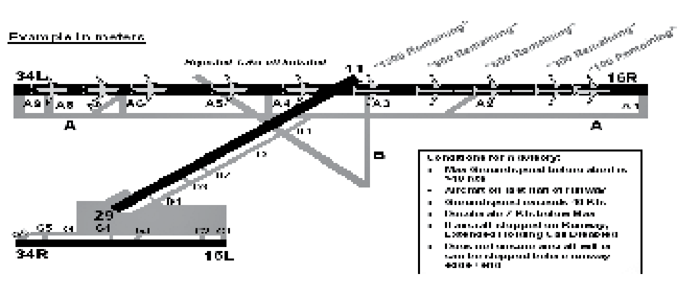
### 2.3.4. Taxiway takeoff advisory

The RAAS-equipped aircraft provides a flight crew an aural advisory when it attempts to take off from non-runway surfaces. If the aircraft exceeds the configurable ground speed (normally 40 knots) while not on a runway, the message "*On Taxiway! On Taxiway!*" is annunciated. It can also be configured to be OFF.




### 2.3.5. Rejected takeoff

The RAAS-equipped aircraft provides a flight crew with aural advisories advising the distance remaining on a runway when the aircraft is executing a rejected takeoff and its ground speed is above 40 knots. Should ground speed during the takeoff roll decrease by 7 knots from its peak and the aircraft is on the last of the runway, the RAAS will provide distance-remaining advisories as detailed under distance remaining—landing and roll-out advisory. Once the ground speed drops below 40 knots, the advisories will terminate. They can also be configured to be OFF.




### 2.4. RAAS configuration options

The RAAS is highly configurable to suit the specific operational needs of different airlines and operators. Configurable items include the use of feet or meters for the "distance remaining" advisories, a male or female voice for the RAAS advisories, aircraft speed trigger levels, timers, etc. Conversely, many of the advisories can be disabled in total.

Please consult the RAAS product specification for additional detail on the configurable items.

Please see Attachment B for an example of the RAAS configuration database worksheet that is to be filled out by users in order to document the manner in which they want to configure their RAAS operation

### 2.5. RAAS notes

The RAAS advisories represent short, discrete aural information for improving airport area positional awareness and breaking the link in sequence of events leading to runway incursions.

The RAAS advisories are not intended for navigation purposes, to ensure protection against loss of separation with other traffic, or to supercede operator standard operating procedure (SOP).

The RAAS does not have access to air/airport traffic control clearance or flight crew intent; therefore, such factors as misunderstood or incorrect clearances may not be mitigated.

The RAAS does not have access to prevailing NOTAMs or ATIS data, therefore such factors as runway closures are not reflected. Flight crews are assumed to be cognizant of such notices.

Data on newly constructed runways or non-temporary changes to existing runways may not be in the RAAS runway database until at least the next update

## 3. RAAS configuration

The RAAS is hosted in the MK V/VII EGPWS software release known as "-218-218/-051" or later. The -218-218/-051 received TSO-C92c, TSO-C117a, TSO-C151b, and (with 965-0976-060 Mercury GPS card equipped MK V EGPWS) TSO-C129a approval in December 2003. The Convair Aircraft Supplemental Type Certification (STC) ground and flight test of the -218-218/-051 software with the RAAS activated was completed in December 2003. Formal STC approval for the -218-218/-051 software with RAAS activation was granted in December 2003.

Upgrading the MK V or MK VII EGPWS computer to host the RAAS and then subsequently activating the RAAS is a simple procedure described as follows:

### 3.1. RAAS software and database

While the RAAS is an offering/capability separate from the terrain awareness and warning and other functionality available in the EGPWS, the RAAS can be hosted in any MK V or MK VII EGPWS computer with the following software and terrain database installed (via the prescribed Honeywell Service Bulletin(s) [SBs]):

• Software

—Part number starting with MK V prefix 965-0976-xxx (where xxx = 003, 020, 040, or 060) and ending with software suffix -218-218 or later; if not installed, update the EGPWS computer using the Honeywell SB 965-0976-0XX-34-76 (for software -218-218);
or

—Part number starting with MK VII prefix 965-1076-xxx (where xxx = 001, 020, 030, 040, or 060) and ending with software suffix -218-218 or later; if not installed, update the EGPWS computer using the Honeywell SB 965-1076-0XX-34-53 (for software -218-218);
or

—Part number starting with MK V prefix 965-1690 and ending with software suffix -051 or later; if not installed, update the EGPWS computer using the Honeywell SB 965-0976-0XX-34-76 (for software -051).

• Terrain database 435 or later; if not installed, update the EGPWS computer using one of the following Honeywell SBs: 965-0976-0XX-34-74 for MK V EGPWS or 965-1076-0XX-34-52 for MK VII EGPWS.

Honeywell provides the indicated SBs and the material they reference free of charge. The user is responsible for any labor costs associated with the SB as well as any labor, material, or costs associated with the computer's removal from and reinstallation in the aircraft.

### 3.2. RAAS activation

Assuming an EGPWS has been equipped with the RAAS-hosting EGPWS software -218-218/-051 or later, there are two steps involved with the RAAS activation within the unit

1. a one-time enabling process involving a unique key based on the unit's serial number, and
2. a functionality configuring process using an user-specific configuration database that functions much like program pins; this file is referred to as the RAAS configuration database (RCD).

#### 3.2.1. RAAS enable key

The RAAS enable key is provided at the time the RAAS enabling is ordered/purchased. The purchase order needs to include a list of the serial numbers for the EGPWS units in which the RAAS is to be enabled. As part of the invoicing process, Honeywell lists the (unique) enabling key associated with each serial number. The purchase order can request a PCMCIA card with the resulting key per EGPWS serial number.

The enabling key is uploaded to a powered-up EGPWS by either entering this key via a user-supplied laptop interfacing to the unit's RS-232 port and running a Honeywell-provided WinView script or plugging the enabling key PCMCIA card into the unit.

The actual process for enabling the RAAS functionality hosted in the EGPWS software is described in one of the following SBs: 965-0976-0XX-34-77 for MK V or 965-1076-0XX-34-54 for MK VII. Note, the RAAS enable key is not provided free of charge; for year 2004, the catalog price is $17,369. Additionally, the user is responsible for any labor costs associated with the SB as well as any labor, material, or costs associated with the computer's removal from and reinstallation in the aircraft.

Once the RAAS enable key is uploaded, the EGPWS software verifies a match between the key and the unit's serial number. If a match is found, the RAAS is enabled, though it will not be active until the RCD step described below is accomplished.

#### 3.2.2. RAAS configuration database

The RCD is uploaded to a RAAS-enabled EGPWS computer via a PCMCIA card. The RCD allows for the setting of the common fleet options, GPS antenna position, and nominal runway lengths. Each RCD can support up to 20 different aircraft types. Thus an operator with a mixed fleet of aircraft can swap RAAS-enabled/configured EGPWS LRUs within the fleet and not necessarily be required to reload the RCD. A RAAS configuration database worksheet is included in Attachment B.

The RAAS functionality hosted in the EGPWS software is configured (for the desired advisories and associated characteristics) using the RCD as described in one of the following SBs: 965-0976-0XX-34-77 for MK V or 965-1076-0XX-34-54 for MK VII.

The RCD card and associated part number are created by Honeywell upon receipt of a properly filled out RCD worksheet. This worksheet should be completed by the operator and forwarded to the appropriate Honeywell EGPWS applications/certification focal.

The initial RCD card per aircraft will be provided free of charge. A fee may apply to providing additional copies of the RCD as well as adjusting the configuration/advisory selections covered by the RCD, card, and associated part number.

Given that one RCD can cover up to 20 aircraft types/fleets for which the RAAS functionality is configured the same, it is possible that as few as one RCD PCMCIA card may be needed. For example, if the same RAAS functionality options are desired for two different aircraft types/fleets, then both could be covered under the same RCD and only one PCMCIA card would be needed to configure all involved units. If different RAAS functionality options are desired between the two aircraft types/fleets (or even among aircraft within the same type/fleet), then separate RCDs would be needed.

The user is responsible for any labor costs associated with the SB as well as any labor, material, or costs associated with the computer's removal from and reinstallation in the aircraft.

Once the RCD is uploaded and unit self-test is passed, the RAAS is configured and now fully active (assuming it has been previously RAAS enabled as described in the previous subsection).

### 4. RAAS installation

In the STC configuration (for example, as approved on the Convair Aircraft), there are no pin programming changes to the aircraft installation associated with activating (i.e., enabling or configuring) the RAAS. It is Honeywell's STC plans to not require installation wiring changes in order to support RAAS activation.

In anticipation of eventual RAAS type certifications, the air transport original equipment manufacturers (OEMs) have introduced the possibility of an activation discrete (in addition to the RAAS enable key) for production aircraft configurations delivered from the factory or updated via an OEM SB. This would require an aircraft wiring change to configure the discrete. While this would need to be supported for the OEMs, it remains Honeywell's intent not to require such a discrete wherever possible for non-production aircraft types or aircraft types updated via a STC process.

There have been discussions of an RAAS advisories inhibit option specifically for inhibiting the RAAS aurals. This would likely necessitate a flight-deck-based inhibit switch. However, extensive human factor studies conducted for the RAAS design and regulatory authority review processes have shown that a RAAS advisories inhibit is not required. The Convair Aircraft STC was FAA-approved without such an inhibit. In the event the user and its regulatory authorities concur with these conclusions, no flight deck changes should be required to support the RAAS activation.

### 5. RAAS certification

The Convair Aircraft STC ground and flight test of the -218-218/-051 software with the RAAS activated was completed in December 2003. Formal STC approval for the -218-218/-051 software with RAAS activation was granted in December 2003.

Honeywell is in discussions with the air transport OEMs regarding RAAS functionality type certifications and SBs for in-production aircraft. Assuming OEM concurrence, the goal is to type certify this functionality on a wide range of major air transport and regional aircraft types, just as the EGPWS itself is type certified across these platforms today. The OEMs reserve the right to determine the charges, if any, for production aircraft configuration requests and SBs; such pricing has not yet been determined.

Honeywell plans to offer STCs for those aircraft that are no longer in production and, if feasible, where a SB solution will not be available in a timely manner. As with the introduction of the EGPWS, Honeywell is committed to supporting STCs to prevent delay in operators benefiting from the safety advancement that the RAAS offers. ◆

## ATTACHMENT A

**EGPWS description and instllation**

### Overview

The Enhanced Ground Proximity Warning System (EGPWS) replaces the GPWS as a line-replaceable-unit (LRU). The mounting tray, connector, and existing wiring are reused when retrofitting a MK III, V, or VII GPWS. The tray, connector, and some of the wiring are replaced when retrofitting an old MK I or II. Additional, yet-minor, wiring/hardware is required to 1) activate enhanced ground proximity warning functionality and 2) interface ground proximity warning functionality with other flight safety functions (e.g., windshear, TCAS). Added wiring, annunciators, terrain activation/inhibit switching, and relays are part of an installation kit.


For retrofit or forward-fit applications, the EGPWS can be delivered without an internal GPS card. Position (lat/long) inputs are provided by the flight management system (FMS) or external GPS source (if available) while altitude input is provided by onboard altimeters.

For retrofit applications where an aircraft manufacturer service bulletin (SB) is not being used, the EGPWS can also be delivered with an internal GPS card. Position inputs come from the internal GPS while altitude input is derived from the GPS as well as onboard altimeters. A separate coax interfaces the card to an active GPS antenna mounted on an aircraft surface. The coax and antenna are part of the EGPWS installation kit.

If an external GPS source is interfaced with the EGPWS (as a direct input or via a FMS), the internal GPS card is not needed. If a card is in the unit, it can remain without affecting operation; position input is still taken from the external source. This allows an EGPWS with internal GPS card to move between aircraft with no external GPS (but with the coax and antenna) and ones with external GPS.

### Internal GPS card options

The EGPWS is available with two versions of an internal GPS card. When the card known as the PExpress is used, position data (e.g., latitude, longitude, altitude, accuracy) are provided by the card directly and solely to the EGPWS. Additionally, a number of operators expressed interest in an internal GPS card option that would capable of outputting position data to other avionics as well as supporting the EGPWS. Honeywell listened and responded accordingly, configuring the MK V EGPWS with the Mercury GPS card that can provide ARINC 743A outputs usable by avionics external to the EGPWS.

The Mercury GPS card, while internal to the EGPWS, provides data to the EGPWS as well as outputs it for use by other avionics. The outputs are two ARINC 429 channels of TSO-C129(C3)/ARINC 743A compliant data as well as a GPS fail indication. These outputs support en-route navigation. They do not support precision/terminal area navigation as these requirements are generally addressed using dual standalone GPS or multimode receivers.

Certification of the outputs' use with other systems (such as a flight management system) is the end-user's responsibility. For example, Boeing certified as part of a SB offering the interface of these outputs with the B737-300/400/500 FMS (contact a Boeing services representative for additional SB details and/or pricing information).

In comparing the PExpress to the Mercury GPS card, the former uses an 8-channel tracking, 8-channel solution approach while the latter uses a 24-channel tracking, 8-channel solution approach.

The PExpress GPS card has no power-down means of saving the last operation so it does a full start during turn on. Time-to-initial (position) acquisition is 2 to 3 minutes typically with worst-case times of 7 minutes on the ground or 20 minutes if the aircraft is moving. The Mercury GPS card has a "super cap" memory back up that recovers from a power cycle in about 30 seconds for up to a day after power down; initial start is not more than a few minutes worse case.

The PExpress GPS card is designed to only provide position data to the EGPWS and has no output available to external avionics. The Mercury GPS Card has been TSO C-129a approved as a Class C3 supplemental navigation GPS per DO-208 and the TSO. Its dual ARINC 429 outputs provide ARINC 743A data meeting the Boeing FMS GPS input specifications. As mentioned, these outputs have been certified for use with the B-737-300/400/500 FMS by Boeing as part of a Boeing SB. In actual function, the card goes beyond Class C3 by providing RAIM and NISF indications per the Boeing GPS specifications.

The EGPWS with internal (PExpress) GPS card is available today in both the MK V and MK VII variants (part numbers 965-0976-020-xxx-xxx and 965-1076-020-xxx-xxx, respectively). Additionally chargeable SBs exist to upgrade the MK V or MK VII EGPWS without Internal GPS card (part numbers 965-0976-003-xxx-xxx or 965-1076-001-xxx-xxx, respectively) to the MK V or MK VII EGPWS with internal (PExpress) GPS card variants.

The EGPWS with Mercury GPS card is available today for the MK V (part number 965-0976-060-xxx-xxx). Converting a MK V EGPWS without Internal GPS card or with internal (PExpress) GPS card to a unit with Mercury GPS card is accomplished via a chargeable, one-for-one exchange program.

# ATTACHMENT B
## RAAS configuration database worksheet

**RUNWAY AWARENESS ADVISORY SYSTEM (RAAS) CONFIGURATION DATABASE WORKSHEET**

There are two parts to this worksheet. To have RAAS enabled, each individual aircraft type must be listed in Part B. This page contains notes to aid in filling out the following worksheet. To complete a worksheet, go to the EGPWS website (www.egpws.com) and submit the completed form.

**Enter data by mouse clicking in the desired box, then typing information or using the up/down arrows to make a selection. Click on the Acrobat Text Select Tool icon if the worksheet appears unresponsive.**

**NOTE 1:** All options in Step 1 (Part A) must be completed. Worksheets with blank selections CANNOT be accepted.

**NOTE 2:** MK V EGPWS Type is one of the following part numbers: 965-0976-XXX-XXX-XXX or 965-1690-XXX

MK VII EGPWS Type is one of the following part numbers: 965-1076-XXX-XXX-XXX

**NOTE 3:** A/C Type number is the 2 or 3-digit aircraft-type number defining the EGPWS installation. This number can be found using one of the following methods:

- Conducting a Level 3 Self-Test on the aircraft per *Line Maintenance Manual - MK V, MK VI, MK VII, MK VIII, Enhanced Ground Proximity Warning System*, Honeywell Document 060-4199-180.
- Examining EGPWS-aircraft program pin wiring against the *Interface Control Document for the Mark V Enhanced Ground Proximity Warning System (MK V EGPWS)*, Honeywell Document 993-0976-401.
- Examining EGPWS-aircraft program pin wiring against the *Interface Control Document (ICD) for the Mark VII Enhanced Ground Proximity Warning System (MK VII EGPWS)*, 993-1076-401.

**NOTE 4:** MK VII Aircraft-Types 3, 4, 5, 7 are generic, non-windshear aircraft types that can be used with multiple airframes. For example, MK VII EGPWS A/C Type 5 is a generic, Air Transport, non-windshear configuration that may be used on DC-9-32, B747-200 and A300B4-200 aircraft. The ICD will not distinguish between aircraft models, only aircraft-type number. If more than one aircraft model has EGPWS installed and is using a MK VII generic aircraft type, then multiple ICDs will be required. Complete the worksheet listing all aircraft using the generic aircraft-types and send to Honeywell for evaluation.

**NOTE 5:** Enter the distance GPS antenna is located from nose of aircraft to center of antenna rounded up to the nearest 5 foot. (i.e. If distance measured is 11 feet, then round up to 15 feet).

**NOTE 6:** RAAS Short and Insufficient Runway Advisories do not take into account aircraft performance factors such as aircraft weight, wind, runway condition, slope, air temperature and altitude of airport. This is an informational advisory that is intended to enhance flight crew awareness by identifying that the runway length available may be marginal for the aircraft type.

Nominal Runway Lengths: Enter value rounded up to the nearest 100-ft (30-metres). If advisory is turned OFF in Part A, leave blank. If available runway length is to always be annunciated, then enter ALWAYS

The RAAS algorithm processes distances in feet. If the operator selects the Metres option, and the nominal runway lengths listed in Part B are in metres, Honeywell will convert the metres value into feet using the formula (Feet = Metres x 3.2808398950). When the advisories are triggered, the algorithm recalculates and provides distance advisories in metres.

www.egpws.com    Complete ALL of PART A: Selection Boxes

| | | | |
|---|---|---|---|
| **Aircraft Operator:** | | **Date:** | |
| **Customer Name/Company:** | | **P.O. #:** | |
| **Customer Phone/Fax/email:** | | | |
| **HONEYWELL USE ONLY:** | | | |

1. **Complete PART A: Global Options (applicable to all aircraft)**

| **DESCRIPTION** (reference the Product Description section in brackets for more details) | **OPTIONS** | **SELECTION** - *Note 1 CLICK IN BLANK BOX, MAKE SELECTION VIA UP/DOWN ARROWS YOU MUST CLICK IN BOX AFTER SELECTING BEFORE GOING TO NEXT BOX |
|---|---|---|
| Distance unit of measure (All Advisories) | Select Feet or Metres in the box | |
| Voice Gender (All Advisories) | Select Female or Male in the box | |
| Approaching Runway - In Air (4.1) | Select ON or OFF in the box | |
| Advisory Suppress Window (4.1) | Select 450-650 ft or 350-450 ft in the box | |
| Distance remaining, Landing & Roll-out (4.4) | Select ON or OFF in the box | |
| Runway End Advisory (4.5) | Select ON or OFF in the box | |
| Approaching Short Runway Length In Air Advisory (5.1) | Select ON (and enter Nominal Runway Length in Part B for each aircraft type) or OFF or ALWAYS (length always voiced) | |
| Insufficient Runway Length – On Ground Advisory (5.2) | Select ON (and enter Nominal Runway Length in Part B for each aircraft type) or OFF or ALWAYS (length always voiced) | |
| Extended Holding Time on Runway, initial (5.3) | Enter value of 60, 90, 120, 180, 240, 300, seconds or OFF in the box | |
| Extended Holding Time on Runway, repeats (5.3) | Enter value of 30, 60, 90, 120, 180, 240, 300, seconds or OFF in the box | |
| Taxiway Take-Off (5.4) | Select ON or OFF in the box | |
| Distance Remaining - Rejected Take-Off (5.5) | Select ON or OFF in the box | |

3. **Complete PART B: Individual Aircraft-Type Options**

| | | | |
|---|---|---|---|
| **Aircraft Operator:** | | | |
| Customer Name/Company: | | Telephone: | |

| The fields below MUST be completed for each aircraft type | | | | The fields below are required ONLY IF those Advisories are enabled | |
|---|---|---|---|---|---|
| Fleet or Aircraft Type (i.e. Q-1Y or B737-300) | EGPWS Version (MK V or MK VII) [NOTE 2] | A/C TYPE Number [NOTE 3] [NOTE 4] | GPS Antenna Location (All Advisories) (Distance from A/C nose in feet between 0 and 200 rounded up to the nearest 5 ft) [NOTE 5] | Approaching Short Runway Length - In Air Advisory (5.1) Nominal Runway Length distance rounded up to the nearest 100 ft. (30 metres) [NOTE 6] | Insufficient Runway Length - On Ground Advisory (5.2) Nominal Runway Length distance rounded up to the nearest 100 ft. (30 metres) [NOTE 6] |
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Notes 1 to 6 are listed on the first page of this document

## Endnotes

1 GPS fine latitude and longitude data as well as other lateral (horizontal) GPS position-related information are required for the RAAS due to the position accuracy requirements associated with "on ground" aircraft operations.

2 Primary, alternate, and emergency airports are included in the RAAS portion of the runway database as they are validated using EGPWS flight history data and Honeywell's wide range of data-validation tools.

# Rotor Seizure Effects

By Al T. Weaver (MO4465), Southern California Safety Institute

***Al Weaver** is a Senior Fellow Emeritus having retired from Pratt & Whitney after a long career in promoting flight safety initiatives and expertise in accident investigation. He currently teaches the gas turbine investigators course for Southern California Safety Institute.*

## Abstract

This paper is an explanation of rotor seizure effects in the gas turbine powerplant systems on large transport engines. It explains some of the secondary damage effects seen in gas turbine engine failures where a significant degree of rotor seizure has taken place. Rotor seizure in this context is a deceleration rate effect producing torque loads on the powerplant components. The results of rotor seizures may extend beyond the confines of the engine itself and involve the engine nacelle, reverser, or pylon system.

Rotor seizure effects refer to the permanent distortions in the engine/pylon system related to the torsional effects brought about by rapid stopping of a gas turbine engine.

The gas turbine engine develops normal torque loads on its rotor components, including the drive shafts, by virtue of accelerations and decelerations between the driving force (turbine) and the loading force (compressor). Aerodynamic reaction torque loads are produced on the stationary airfoil components (compressor stators) by virtue of their turning or aerodynamic lift forces. The forces on the engine static parts are then transmitted to the mount structure of the pylon.

In the case of internal engine failures within the engine, abnormal torque loads may be developed leading to distortion or failure of parts within the load path. In its simplest form, to visualize the results of abnormal seizure loads, one typically thinks of twisted drive shafts (a rotor component) and/or sheared mounting bolts (a pylon component). However in modern gas turbine engines abnormal torque loads have been anticipated and large margins applied to the designs to minimize either a shaft failure or a mount fracture due to torsion-induced loading.

Incident history associated with the failure within gas turbine engines is largely devoid of complete engine seizures (sudden stoppages) or mount failures associated with only torsion loading. However, this history does contain incidents of intermittent very high torsion loading as well as mount failures allowing the engine to be released. A clarification and explanation is then given. The inertial energy contained within the rotor system of the gas turbine under flight conditions (ram air in the inlet) is such that bearing failures are overcome with friction creating molten metal, thus reducing the friction to well below any force capable of stopping a rotor with ram air still trying to windmill the compressor/turbine. The meshing or tangling of broken blades and stator vanes as well as initial frictional forces between blades and cases under extreme imbalance loading produces a more pronounced level of torsion loading on the system.

The torsion produced by the tangling of blades (a rotor component) and stator vanes (a stationary component) is typically short-lived with both of these parts fracturing early in the event, thus significantly reducing the seizure torque to a slightly depressed windmill condition—albeit after landing the rotor may not be able to be turned by hand (and thus reported seized). At the same time, the initial rubbing of large fan blade tips against their casing material may bring about a significant component of torsion loading. The seizure loading in itself is typically not enough to fracture mounting components unless it is combined with very high imbalance forces at the same time. Such combinations have occurred in the case of some partial disk fractures, leaving the rotor structure with a rotating imbalance force to superimpose imbalance loading with torsion loading.

An example of such is shown in Figure 1. Torsion-caused distortion is evident to the holes in the conical-shaped drive hub for the fan system.

At the same time as the torsion are producing distortions within the rotor system, the same loads are being driven through the case structure to the engine mounts. In this case, the mounts are behind the source of the tangling and friction-induced torsion.

Caution must be taken in reading distortion patterns or buck-

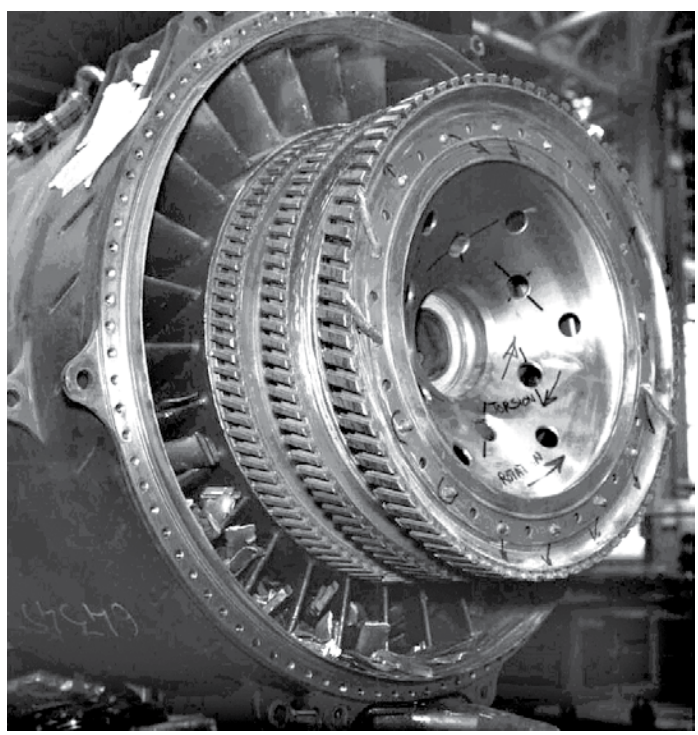

*Figure 1. Torsion loading effects on rotor.*


*Figure 2. Torsion buckling in an engine case.*

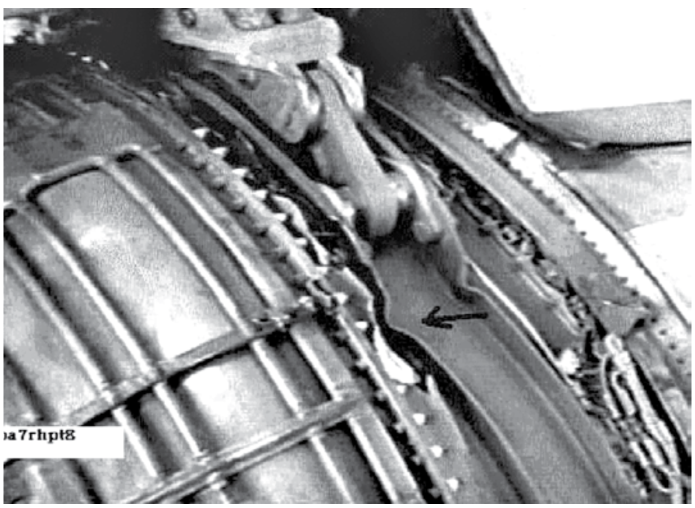


*Figure 3. Local mount-load distortion to case.*

ling in engine parts. If the engine has impacted the ground, some bending of the engine may occur resulting in similar-appearing buckling or distortions. It is important to establish if the distortions are uniformly in the same direction (typically 45 degrees offset to the torsion) as significant asymmetry may only confirm bending loading.

With the introduction of the high-bypass-ratio engines, the significance of the fan and its large drive turbine is important. The mount system for the engine is typically, but not always, behind the fan (front mount) and aft of the turbine (rear mount). The large diameter of these blade tips significantly influence the torsion loading when major imbalance loadings due to failures occur in the rotor system. The engine design has typically provided for large margins against the rotor shaft system showing signs of excessive seizure forces in these engines. However, there have been events where the case structure immediately behind the fan blade tips has been fractured due to a combination of imbalance and intermittent seizure loading. This has the effect of signifi-

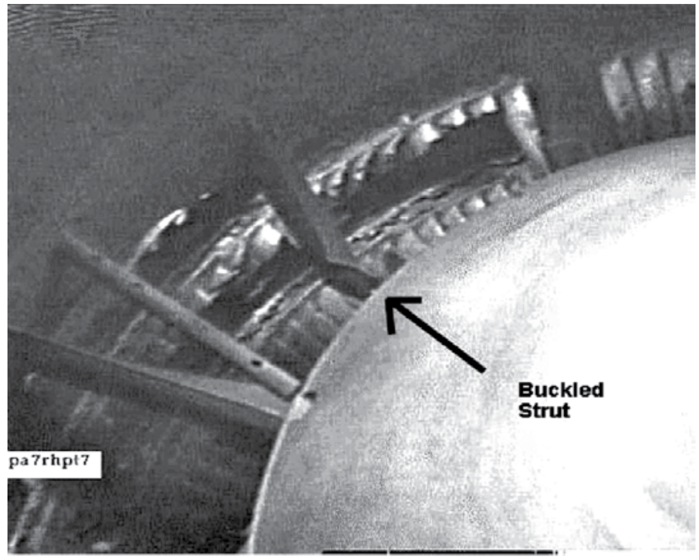


*Figure 4. Buckled strut in turbine support.*

cantly altering the load path between the engine and the pylon.

In addition, there have been cases where uncontained damage to the engine has severed or partially severed the engine load path between the engine mounts, allowing a combination of bending (engine sag under its own weight) and torsion to be applied to engine nacelle and pylon structures, which were typically free of significant torsion effects.

Consider the effect of either a burner rupture or an uncontained large circumferential tear in an engine turbine case. In a burner rupture, the engine will sag on the drive shafts producing significant torsion loading by virtue of turbine blades being driven into their surrounding cases. In some events, this rotor distortion cannot normally be reacted out to the case structure in the immediate vicinity of the aft section of a ruptured burner case. This then drives the rotor loads through the turbine inlet nozzle guide vanes, which may not be firmly bolted into place, due to their need to resist thermal expansion. This in turn often leads to more severe rubbing of the turbine blades on the surrounding structure and seizure loading, which may not be totally reacted out through to the mount structures.

In other events, a circumferential uncontained separation may occur in the turbine section, effectively isolating the aft turbine mounting structure from reacting all of the torsion seizure loads generated ahead of the split in the cases that are associated with rubbing and tangling of blades and nozzle vanes. This abnormal load shift may result in significant twisting of the engine and its associated nacelle system ahead of the circumferentially split case. Where the circumferential uncontained separation is only partial, but yet extensive (greater than 90 degrees), the portion of torsion loading that does reach the rear mounts may be distorted to the point where significant "punch loads" are reacted back to the case structure by the local mount structure. Such loads are evident in Figure 3.

These punch loads may result in local collapsing of the turbine-bearing support struts or buckling of the diaphragm between the bearing and these support struts, resulting in further seizure loading to the turbine blade tips in this area. (See Figure 4.)

The further signatures of seizure loading may be due to the clocking of the engine nacelle structure that is attached to the

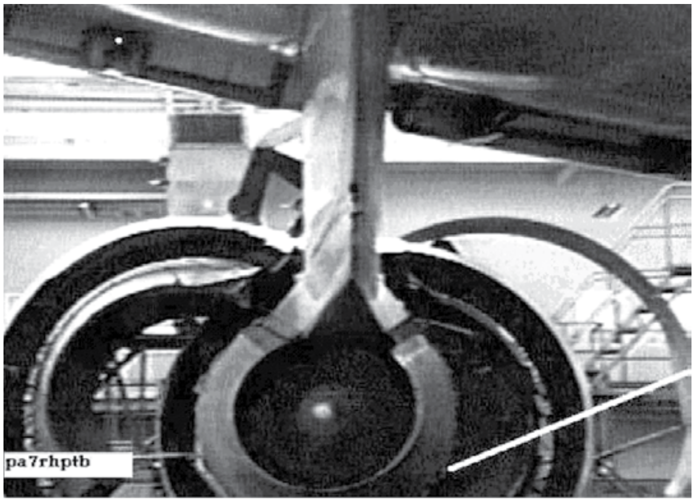


*Figure 5. Clocking of engine nacelle due to seizure.*

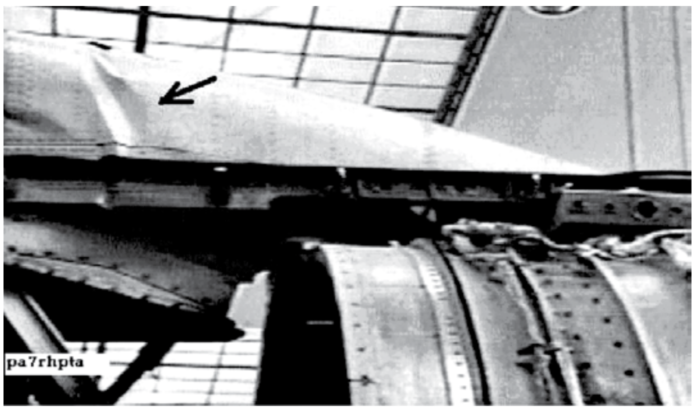


*Figure 6. Pylon buckling and fractured nacelle hinges due to seizure loading.*

engine cases via a non-slipping friction joint (for sealing purposes). This clocking attempts to follow the clocking in the engine cases ahead of a significant split in an engine (either burner rupture or caused by a turbine uncontainment) followed by rotor seizure loading. (See Figure 5.)

Once clocking of the nacelle begins, the nacelle drives torsion type loads into its own mount lugs typically attached to a pylon. These loads have been seen to be of a magnitude sufficient to fracture the nacelle attachments at these points, deform the pylon in buckling, deform the nacelle structures in buckling, and/or to deform the reverser blocker doors. (See Figures 6, 7, 8, and 9.)

The result of pylon buckling is to distort the pylon, in this case, sufficient to drive a vertical load into either the inlet cowl or the engine fan case sufficient to create additional seizure loading at the fan blade tips due to severe rubbing. (See Figure 7.)

Note: The preceding examples are not all from the same incident, nor are they meant to convey an expected result following a rotor seizure event. They are intended only to show possible signatures that rotor seizure of a high magnitude has taken place. The accident/incident investigator needs to be concerned with the possible cascading effect of rotor seizure that may lead to a threat to continued safe flight and landing. ◆

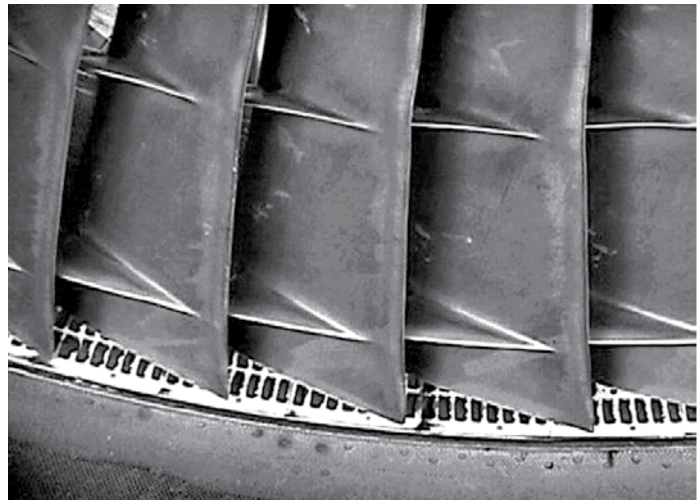

*Figure 7. Fan blade tips seized into fan case.*

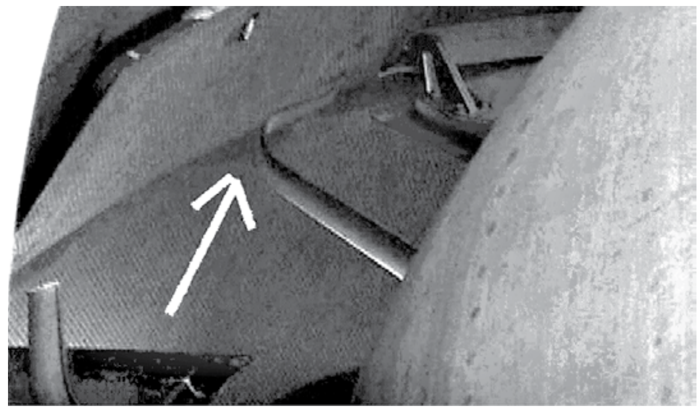

*Figure 8. Buckled rod and partially deployed reverser door.*

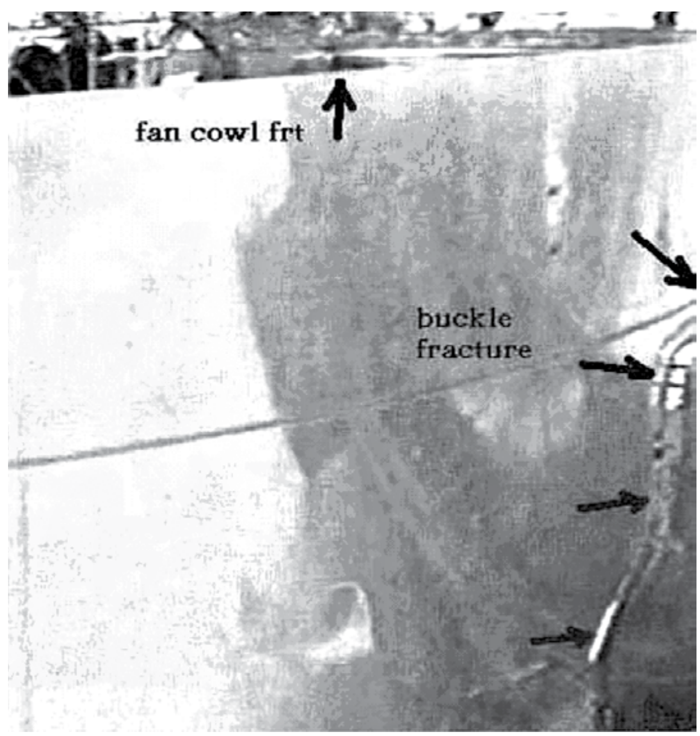


*Figure 9. Buckled fan cowl due to seizure loading.*

# 3-D Photogrammetric Reconstruction In Aircraft Accident Investigation

By Michiel Schuurman (ST4721), Investigator, Dutch Safety Board, the Netherlands

*Michiel Schuurman* is an investigator for the Dutch Safety Board in the Netherlands. He has a BSc degree in aeronautical engineering from the Technical University Delft. During his studies for his MSc degree, Michiel has been training at the Southern California Safety Institute (SCSI) and received both the certificate of aircraft accident investigation and cabin accident investigation. As part of his masters degree, he conducted a study to determine the value of photometric reconstruction in accident investigation. The following paper is a summary of this study.*

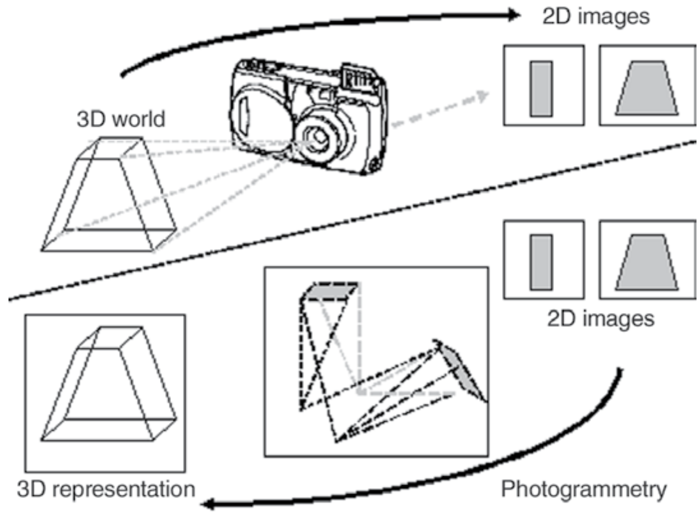


***Figure 1. Relationship photography and photogrammetry.***

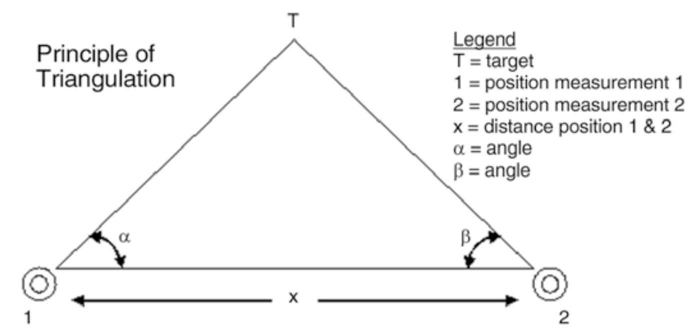


***Figure 2. Principle of triangulation.***

## Introduction

During the investigation of the CI611 accident, the Aviation Safety Council (ASC) of Taiwan developed a three-dimensional (3-D) software reconstruction program that has greatly advanced accident reconstruction. Using a laser scanner, investigators were able to digitize recovered wreckage and create a computer model. This model was then successfully used by investigators to determine the sequence of events. Traditional 3-D hardware reconstruction was replaced by a less-expensive 3-D software reconstruction; a new tool in accident investigation was developed.

A more traditional way of reconstructing the accident sequence is to use accident scene photographs. This is why investigators take numerous photographs at an aircraft accident site. This raises the question Is there a way to make better use of accident scene photographs? Is it possible to use these accident scene photographs to obtain a 3-D reconstruction model as has been done by the ASC of Taiwan? And what details and information can aircraft accident investigators gather using photometric reconstruction techniques?

## The science of photogrammetry

Photogrammetry is the science of precise measurements using photographs. Although photogrammetry is mainly used in earth observation and (road) map making, other areas of application are being explored. For example, photogrammetry can also be used to produce a 3-D representation of an object. However, a photograph is a flat two-dimensional (2-D) image representing the (real) 3-D world. As a consequence, the dimension depth is lost in the process of taking photographs (Figure 1). In other words, the camera maps a three-dimensional point of an object onto a two-dimensional image. With photogrammetry, this lost (third) dimension can be reconstructed.

Using the principle (see Reference note) of triangulation (Figure 2), the location of a point (target) can be calculated in all three dimensions of space. The two-dimensional (x, y) location of the "target" is measured on the image to produce the line of sight. By taking pictures from at least two different locations and measuring the same target in each picture, a "line of sight" is developed from each camera location to the target. If the camera location and aiming direction are known, the lines can be mathematically intersected to produce the global XYZ coordinates of each targeted point. The ideal situation would require only two photographs to reconstruct the third dimension. In most cases, however, multiple images are needed to increase accuracy and compensate for image/recording imperfections.

The overall accuracy that can be accomplished by photogrammetry depends on several factors such as object size and geometry. The number of photographs and resolution increase or decrease the accuracy also. When high-quality photographs are taken the right way and sufficient reference points can be identified, the inaccuracy is between 0.5–2%. The discussion on the four factors influencing the accuracy is beyond the scope of this paper and will not be discussed.

## Using photogrammetry

During the study, three different techniques were used and examined. The first photometric technique focused on scene reconstruction. The second technique focused on both the acquisition and analysis of the 3-D model (comparison and overlay). The third technique is the inverse camera technique. This technique does not reconstruct an object but uses photogrammetry to reconstruct camera position. This technique and the two object reconstruction techniques will next be discussed in more detail.

*Photometric technique #1—Scene/object reconstruction*

Photometric (and laser) reconstruction allows investigators to digitize the accident scene. In this way not only relevant documents but also the accident scene itself can be stored electronically. The mental picture of a scene an investigator has gathered at an accident site can now also be conveyed to investigators or people who were not present at the accident scene. A laser scanner scans the whole scene and gives a mesh that needs to be filtered and adapted for use. Photogrammetry allows the investigator to reconstruct a single object or important feature. In some instances, only partial features are important and a scene mesh is unnecessary. Although in some cases this will be of great benefit, the investigator should use care when applying this technique. Information is lost when performing a partial reconstruction and might hide another important piece of information.

*Photometric technique #2—Damage overlay*

Another photometric technique is the damage overlay; the goal of the overlay is to illustrate the damage and compare it to an undamaged (pristine) model. By comparing a pristine and accident model, the extent of damage found at the accident scene can be grasped by others. To create an overlay, a couple of steps have to be taken.

The first step is to create a reference model. Photographs of a similar aircraft type and model have to be taken. A major advantage was found in this instance. Because of the high degree of uniformity of aircraft (certification), making a reference model is easy. It has been demonstrated that using an identical aircraft of the operator, photometric reconstruction is made even easier. Operator logo and other specific aircraft markings allow for easy photograph referencing. In other modes of transport with uniformity in types and models, this technique is also applicable. However, it has been found that in the marine world with large ships and tankers deviations are common. Thus care must be taken when performing overlay and choosing a reference model.

The second step is to take the photographs of the same type and model and create the 3-D reference model. Photomodeler together with operator input create a digital 3-D model that can be exported as an AutoCAD or other 3-D coordinate file.

The next step is to "freeze" the 3-D coordinates of the reference model. This can be done by importing the 3-D (AutoCAD) coordinates obtained by the previous photometric reconstruction. Now the accident photographs can be used and the reference model can be positioned. When these points are chosen the right way, an overlay has been created.

The last step is to compare the accident model and the 3-D reference model (Figure 3). Depending on the availability of a reference model, a damage overlay can be created within a day.

In summary, the steps for creating a photometric damage overlay are

- obtain reference model photographs,
- build reference model,
- "freeze" reference model (points), and

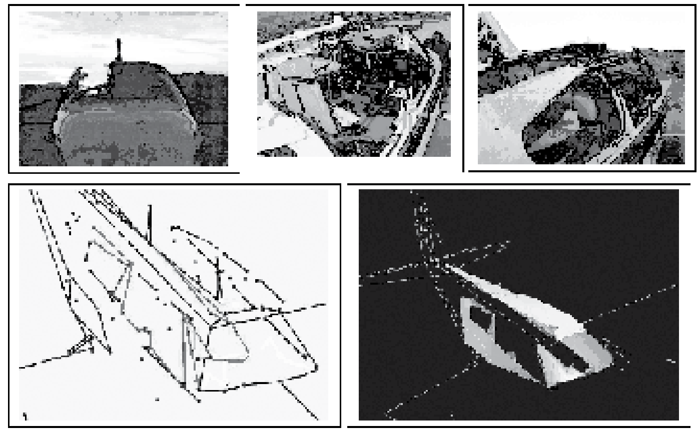

***Figure 3. Overlay technique; Barron B55 Mid air collision (Lower illustrations: black/light gray = normal, dark gray = damage)***

- object reference using accident photographs to frozen model.

In order to create an overlay using a laser scanner, different steps have to be taken as stated above. Both models must be laser scanned and acquired. Next, the two models need to be exported into a 3-D modeling (CAD) program. After this has been done, the investigator is able to compare the two models. With a photometric program, this export/import is not necessary. Both object photographs can be used and compared in Photomodeler itself.

*Photometric technique #3—Inverse use of photographic material*

The same technique to acquire a 3-D image using a photograph can be used in reverse to determine the position of the camera at the time a photograph was taken. Using objects as references and knowing the camera lens, the third unknown camera position can be determined. Research found that the Transportation Safety Board of Canada (TSB) has performed photometric analysis on a number of occasions in the past. The TSB Engineering Branch took film found at an accident scene and developed the photographs. From these photographs, a flight track (different positions in time) and aircraft height could be determined.

## Effectiveness of photogrammetry in accident investigation

Several safety boards throughout the world use or have used laser reconstruction in the past for model acquisition. At an early stage of the investigation a decision has to be made whether to perform a laser scan of the accident scene. When a decision has been made, the area to be scanned has to be cleared, after which the accident scene can be digitized. Next, this model is exported and used for analysis purposes. Another application, as has been done by the ASC, is to digitize wreckage pieces of an aircraft after for, example, a mid-air breakup. In this case, a decision to make a laser scan and a 3-D model can be delayed.

A laser scanner scans the whole scene and gives a mesh that needs to be filtered and adapted for use. Photometric reconstruction allows a partial reconstruction of the accident scene. When photographs are taken in a correct way, it is even possible to reconstruct the accident at a later date. In case of a major accident or limited onsite resources, the reconstruction can be done at the safety board itself.

On-scene reconstruction can be done using a digital camera and laptop. Using multiple sources of photographs (two or more investigators) a more rapid reconstruction can be obtained. When precise measurements are needed, additional requirements have to be met (high-quality good positioned photograph and calibrated camera).

Acquisition of general aviation aircraft and a generic accident model is straightforward. An increase in complexity of aircraft and accident scene requires more human resources, which decreases the benefit of photometric reconstruction. Although no study has been performed, a combination of photogrammetry and laser reconstruction may complement each other.

A 3-D model supplements accident scene photographs and is effective for analysis purposes. Is has been acknowledged that the 3-D reconstruction model is emotionless. It is, therefore, suitable to inform the investigative group or board members on the progress of the investigation. The scene reconstruction model further allows investigators to take a "different look" at an accident and its surroundings. This can be achieved without having to make photographs of all different angles. In the case of a major accident, a photometric model can visualize the accident and enable the IIC to point out the areas of interest. The virtual model can be used for the daily briefings to point out the position of the wreckage piece.

The digitalization of the accident, the accident scene, and accident models, opens up the possibility for safety boards to send the accident scene electronically to other safety board for consultation and analysis. A comparison can be made between two accidents, and vital information may be derived from that. Although no further research has been performed, in the future safety boards may be able to even exchange digital information on failures of aircraft components.

The third photometric technique focuses on the use of images taken by passengers or witnesses of an accident. Using photogrammetry, the investigator is able to derive a number of parameters (for example, aircraft height) within a certain error margin depending on the camera.

### Value of photometric reconstruction

Photometric reconstruction is more flexible compared to laser reconstruction. The model or scene acquisition using a laser has to be done at an early stage of the investigation. Reconstruction using photogrammetry can be done onsite using a laptop or offsite when the photographs are sent to the safety board headquarters. Photogrammetric reconstruction compared to laser scanning is very inexpensive—the investment is small and no extra equipment has to be taken to the accident scene.

It is apparent that photogrammetry is a flexible method that can be used when necessary. Photometric reconstruction shows different areas of application, which is useful in an investigation. This thesis has only touched the surface of photometric reconstruction. It is recommended to further develop this methodology and look at the different photometric techniques in more detail. ◆

### Acknowledgments

Aviation Safety Council (ASC), Taiwan—M. Guan Ph.D.
Dutch Safety Board (DSB), Netherlands—G.J. Vogelaar, LL.M. BSc., et al.
Transportation Safety Board of Canada (TSB)—J.H. Garstang, P. Eng.

### Reference

In trigonometry and elementary geometry, triangulation (see Figure 2) is the process of finding a distance to a point by calculating the length of one side of a triangle, given measurements of angles and sides of the triangle formed by that point and two other reference points.

Some identities often used (valid only in flat or Euclidean geometry):
The sum of the angles of a triangle is (180 degrees).
- The law of sines
- The law of cosines
- The Pythagorean Theorem

Using a number of observations, a solution of position can be obtained. In most instances, a large number of observations are simultaneously solved and thus the positions calculated.

# Do You Smell Smoke? Issues in the Design and Content of Checklists for Smoke, Fire, and Fumes

By Barbara K. Burian, Ph.D., SJSUF at NASA Ames Research Center

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## Abstract

An inflight smoke or fire event is an emergency unlike almost any other. The early cues for nonalerted conditions, such as air conditioning smoke or an electrical fire, are often ambiguous and elusive. Crews may have very little time to determine if there really is smoke, fire, or fumes, and if so, to locate the source and extinguish it. The checklists crews use for these conditions must help them respond quickly and effectively and must guide their decisions. A small group of individuals from the aviation industry has recently developed a template to be used for the design of nonalerted smoke, fire, and fumes checklists. In this paper I discuss some of the issues addressed by this template and implications this guidance has for the design of checklists for these time-critical events.


## Introduction

When a smoke, fire, or fumes (SFF) event occurs in flight, time is the most precious resource available to crews. Yet, at least some of this resource must be invested to determine if suspicious cues do in fact indicate smoke or fire, as cues are often ambiguous, especially for air conditioning, electrical, and other nonalerted sources (i.e., SFF for which there are no aircraft detection systems). Also, false alarms occur frequently enough (e.g., Blake, 2000) to make crews want to have a definitive picture of their situation before committing to a diversion and emergency landing.

When smoke or fire does occur, a cascading loss of systems is likely if it spreads, and crews' ability to respond effectively may be impaired (e.g., National Transportation Safety Board (NTSB), 1974, Transportation Safety Board (TSB) of Canada, 2003). Thus, rapid isolation and elimination of the ignition source are necessary to prevent the condition from escalating. However, timely decisions to divert and complete an emergency landing are also essential if the ignition source cannot be identified or if efforts to extinguish a fire are unsuccessful.

The stress and workload of responding to these events is exceptionally high and unlike many other types of emergency or abnormal situations, the flight and cabin crews absolutely must communicate and coordinate their assessment and response. However, even the most rigorous joint training cannot realistically present crews with the full extent of the demands they will face when dealing with smoke, fire, and fumes in flight.

Checklists are indispensable tools to guide crews' decision-making and response when faced with multiple tasks during these high-stress events. Checklist designers must carefully consider all essential tasks crews must perform and prioritize how those tasks are to be accomplished, given the wide range of potential SFF events: those that are easily identified, isolated, and extinguished as well as those whose sources are unknown, hidden, and cannot be put out. This paper will focus on some of the many design and content issues for checklists that are used by flight crews to respond to nonalerted SFF events. Current titles of such checklists typically refer to the ignition source (e.g., air conditioning smoke; electrical smoke, fire, or fumes; fluorescent light ballast smoke or fire), to the location of the event (e.g., galley fire, cabin fire), or to the fact that the ignition source and/or location is unknown (e.g., fires of unknown origin).

## Issues in nonalerted SFF checklist content and design

A variety of difficult issues face designers of all emergency and abnormal checklists but particularly checklists involving inflight SFF. Several are listed below in the form of questions; they are examined more thoroughly in a document that is currently in preparation (Burian, 2005).

- What is the best way to help crews access the correct checklist quickly, especially when they may not be able to tell what kind of SFF they are dealing with?
- How many checklists for nonalerted SFF are necessary?
- What is the best way to guide crews when the SFF is of an unknown origin/hidden?
- What should the relationship be, if any, regarding the completion of nonalerted SFF checklists if an alerted checklist (e.g., engine fire, cargo fire) is ineffective?
- What size font should be used to increase checklist readability in a smoke-filled cockpit?
- What colors of text and background are the most readable if there is smoke?
- Do choices of font size and color of text and background differ if the checklist is presented in an electronic format as compared to paper?
- What is the best way to design a checklist that accommodates the normal cognitive performance limitations the crew may experience under the high stress and workload typical of SFF events?
- Should any memory items be included, and if so, involving what actions?
- Should the donning of smoke masks and goggles be required?
- How long should a SFF checklist be—both in terms of physical length but also in terms of amount of time it takes to complete it?
- What is the best way to design a checklist that has applicability for serious SFF events as well as for SFF that is relatively minor and easily eliminated?

- How much time should crews spend on source identification/troubleshooting?
- Within a checklist, what should the relative priority of items be for a) source identification, b) smoke removal, c) descent initiation, and d) fighting/extinguishing a fire?
- Should crews be prompted to divert and, if so, where in the checklist should this guidance be given?
- Should guidance regarding different descent profiles be included in a SFF checklist?
- What kind of special guidance, if any, should be given to crews who are transporting dangerous goods (hazardous materials)?
- Should checklist actions differ for extended-range operations as compared to actions for flights flown over land?
- What kind of guidance, if any, should be given related to expediting a descent/approach, ditching, conducting an overweight landing, an off-airport landing, a downwind landing, or other types of non-normal landings?
- What is the best way to construct a SFF checklist to accommodate and support the high degree of communication and coordination that is needed between flight and cabin crews?

Part of what makes responding to some of these issues so difficult is that they involve tradeoffs that require making choices that may conflict with each other. For example, toxic fumes and smoke can quickly enter a cockpit during a SFF event. Therefore, oxygen masks and goggles should be donned by a flight crew at the first sign of SFF (NTSB, 1998). On the other hand, oxygen masks can make communication difficult and goggles can restrict one's vision; should donning such protective gear be required if the SFF event is unlikely to cause the flight crew difficulty (e.g., a burned muffin in the back galley)?

### Drivers of nonalerted SFF checklist design and content

Various interrelated factors have traditionally influenced how the issues listed above are dealt with but not *all* of these factors have affected the design of *every* nonalerted SFF checklist currently in use (Burian, 2005). These factors are

*Differences in aircraft equipment design*. Obviously, the way a particular system and aircraft is designed will largely determine the steps crews are to take to isolate and eliminate a source of SFF. Aircraft design will also affect steps taken to remove smoke. For example, smoke removal in some aircraft requires depressurization, thus necessitating a descent from cruise altitude when passengers are on board.

*Different types of operations*. Different procedures may be desired for extended-range operations (i.e., involving flight over an ocean) as compared to those for short-haul operations flown within easy reach of land. Similarly, procedures such as depressurizing an aircraft to minimize the amount of oxygen available to feed a fire may be appropriate for cargo-only operations (NTSB, 1998) but, of course, not when transporting passengers.

*History of an air carrier and history within the industry*. Lessons learned from earlier SFF events that have occurred within an air carrier as well as those that have occurred across the aviation industry as a whole clearly influence the design and content of SFF checklists and the priority placed on items within them (NTSB, 1998, TSB of Canada, 2003).

*Knowledge of how different types of fires are ignited, fed, and spread*. Closely related to an understanding of how differences in aircraft and system design influence procedures is knowledge of how various types of fires are ignited, the availability and flammable properties of various materials aboard the aircraft, and how smoke and fire may be spread (such as by a ventilation system).

*Assumptions about efficacy of crew response*. Some current checklists appear to be written with the implicit assumption that the actions specified will be successful (or that guidance about other actions is not necessary); in other words, there are no references to diverting or instructions regarding smoke evacuation included in the checklists. Likewise, some checklists may take quite a bit of time to complete, seeming to imply that time is not a factor when responding to the event. Also, many procedures assume that the crew is aware of the type/source/seriousness of SFF and thus can readily identify and execute the appropriate checklist or procedure, leaving crews uncertain about how to proceed in more ambiguous situations. These implications and assumptions are inherent in the design of the checklists and may not have even been apparent to the developers who constructed them.

*Human factors considerations.* A larger-than-normal font size is used for some SFF checklists to make them easier to read when smoke is in the cockpit. Attention is also sometime given to accommodate stress-induced human performance limitations. For example, in one of the SFF checklists provided to the crew of Swissair 111 (TSB of Canada, 2003), a great deal of information was provided regarding aircraft limitations when configured in a particular manner, thereby reducing crews' cognitive processing requirements and memory load.

*Regulations, advisory, and guidance material*. Often (but not always) as a result of accidents or incidents involving SFF, various regulations, recommendation letters, bulletins, advisory circulars, and other guidance materials are developed that pertain to the design and content of checklists (e.g., FAA, 1996).

*Various philosophies, company policies, and economic considerations*. Of course, philosophies (both implicit and explicit) and company policies may influence SFF checklist design and content, as can a variety of economic considerations related to the handling of these events (e.g., cost of diversions in terms of fuel, scheduling issues, etc.). Many of these issues implicitly shape procedures and guidance for crew response and are not a part of any stated policy or philosophy.

### New industry approach to SFF checklist content and design

Because there is so much variability across air carriers in terms of types of aircraft flown, types of operations, history, philosophies, and policies, up until very recently there has been no industrywide agreed-upon approach regarding crew response to SFF events and the design and content of checklists that guide this response. However, beginning in 2004, a small group of individuals (a "steering committee") began meeting to develop checklist content and design guidance that could be adopted across the industry. The committee was comprised of individuals representing four major aircraft manufacturers (Airbus, Boeing, Bombardier, and Embraer), the International Federation of Air Line Pilots Associations (IFALPA), and four air carriers (Air Canada, British Airways, Delta, and United). During the development process, one meeting was also held, which I attended, whereby feedback was solicited from individuals representing other industry groups (e.g., FAA, NASA, NTSB, TSB of Canada, etc.).

The steering committee has recently completed two products it hopes will be adopted by the international aviation industry as the standards that will guide the design and content of nonalerted SFF checklists. One product is a template to be used by designers when developing a nonalerted SFF checklist (see Appendix A) and the other is a description of the philosophy upon which the template is founded, as well as a few definitions of various terms and concepts used in the template (see Appendix B). Both products are currently available through the Flight Safety Foundation. It is important to note that the template is not, in and of itself, a checklist. As its name states, it is a framework to guide checklist design and content. Some of the steps on the template are actually sections and several checklist items might be developed for a single template "step." The accompanying philosophy and concept definitions must also be consulted during checklist development so that the resulting checklist is truly in keeping with the intent of the template.

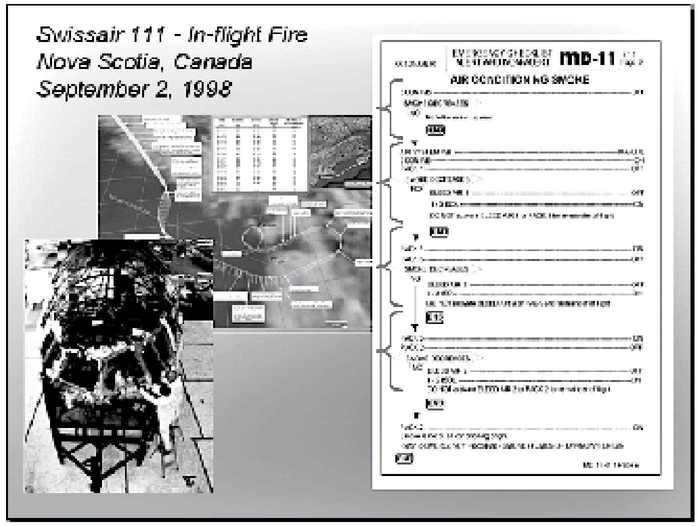
Below I discuss a few of the SFF checklist issues listed earlier as they are typically treated in current checklists and also as they are treated in the newly developed template/philosophy. In this discussion you will see that the template/philosophy represents a significant change in the approach to these issues and that some of the difficult tradeoffs these issues pose have been addressed.

**Access—separate checklists vs. an integrated checklist**

Currently, when crews wish to complete a checklist for a nonalerted SFF situation, they must typically access a checklist that has been developed for a specific type of smoke, fire, or fumes, e.g., air conditioning smoke, electrical smoke, fire, or fumes, etc. Thus, crews are presented with a list of several different SFF checklists and they must first determine what type of SFF they have in order to select the proper checklist from the list. However, recall that the cues for nonalerted events are often quite ambiguous and making a distinction between air conditioning, electrical, materials, florescent light ballast, dangerous goods (i.e., hazardous materials), or some other type of SFF can be quite difficult. Precious time may be wasted if a crew was to complete a checklist for one type of SFF but, in reality, was faced with a different type.

In response to these issues, several air carriers (e.g., Delta, United) have independently developed a single integrated checklist to be used for multiple types of nonalerted SFF events. With such an integrated checklist, the time crews would initially spend trying to figure out which checklist to complete is actually spent by completing actions that have applicability for all types of nonalerted events. Similarly, the template developed by the steering committee is for an integrated nonalerted SFF checklist. As can be seen in Appendix A, the first 11 steps/sections are to be accomplished irrespective of the specific type of SFF faced. Actions that are pertinent to specific types of SFF are to be grouped according to SFF type and appear in Sections 12, 13, and 14 of the template.

Even though the template guides development of a single checklist to be used for multiple types of SFF events, crews may still be required to access more than one checklist during their response to such events, however. For example, the template and philosophy call for crews to refer to a separate smoke removal checklist when necessary, and to return to uncompleted sections




of the nonalerted SFF checklist, if any, following smoke removal. (A template for the separate smoke removal checklist was not developed by the steering committee; manufacturers and/or air carriers are expected to provide them.)

The philosophy document states that a checklist developed using this template "does not replace alerted checklists (e.g., cargo smoke) or address multiple events" (see Appendix B). Some air carriers, however, may choose to have their crews complete the integrated nonalerted SFF checklist after having completed an alerted checklist if the alerted checklist did not resolve their situation. Thus, these crews would need to access two SFF checklists (one each for alerted and nonalerted events) and possibly also a third (for smoke removal). The use of the nonalerted checklist following completion of an ineffective alerted checklist is not addressed by the template or accompanying philosophy document.

**Diversion and landing guidance**

Giving guidance to crews to divert and complete an emergency landing, and *when* crews should be given this guidance are some of the most hotly debated issues in the design of nonalerted SFF checklists. In many current nonalerted SFF checklists, guidance to complete a diversion and/or emergency landing is given as one of the last steps, if it is given at all, and the guidance to complete such a diversion is only pertinent if efforts to extinguish the SFF were unsuccessful (e.g., TSB of Canada, 2003, NTSB, 1998). The philosophy implicit in this design is that continued flight to a planned destination is acceptable if inflight smoke or fire is extinguished. If crews follow these types of checklists exactly as written, a diversion is initiated only after the completion of steps related to other actions, such as crew protection (i.e., donning of oxygen masks and goggles), establishing communication and source identification, troubleshooting, source isolation, firefighting, and smoke removal, and then only if the SFF is continuing.

In a study of 15 inflight fires that occurred between January 1967 and September 1998, the TSB of Canada determined that the amount of time between the detection of an onboard fire and when the aircraft ditched, conducted a forced landing, or crashed ranged between 5 and 35 minutes (TSB of Canada, 2003). These findings indicate that crews may have precious little time to complete various checklist actions before an emergency landing needs to be completed and, hence, the checklist guidance to initiate such a diversion should be provided and should appear early in a checklist.

However, some types of fire or smoke may be relatively simple to identify and extinguish, such as a burned muffin in a galley oven. Few people would argue that an emergency landing is necessary in such a situation and it is undesirable to complete an unscheduled landing unnecessarily because of the many safety and operational concerns involved (e.g., tires bursting and possible emergency evacuation after an overweight landing). Thus, developers struggle with the priority to place on guidance to complete a diversion in nonalerted SFF checklists.

In the newly developed template, the very first item states that "Diversion may be required." The intent of this item, and the reason it appears first in the checklist, is to "establish the mindset that a diversion may be required." (See Appendix B) The placement of this item as the very first in a SFF checklist represents a significant change from the current philosophy about how crews are to respond to SFF events described above. It is not intended that crews read this item as direction to immediately initiate a diversion or even begin planning a diversion, however, just that they should keep in mind that a diversion may be necessary. It is possible that under stress, crews may misread this item and begin a diversion right away, so training and/or a change in wording to emphasize that they are only to *remember* that diversion is an option may be needed (e.g., remember that a diversion may be necessary).

One other concern about this item as it appears in the template is that it is followed by three items that currently are often completed from memory during SFF events: crew protection items (donning smoke masks and goggles—Steps 2 and 3) and establishing crew communication (Step 4). Neither the template nor the accompanying philosophy mentions anything about items on the checklist being or not being completed from memory—this decision is left up to the individual air carriers and manufacturers using the template. Crews who complete these actions from memory, whether by requirement or out of habit, may miss the first item reminding them about a possible diversion unless it, too, is considered a memory item.

Step 10 is the first place in the checklist where crews are specifically directed to "Initiate a diversion to the nearest suitable airport" and they are to do this "while continuing the checklist." (See Appendix A) This step follows five steps (5, 6, 7, 8, 9) pertaining to source identification and/or source isolation/elimination. The steering committee believe that crews will be able to complete all of actions in these five steps fairly quickly—the philosophy even states "Checklist authors should not design procedures that delay diversion." (See Appendix B) Thus, using a checklist developed according to the template, crews will complete self-protection and establishing communication items (Steps 2, 3, and 4), five sections of "quick" actions to eliminate probable sources of SFF and then initiate a diversion in Step 10 if the earlier actions to eliminate the SFF source were unsuccessful. A more-thorough discussion of the source identification, isolation, and elimination items in Steps 5 through 9 is provided below.

Following Step 10, wherein crews are directed to initiate a diversion, the template includes the following: "Warning: If the smoke/fire/fumes situation becomes unmanageable, consider an immediate landing." If "landing is imminent" (Step 11) crews are directed to review various operational considerations (e.g., "overweight landing, tailwind landing, ditching, forced off-airport landing, etc.") and to accomplish a separate smoke or fumes removal checklist, if needed. The nonalerted SFF checklist is then "complete" and crews are left to focus upon landing the aircraft (see Appendix A). Thus, landing has a higher priority at this point than the continued completion of additional SFF identification items, such as those in Sections 12, 13, and 14.

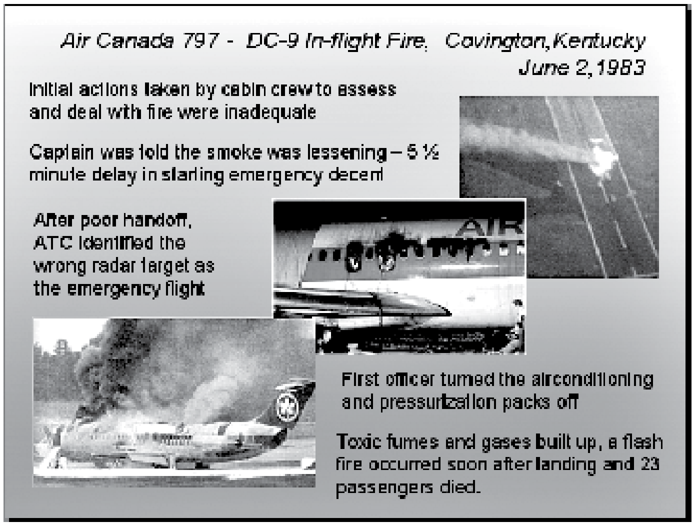
The last template step involving guidance to land is Step 15: "Consider landing immediately." (See Appendix A) Crews will reach this step only if all checklist actions involving source identification, isolation, and elimination within the checklist were ineffective and the SFF was continuing. It is difficult to imagine a situation such as this where the crew would not choose to land immediately.

It may not have been obvious from the discussion above but the template never directs crews to initiate a *descent*—only a diversion. Some in the industry believe that at the first sign of SFF, crews should initiate a descent to the minimum enroute altitude or get fairly close to the water if flying over the ocean. This would allow a crew to complete the descent and landing/ditching quickly in the event that a situation becomes uncontrollable. Others in the industry point out that such a descent may commit a crew to completing an unscheduled landing as they may no longer have enough fuel to reach their planned destination (due to the higher rate of fuel consumption at lower altitudes). The template is constructed so that crews will always have the option to continue to their planned destination if the source of SFF "is confirmed to be extinguished and the smoke/fumes are dissipating." (See Appendix B)

## Source identification/isolation/elimination

In many current nonalerted SFF checklists, a number of items are devoted to identifying the specific source of SFF and concurrently isolating and eliminating it. Thus, in a checklist for air conditioning smoke, crews are often told to, in a stepwise fashion, turn off various pack switches, bleed air switches, and other air conditioning system components and, after each configuration change, make a determination about whether the smoke is continuing or decreasing. If it is continuing, crews are commonly instructed to reverse the action(s) just taken (i.e., turn the switch(es) back on) and proceed with making the next configuration change. The checklist template developed by the steering committee also includes a place for such system-specific source identification items (Sections 12, 13, and 14), but these actually appear after three other steps (or sets of steps) involving source identification and/or source isolation/elimination. All source identification/isolation/elimination steps are discussed below in the order in which they are presented to crews on the template.

*Step 5*. Following the completion of crew self-protection and communication steps, crews would complete items related to template Step 5, which states "Manufacturer's initial steps... Accomplish." (See Appendix A) In the accompanying philosophy, "manufacturer's initial steps" are described as those "that remove the most probable smoke/fumes sources and reduce risk….These steps should be determined by model-specific historical data or analysis." (See Appendix B) Furthermore, the philosophy specifies that these initial steps "should be quick, simple, and reversible; will not make the situation worse or inhibit further assessment of the situation; and do not require analysis by the crew." (See Appendix B) Thus, when using a checklist designed according to the template guidance, crews will eliminate the most likely sources of SFF early on in checklist completion *without* making a determination first as to whether one of these sources is in fact




causing the smoke, fire, or fumes; this step involves source isolation/elimination but *not* source identification.

*Steps 6, 7, and 8*. In Step 6 crews are asked if the source of the SFF "is immediately obvious and can be extinguished quickly" and, if so, are told to extinguish it in Step 7. (see Appendix A) In Step 8, if the "source is confirmed visually to be extinguished" it is suggested that crews consider reversing the manufacturer's initial steps accomplished in Step 5, presumably if they know which actions were and were not related to causing the SFF although this is not addressed in the template. It is then suggested that crews complete a smoke removal checklist, if necessary, and this marks the completion of the nonalerted SFF checklist. These three steps have been developed for those types of smoke or fire that are relatively simple to identify and extinguish (recall the burned muffin in a galley oven). Note that if extinguishing is successful and can be *visually* confirmed, continued flight to the planned destination is implied.

The steering committee believes that these steps will be quick and easily accomplished. However, identifying a source of SFF (even when it appears to be obvious) and then extinguishing it can take some time. For example, imagine that a burned muffin in a galley oven is the source of smoke/fire. Cabin crew must let the flight crew know there is smoke/fire, confirm that a muffin is the source (and not something like an electrical short in the oven), turn off the oven, possibly locate a fire extinguisher, put out the fire with the extinguisher or by some other method (e.g., put the smoking muffin in the sink and douse it with water), respond to passenger questions/concerns, confirm that the fire/smoke is extinguished, and get that information back to the flight crew. Thus, even relatively simple events can take some time to resolve. As a result, Steps 6 and 7 in the template represent a bottleneck, but the time these actions require cannot be helped. Crews should be aware of this and in training, they may wish to address how much time should be devoted to these efforts before moving on to subsequent items on the checklist.

*Step 9*. The 9th step of the template states. "Remaining minimal essential manufacturer's action steps… Accomplish" and is followed by a note to the checklist developer indicating that "These are steps that do not meet the 'initial steps' criteria but are probable sources." (See Appendix A) This step was one of the last to be added to the template during its development, and no other information pertaining to it is included in the philosophy document. Therefore, what is meant by "minimal essential" is unclear. However, because the additional note specifies that these steps still pertain to "probable sources," it can probably be safely inferred that crew analysis should still *not* be required when completing them.

During the feedback meeting with the larger industry group, one manufacturer representative to the steering committee expressed the need for crews to be able to complete quick and simple items that did not entail crew analysis but might *not* be able to be reversed or *might* inhibit further assessment of the situation (by cabin crew). Thus, these additional steps would meet only some of the criteria for the "initial steps" in Section 5. It is likely that Section 9 was added to meet this need expressed by the manufacturer.

*Steps 12, 13, and 14*. As mentioned earlier, according to template specifications, traditional types of source-specific identification, isolation, and elimination actions are included in Sections 12, 13, and 14, with each section including items for a different aircraft system (for example, section 12 might include items for systematically identifying and isolating an electrical source of SFF). The actual steps to be included within these sections are to be determined "based on model-specific historical data or analysis." (see Appendix B) Although it is not explicitly stated in the philosophy document, historical data for a particular aircraft model could also be used to determine the *ordering* of the various system-related items across Steps 12, 13, and 14. Thus, if aircraft model X has historically had more problems with air conditioning smoke than any other type of SFF, source identification and isolation items for air conditioning smoke or fumes would be presented first (i.e., in Section 12).

After each of the system-specific sections of items is completed, the crew is to determine if their efforts have been successful (i.e., the fire is extinguished, the smoke is dissipating). If so, they are to skip the remaining system-specific sections. If their actions were not successful, they are to complete the next set of system-specific items. For example, if the actions related to Step 12 in the template are not successful, they should complete items related to Step 13. If Step 13 actions *are* successful, they should not complete the items in Section 14. Once crews have completed a set of system-specific items that have successfully dealt with the SFF, the template directs them to review operational considerations for their landing and accomplish a smoke removal checklist, if necessary (recall that if crews are completing any system-specific items in Steps 12, 13, or 14, they should concurrently be diverting and conducting an emergency landing as directed in Step 10).

Thus, in contrast to some current nonalerted SFF checklists, checklists developed according to the template include both system-specific source identification items as well as smoke elimination items that do not require source identification. Additionally, crews may complete a template-driven checklist successfully (i.e., fire is extinguished, smoke is dissipating) without ever having positively identified the source of the SFF.

## Conclusion

The construction and design of checklists to be used for nonalerted SFF events is very challenging. The types of events for which they might be needed vary widely, but, at their extreme, are highly time critical and life threatening. Additionally, the cues available to crews may not be very helpful in determining their situation and at times may actually be misleading. The steering committee that developed the attached template and supporting philosophy document should be commended for addressing a number of difficult issues and for helping to move the industry forward in thinking differently about response to inflight SFF. There are a number of other issues beyond the scope considered by the steering committee that checklist designers will also need to consider, however (Burian, 2005). The treatment of these issues within a SFF checklist will not necessarily contradict the framework for response established within the template, but will also need to be addressed as nonalerted SFF checklists are developed.

**Acknowledgements**
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## Appendix A

Smoke/Fire/Fumes Checklist Template

1. Diversion may be required.
2. Oxygen masks (if required) .................................... On, 100%
3. Smoke goggles (if required) ............................................ On
4. Flight crew and cabin crew communication ............ Establish
5. Manufacturer's initial steps[1] ...................................... Accomplish

If smoke or fumes become the greatest threat, accomplish *Smoke or Fumes Removal Checklist,* page __.[2]

6. Source is immediately obvious and can be extinguished quickly:
If yes, go to Step 7.
If no, go to Step 9.
7. Extinguish the source.
If possible, remove power from affected equipment by switch or circuit breaker on the flight deck or in the cabin.

8. Source is confirmed visually to be extinguished:
If yes, consider reversing manufacturer's initial steps. Go to Step 17.
If no, go to Step 9.

9. Remaining minimal essential manufacturer's action steps .... ............................................................................. Accomplish
[These are steps that do not meet the "initial steps" criteria but are probable sources.][3]

10. Initiate a diversion to the nearest suitable airport while continuing the checklist.

Warning: If the smoke/fire/fumes situation becomes unmanageable, consider an immediate landing.

11. Landing is imminent:
If yes, go to Step 16.
If no, go to Step 12.

12. XX system actions[4] ...................................................... Accomplish
[Further actions to control/extinguish source.]
If dissipating, go to Step 16.

13. YY system actions ............................................ Accomplish
[Further actions to control/extinguish source.]
If dissipating, go to Step 16.

14. ZZ system actions ............................................. Accomplish
[Further actions to control/extinguish source.]
If dissipating, go to Step 16.

15. Smoke/fire/fumes continue after all system-related steps are accomplished:
Consider landing immediately.
Go to Step 16.

16. Review *Operational Considerations,* page __.

17. Accomplish *Smoke or Fumes Removal Checklist,* if required, page __.

18. Checklist complete.

**Operational Considerations**

[These items appear after "checklist complete." This area should be used to list operational considerations, such as an overweight landing, a tailwind landing, a ditching, a forced off-airport landing, etc.]

Notes
1. These aircraft-specific steps will be developed and inserted by the aircraft manufacturer.
2. The page number for the aircraft-specific *Smoke or Fumes Removal Checklist* will be inserted in the space provided.
3. Bracketed text contains instructions/explanations for the checklist author.
4. "XX," "YY," and "ZZ" are placeholders for the environmental control system, electrical system, inflight entertainment system, and/or any other systems identified by the aircraft manufacturer.

## Appendix B

Smoke/Fire/Fumes Philosophy and Definitions

This philosophy was derived by a collaborative group of industry specialists representing aircraft manufacturers, airlines/operators and professional pilot associations. The philosophy was used to construct the *Smoke/Fire/Fumes Checklist Template*.

### General

- The entire crew must be part of the solution.
- For any smoke event, time is critical.
- The *Smoke/Fire/Fumes Checklist Template:*

– Addresses nonalerted smoke/fire/fumes events (smoke/fire/fumes event not annunciated to the flight crew by aircraft detection systems);
– Does not replace alerted checklists (e.g., cargo smoke) or address multiple events;
– Includes considerations to support decisions for immediate landing (an overweight landing, a tailwind landing, a ditching, a forced off-airport landing, etc.); and
– Systematically identifies and eliminates an unknown smoke/fire/fumes source.

- Checklist authors should consider a large font for legibility of checklist text in smoke conditions and when goggles are worn.
- At the beginning of a smoke/fire/fumes event, the crew should consider all of the following:

– Protecting themselves (e.g., oxygen masks, smoke goggles);
– Communication (crew, air traffic control);
– Diversion; and
– Assessing the smoke/fire/fumes situation and available resources.

### Initial Steps for Source Elimination

- Assume pilots may not always be able to accurately identify the smoke source due to ambiguous cues, etc.
- Assume alerted-smoke-event checklists have been accomplished but the smoke's source may not have been eliminated.
- Rapid extinguishing/elimination of the source is the key to prevent escalation of the event.
- Manufacturer's initial steps that remove the most probable smoke/fumes sources and reduce risk must be immediately available to the crew. These steps should be determined by model-specific historical data or analysis.
- Initial steps:

– Should be quick, simple, and reversible;
– Will not make the situation worse or inhibit further assessment of the situation; and
– Do not require analysis by crew.

### Timing for Diversion/Landing

- Checklist authors should not design procedures that delay diversion.
- Crews should anticipate diversion as soon as a smoke/fire/fumes event occurs and should be reminded in the checklist to consider a diversion.
- After the initial steps, the checklist should direct diversion unless the smoke/fire/fumes source is positively identified, confirmed to be extinguished, and smoke/fumes are dissipating.
- The crew should consider an immediate landing anytime the situation cannot be controlled.

### Smoke or Fumes Removal

- This decision must be made based upon the threat being presented to the passengers or crew.
- Accomplish *Smoke or Fumes Removal Checklist* procedures only after the fire has been extinguished or if the smoke/fumes present the greatest threat.
- Smoke/fumes removal steps should be identified clearly as removal steps and the checklist should be easily accessible (e.g., modular, shaded, separate, standalone, etc.).
- The crew may need to be reminded to remove smoke/fumes.
- The crew should be directed to return to the *Smoke/Fire/Fumes Checklist* after smoke/fumes removal if the *Smoke/Fire/Fumes Checklist* was not completed.

### Additional Steps for Source Elimination

- Additional steps aimed at source identification and elimination:

– Are subsequent to the manufacturer's initial steps and the diversion decision;
– Are accomplished as time and conditions permit, and should not delay landing; and
– Are based on model-specific historical data or analysis.

- The crew needs checklist guidance to systematically isolate an unknown smoke/fire/fumes source.

## Definitions

**Confirmed to be extinguished:** The source is confirmed visually to be extinguished. (You can "put your tongue on it.")

**Continued flight:** Once a fire or a concentration of smoke/fumes is detected, continuing the flight to the planned destination is not recommended unless the source of the smoke/fumes/fire is confirmed to be extinguished and the smoke/fumes are dissipating.

**Crew:** For the purposes of this document, the term "crew" includes all cabin crewmembers and flightcrew members.

**Diversion may be required:** Establishes the mindset that a diversion may be required.

**Land at the nearest suitable airport:** Commence diversion to the nearest suitable airport. The captain also should evaluate the risk presented by conditions that may affect safety of the passengers associated with the approach, landing, and post-landing.

**Landing is imminent:** The airplane is close enough to landing that the remaining time must be used to prepare for approach and landing. Accomplishing further smoke/fire/fumes-identification steps would delay landing.

**Land immediately:** Proceed immediately to the nearest landing site. Conditions have deteriorated and any risk associated with the approach, landing or post-landing is exceeded by the risk of the on-board situation. "Immediate landing" implies immediate diversion to a landing on a runway; however, smoke/fire/fumes scenarios may be severe enough that the captain should consider an overweight landing, a tailwind landing, a ditching, a forced off-airport landing, etc.

# Selecting the Next Generation Of Investigators

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## Introduction

One of the important aspects of improving aviation safety is to select the right people as Air safety investigators. While selecting a systematic and objective investigator is the goal of the selection process, seldom is the selection process itself also systematic and objective. This paper is an overview of the characteristics essential to being a successful air safety investigator and how to evaluate these traits during the selection process. The paper will go beyond the traditional approach of classifying people based on their technical skills and look at aspects such as logical thinking, objective approaches, and the ability to communicate effectively. While technical skills are important, the more process-oriented traits have shown to be critical characteristics of a good investigator that are not adequately evaluated prior to their selection. Since training programs are of limited value in dealing with these areas, the emphasis of the paper is on how to determine these characteristics prior to selecting a new investigator. Using the premise that some traits, such as a logical thought process, can be enhanced but not truly taught during a training program, the paper will concentrate on ways to evaluate these traits during the selection process.

## A review of the characteristics found in good investigators

A logical starting point for determining the desired characteristics for an air safety investigator is to look at the characteristics found in successful investigators. Admittedly, the evaluation of who is a successful investigator is somewhat subjective, but there are some objective measures that can be used. Has the investigator been directly involved in the investigation process with responsibility for results or have they been on the fringes of the investigation with little responsibility and influence? What results has the investigator produced in previous investigations? Have they been able to resolve complex issues without becoming fixated on irrelevant details? Do they work well with others and effectively elicit the expertise of others to thoroughly examine all aspects of an investigation?

While not an exhaustive list, some of the characteristics associated with good air safety investigators are

*Technical Competence*

While much of the technical knowledge necessary to perform an investigation can be learned after starting the position, the ideal candidate will already have an extensive background in the aviation industry

*Trained in the Investigative Process*

Some investigators come to a new position with experience in investigations but most do not. While there are certainly advantages to selecting an experienced investigator when the position requires an immediate contribution, many organizations prefer to train new people from the beginning rather than trying to retrain previous thought processes. Either way, there needs to be a combination of formal training and structured OJT (on-the-job training) provided to the investigator.

*Thorough*

The thorough investigator has a balanced approach to gathering factual information during an investigation. While all aspects of the accident will be considered, only the relevant facts are developed in depth. As the investigation develops, the investigator will exercise appropriate judgment of the available facts to decide what areas need more development.

*Accurate*

The facts developed and reported accurately portray the accident sequence. While the reports written may vary in the space given different subjects, that determination is a result of their relevance rather than the investigator's bias or specific background.

*Experienced*

Experience is a necessary part of being a good investigator. However, as with most occupations, for the experience to be effective it has to be varied, progressive, and mentored. There also needs to be a level of responsibility for the experience to be meaningful. While it is helpful to indirectly assist the investigative process, there is a unique learning experience when you actually have the responsibility for some portion of the investigation.

*Logical and Systematic*

The investigation is done in a sequential and consistent manner so that all the relevant facts are collected before any conclusions are formed. What happened is determined before an attempt is made to determine why it happened. The facts lead to a conclusion rather than the other way around.

*Objective*

The Investigator has an open mind and does not concentrate on any one area early in the investigation to the exclusion of other areas. Even though some evidence may quickly indicate causal factors in the accident, a thorough review is done of all of the conditions surrounding the accident. This not only provides accurate conclusions but also develops all of the contributing factors in an accident so that there is an opportunity to address the safety issues inherent in the underlying factors.

*Good Writing Skills*
The investigator's written reports create an accurate picture of the facts developed during the investigation. They are grammatically correct, accurate, timely, and create a word picture that is easily understood by the reader. While the significance of the facts reported might not be completely understandable to a layman unfamiliar with aviation, the facts themselves should be presented in a clear manner.

*Strong Interpersonal Skills*
Air safety investigators do not operate alone as technical experts who know everything about all aspects of aviation. Instead, they need to gather information from other people and rely upon the inputs of other people. Some of the information will come from aircrew members or witnesses who observed portions of the accident sequence. Other information will come from technicians who are involved in the testing of aircraft components or providing technical information. In all areas of the investigation, the interpersonal skills of the investigator will influence the quality of the cooperation and, therefore, the quality of the investigation.

*Psychologically and Physically Prepared*
Many air safety investigators will be working under stressful and physically challenging conditions. This is particularly true for those who have responsibility to respond to the accident scene or process data immediately after the accident. Since stress is a common aspect of the job, it is important to know how a prospective investigator deals with it.

*Continually Learning*
One of the subtle, but important, traits of a good investigator is the ability to continually lean new things. While this is most obvious in the technology area, it is actually more important in terms of a mind set. The investigators who "know it all" will find it very difficult to use the input from other participants in the investigation and will frequently defend inaccurate positions because they do not want to ever be wrong.

## Which investigator characteristics can training improve?

Traditionally, many organizations have selected new investigators based on their technical qualifications. A look at most recruiting announcements reveals requirements like pilot certification, number of flight hours, engineering degrees, and experience in investigations, perhaps with specific desired job titles and responsibilities. Once an individual is selected, then training is provided to enhance the weaker skills. This works well with technical skills since it is easier to quantify weak areas and provide knowledge to improve those areas. Unfortunately, thought processes and "people skills" are not so easily taught. If the selected investigator does not have a logical thought process when selected, no training course will completely change that. Certainly, there are courses that will improve these abilities, but they will not improve like technical skills can improve.

## Developing a training program for the new investigator

Once a new air safety investigator is selected, it is important to tailor the training to the individual. This starts with the orientation to the organization and carries through to the journeyman level. After that, the training shifts to maintaining some skills and developing new ones.

Most people will need a course covering the basics of investigation methodology and organizational procedures applicable to their position. For some people who are not going to be deeply involved in accident investigation, this basic overview may be sufficient exposure. However, for a professional investigator, there needs to be ongoing specialized courses to develop technical skills, as is applicable to the individual investigator's job duties. If the investigator is going to be responsible for overseeing an entire investigation, then the specialized courses might educate him or her in areas not already worked in and build on the basic subjects covered in the indoctrination course. For example, if the initial course includes an overview of inflight fires, then an advanced course in inflight fires can be planned for a few years later in the career. This provides a refresher in the principles of investigating an inflight fire as well as the opportunity for the investigator to use his or her increasing experience in the field to understand more complex techniques. If the person is a specialist, then the courses will typically involve more narrow and detailed instruction into how that specialty is incorporated into the accident investigation process. A corporate safety position may need only limited training in accident investigation but extensive education in trend analysis of data from FOQA, system safety, or incident investigation. The important point is that a training program is tailored to the individual needs of both the investigator and the organization using the investigator's services.

Formal training programs can be a valuable resource in providing help to a new investigator but they need to be coordinated with structured OJT training. Most investigators will learn more from a good mentor(s) than they will learn from the classroom. Unfortunately, many organizations do not have a structured program of mentoring new investigators.

## Techniques for selecting investigators

*Most managers select someone like themselves*
It seems that anytime the discussion about successful investigators comes up in a group of investigator managers, the opinions expressed will closely resemble the background of the manager expressing the opinion. In other words, managers tend to pick people like themselves. Complicating this situation even more, many managers feel that they are able to select good candidates based on their review of a resume and/or an interview. We expect the investigators to be objective, thorough, and systematic but we frequently don't use those same techniques in the selection process. However, using an objective and systematic approach to selecting investigators will produce a distinctively better product than the common "resume review and/or interview" approach used by so many managers.

*Suggested elements in the selection process*
Prepare for vacancies before they happen.
Whenever you can anticipate that a person will be needed in advance, you can develop sources of potential investigators and perhaps even a pool of applicants.

*Determine what it is that that you want done.*
While this sounds easy, it can be difficult to get agreement if there

are multiple people involved in the decision process. Do you want an investigator who is capable of quickly filling a critical position temporarily or do you have the time to find a potentially long-term employee who will provide continuity in the safety department for many years? Perhaps you need someone who can not only investigate a variety of accidents but also provide air traffic control expertise for the rest of the team? These qualities have to be determined ahead of time in order to produce good applicants.

*Publicize the position*

Where you publicize the position will depend on where the largest pool of potential applicants exists and the limitations on your selection process. While a newspaper ad may result in numerous calls of interest, it will probably not result in as many qualified applicants as an ad in a specialized website or an aviation magazine. However, if the qualifications are more general and you are limited to a specific geographic area, a local newspaper ad may be appropriate.

*Screen the applicants*

Review of the written applications—The first stage is to eliminate applicants who are clearly not qualified applicants and then rank the qualified applicants. It is best if someone knowledgeable about investigations and the language of aviation does this since the written applications may not always have the right "buzz words" that a personnel specialist may be looking for.

Telephone screening—Once the qualified applicants are ranked, a knowledgeable person can further screen the applicants during a telephone conversation. One recommended approach for the telephone interview is to check the accuracy of the resume by asking questions about who can confirm the experience of the applicant and asking technical questions appropriate for the level of experience listed in the resume. Unfortunately, some resumes are exaggerated, but this can usually be evaluated during the telephone interview. If the resume lists an engineering degree but the applicant can't use basic mathematical equations to solve a scenario posed to them, then the entire resume becomes questionable. If the resume isn't accurate, the reports later filed by the individual, as an investigator, may not be accurate either.

Personal interviews—It is recommended that the personal interviews be done by the hiring manager and one other person knowledgeable about the job to be filled. This provides a broader, more objective evaluation of the applicant. Likewise, if the applicants do well during the management interview, they should be introduced to several of the people they would be working with and allowed to informally discuss the job one-on-one with these staff members. The feedback from the staff will be very valuable.

Scenarios—One helpful technique is to provide scenarios to the applicants to see how they handle various situations. During the oral part of the interview, the way the applicants handle difficult scenarios may be an indication of the way they will respond to people as an investigator. Likewise, written scenarios can be used to evaluate the applicant's ability to work under stress and time constraints. Using photos and/or diagrams, applicants can be asked to write a written description of what they see. In addition, a series of increasingly difficult scenarios can be developed to evaluate the applicant's thought processes. If all of these scenarios are given to the applicant at once with a set time limit, the way the applicant allocates his or her time can be evaluated.

Background evaluations—One of the most common mistakes is not thoroughly checking an applicant's background. References given in a resume are useful, but they rarely provide any negative information about the applicant. Likewise, the current supervisor of the applicant may not provide an accurate picture of the applicant. For legal reasons, or perhaps even from a desire to get rid of the applicant, a current supervisor may have nothing bad to say about the applicant. A better source of information is previous supervisors who have nothing to gain or lose by being honest. In one actual case, a potential employee was receiving very high praise from his current supervisor, but the previous supervisor stated, "It was the happiest day in my life when he left."

The hiring managers also need to network until they find people they know or were referred to them by people they know who can give a candid evaluation of the applicant. Since the reputation of the person being interviewed is then at stake, you will usually get a more accurate evaluation of the applicant.

Select the best match—No single candidate will be the perfect candidate, but an objective review of the information gathered during the evaluation process will provide a ranking of the candidates. The person at the top of the list will not necessarily be the "best person" but the "best match" for the job at hand.

## Summary

The selection process for new air safety investigators is a critical item that requires the same thorough and objective investigation as what we give our accident investigations. The quality of the next generation of investigators needs to be established through a systematic approach of evaluating both technical and logic skills. While technical skills are necessary for a successful investigator, they can be provided through training later. However, characteristics such as logic, objectivity, and writing are very difficult to improve significantly through training, so these skills need to be identified during the selection process. Just like a good accident investigation, where the facts lead to a conclusion, a thorough, objective evaluation of both technical and subjective characteristics will lead to the best investigators. ◆

The views expressed in this paper are those of the author and not necessarily the views of the NTSB.

# Applying Human Performance Lessons to Smaller Operators

By Kathy Abbott, Ph.D., FRAeS, Chief Scientific and Technical Advisor, U.S. FAA

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Human performance, especially flight crew error, has long been identified as a primary factor in a significant percentage of accidents. This has been addressed in a number of ways in the larger air carrier operations, including improved equipment, safety data monitoring of service experience, improved flight crew procedures, and improved flight crew training and qualification (including crew resource management and threat and error management knowledge, skills, and procedures). All of these human performance lessons have contributed to the "safety net" that has resulted in reduced accident rate for these larger operators. These lessons have not yet made their way in a widespread manner to the smaller operators.

Applying the human performance lessons to allow more widespread use of such knowledge, skills, and procedures could contribute to improved safety in smaller operators, as well. This is increasingly important because of the evolution of the airspace system and introduction of many new technologies. These new technologies are coming quickly, especially to smaller operators and aircraft. Changes such as these can bring risk as well as benefits. This paper will discuss the human performance lessons from a flight deck perspective, with primary focus on threat and error management and its role, especially as applied to smaller operators.

## Large versus small aircraft/operators—some differences

Accident rates are declining overall, and this is a tribute to the attention to safety within a very safe industry. But a gap still remains between the accident rates for large jet transports (especially those aircraft operated under US 14 Code of Federal Regulations Part 121 or equivalent) and smaller jet and turboprop aircraft, based on data from the Flight Safety Foundation.[1]

Why do these differences exist? There are many reasons, but it is useful to consider some factors that may contribute to the differences. In the large jet-transport community, the increased reliability of the equipment has contributed significantly to reduced accident rates. As the equipment reliability has improved, attention has turned to other areas, such as flight crew error, because it is cited as a major factor in a significant portion of accidents. This is important because the pilot populations may have very different training and experience between the two communities.

Even within the air carrier community, there are important differences in the pilot population. Research has shown that the regional airline pilot population has some important differences from the larger air carriers (Lyall and Harron, 2003). The regional airline pilots tend to have less experience, higher turnover, and operate a wider range of flight decks. All these factors may contribute to vulnerability to error—and that's within the air carrier community. The range of experience levels, turnover, and operation of flight decks may be even greater when considering the non-air carrier community.

## Addressing flight crew error in larger operators—lessons learned

Mitigation of flight crew error is being done through several mechanisms, including aircraft equipment designed to alert the flight crew to safety threats, safety data monitoring and analysis of service experience, improved flight crew training and procedures, and improved operational concepts (such as Area Navigation [RNAV] and Required Navigation Performance [RNP]).

Implementation of TAWS (Terrain Awareness and Warning System) is an example of aircraft equipment that has had a significant effect on improving safety. Other examples include TCAS (Traffic Alert and Collision Avoidance System), GPWS (Ground Proximity Warning System), and improvements in automation capability and reliability (Matthews, 2004).

Larger operators have also implemented safety data monitoring of service experience, such as FOQA (Flight Operations Quality Assurance), LOSA (Line Operations Safety Audit), ASAP (Avia-

***Hull Loss Record***

| Accident Type | Non-U.S. Carriers, FOQA users | European Carriers, NOT using FOQA | U.S. Carriers, most NOT using FOQA data |
|---|---|---|---|
| **Hull Loss** | 0.51 | 1.10 | 0.60 |
| **Hull Loss Crew Factor** | 0.20 | 0.52 | 0.37 |

tion Safety Action Partnership), and other voluntary reporting systems. See Capt. John Cox's 2005 paper for discussion of the application of this proactive approach to smaller operators.

Larger operators have improved flight crew procedures. Examples include the altitude awareness program that was first implemented by a major U.S. airline to address altitude deviations. This program was quite successful and is now in widespread use by many other airlines. Other programs have recognized the important of addressing flight crew monitoring of flight deck operations (Sumwalt, 2004), so that now many airlines and manufacturers describe pilot roles as "pilot flying and pilot monitoring," (rather than "pilot flying" and "pilot not flying"). And, of course, the importance of standardized and consistent application of procedures is widely recognized as important risk mitigation.

Larger operators have also improved flight crew training and qualification (including crew resource management (CRM) and threat and error management (TEM) knowledge, skills, and procedures). Threat and error management will be discussed in more detail later.

The large jet-transport operators tend to have more substantial infrastructure for implementing safety enhancements. Examples include the infrastructure for

- safety data monitoring and analysis.
- access to and distribution of information for pilots.
- training and flight crew procedures that is tailored to the operator.
- access to information about new types of operations that provide safety and efficiency improvements.

**Error management**

Flight crew error is cited as a primary factor in most accidents and incidents. In many cases, the human operator is blamed for making the error; in some countries the human operator is assigned criminal responsibility. While the issue of personal responsibility for the consequences of one's actions is important and relevant, it also is important to understand why the individual or crew made the error(s). In aviation, with very rare exceptions, pilots do not intend to make errors, especially errors with safety consequences. To improve safety through understanding of human error, it may be more useful to address errors as *symptoms* rather than *causes* of accidents (Abbott, 1999).

The importance of managing errors becomes obvious when it is recognized that errors are a normal byproduct of human behavior and cannot be prevented completely (Reason, 1990). Reason identifies that layers of defense must be breached before an accident occurs; similarly, layers of defense can be applied to manage errors. These layers of defense can be implemented for the latent errors (e.g., organizational factors) as well as individual factors.

*Threat and error management training*

Clearly, pilots provide an important layer of defense with respect to errors. Some of the lessons learned about errors and their management (Amalberti, 2001) are summarized below as they apply to pilots:

- Experienced pilots make just as many errors as less-experienced pilots, except for absolute beginners.
- Experienced/expert pilots make different types of errors than less-experienced pilots. As expertise increases, more routine errors but fewer knowledge-based errors are made.

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- The number of errors made tends to decrease in more-demanding situations (because of cognitive control), but the recovery rate from errors also tends to decrease (because of lack of resources for detection and recovery).
- Some 75% to 85% of errors are detected, with a higher detection rate for routine errors.
- Expert pilots tend to disregard errors that have no consequences for the tasks under way. In fact, detection and recovery from errors are considered to be a true manifestation of expertise.

It seems clear that experienced pilots have developed skills for performing error management tasks. Therefore, flight crew training, procedures, and operations can directly support these tasks.

In addition to training for avoiding, detecting, and recovering from errors, LOSA data have identified the importance of also managing threats. A threat is defined as anything that requires a crewmember's time, attention, or action beyond the tasks of a "pristine flight," where a pristine flight is a normal flight that requires no crew effort to change anything from the original plan, through the execution of flying from departure to destination.

These external threats (weather, maintenance, passenger problems, operational pressures, distractions/interruptions, air traffic control errors (language/communications problems, etc.) are not pilot errors but come from external sources and increase the potential for error, if not managed properly. Analysis has shown that accident/incident crews typically do not recognize all the threats, or their severity. Crews are most vulnerable to making errors when they acquire several threats and have employed no strategies to manage them. See Gunther, 2001, for a more detailed discussion of TEM, which is an important defense strategy to address errors through flight crew training.

*Procedural noncompliance*

Another important safety enhancement that supports error management is the use of standard operating procedures (SOPs). Procedural noncompliance[2] is the failure to follow established procedures. It is generally deliberate (and often well-meaning). An example of procedural noncompliance is continuing on with a landing even when weather minima requirements have not been met.

Procedural noncompliance is a prevalent type of error (more than 50% of the errors, in one study), among larger and smaller operators. This may be a particular concern for smaller operators where the procedures may not be tailored for the operation or where the culture of the company does not foster this. Many larger operators emphasize following SOPs as one way to address safety vulnerabilities, including the situation that commonly occurs when flightcrew members do not fly together often. In comparison, smaller operators may have pilots who fly with each other on a more frequent basis. This familiarity may make the following of SOPs seem less important.

Procedural noncompliance has the potential to introduce significant safety vulnerability:

• Procedural noncompliance takes away an important layer of defense (i.e., the operations manual), which is intended to ensure predictable and safe working practices. Procedures are often put in place because of the lack of other possibilities such as equipment design, hardware, and avoidance of the problems.
• Procedural noncompliance can occur when the individual does not know or understand the procedures or rules. This lack of understanding may be risky in itself.
• Procedural noncompliance can take people into new or unpracticed situations, in which the person is more likely to make an error.

Hudson (1999) identifies five main types of procedural noncompliance that cause problems for organizations. These five types are discussed below, with their applicability to flight operations.

• ***Unintentional procedural noncompliance***. This may occur for several reasons, but one important situation is when pilots do not know or understand the procedures. This may be particularly relevant to new or less-experienced pilots or when completing tasks that require adherence to a large number of rules or procedures. For a smaller operator, it is important to avoid such unintentional deviation from formal procedures.
• ***Routine procedural noncompliance.*** This occurs when deviations from the procedures are perceived to involve little risk and are accepted as the normal way of doing the job. For example, "I know what they taught you in training, but this is the way we really do it." In this case, not following the procedure has become the group *norm.* Accepting these norms in a smaller operator is a tacit endorsement of procedural deviation.
• ***Situational procedural noncompliance.*** This occurs as a result of factors that make it difficult for the pilot to comply. Factors such as time pressure, lack of supervision, unavailability of equipment, and insufficient staff have implications for this type of procedural noncompliance. An example may be when an operator improvises because the equipment specified in the procedure is not available or the paperwork is not complete.
• ***Optimizing procedural noncompliance.*** This category of procedural noncompliance is related to the nature of the job or the task itself. It may involve ways of improving things. This is more common when pilots view the procedures as overly restrictive, out of date, or inappropriate.
• ***Exceptional procedural noncompliance.*** These procedural deviations are rare and tend to happen only in very unusual circumstances, such as an emergency or equipment failure. This is especially challenging because there are cases where the pilot saved the situation by not following the procedures, especially when a novel situation occurs for which the procedures were not designed.

What should be done about procedural noncompliance? Forbidding it is ineffective. An initial step is to recognize its importance and understand it, and find out where and why it is occurring. Then, remove the reasons for it. For example—modify the procedure, change the culture and mindset (easier said than done!), emphasize the reasons for compliance, and allow flexibility within the procedures to manage situations as necessary. These steps can be quite difficult but they are important.

### Applying lessons learned to smaller operators—challenges

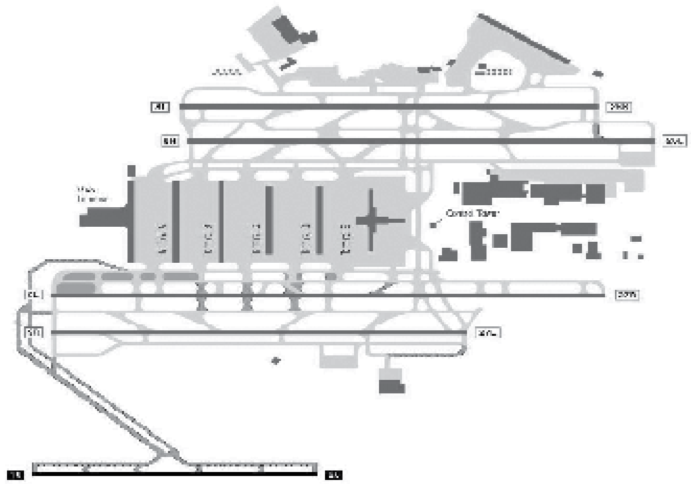
Smaller operators have the potential to improve safety using the same concepts as larger operators. The lack of infrastructure may sometimes make it more difficult, but the concepts are still valid. Some challenges that have been identified based on anecdotal data from smaller operators follows:

• Training—Many smaller operators outsource their training, and while the training meets or exceeds the standards, there are differences. For example, during the simulator training, the pilots may be from different operators. Thus it is hard to have training that is tailored to a specific operator's requirements, and it makes SOPs difficult.
• Operating as a flight crew—Crew pairing can be a challenge (this is true for larger operators as well, but there are more options available. For example, in smaller operators, pilots don't have the option of avoiding people with whom they do not wish to fly).
• Procedures—Callouts are not always spelled out or practiced. The procedures themselves often do not come from the airplane manufacturer.
• Automation training—Not as extensive, and procedures for using automation are not sufficiently detailed. Since operation of automation is an area that has been identified as an area of safety vulnerability for larger operators, and since this is an area where onboard equipage is increasing for all aircraft, increased attention is warranted.
• Pilot roles—Who does what is not always spelled out; e.g., during an engine failure.
• Crew resource management—Threat and error management training may not be included as part of training. For TEM training, the instructor should teach for the intended audience. If the course is too esoteric or targeted to a different audience, it will not be effectively learned.
• Mindset—There may be resistance to implementing some of these ideas, especially ones clearly brought from the large air carrier community. They may be viewed as unnecessary or inappropriate.

### Evolution of the airspace system and introduction of new technologies

Civil aviation is experiencing an unprecedented period with economic, safety, security, and operational challenges, together with technology opportunities. The fleet capability is evolving; there is a significant increase in the presence of regional aircraft. There is potential for introduction of large numbers of very light jets; and a variety of technologies are becoming available (and in many cases, are already installed) for flight deck applications. Many operators (large and small) are now operating all "glass flight deck" airplanes, with advanced avionics and navigation capability. This is increasingly true for smaller aircraft as these technologies become more affordable and widely available.

Experience has shown that technologies bring operational issues that may not have been anticipated. An example of this occurred



***Simultaneous RNAV departures.***

during the introduction of advanced automation in large air carrier operations (Billings, 1997, FAA, 1996). If smaller operators do not learn the lessons of the larger operators when advanced technology and automation were introduced, they may experience the same safety vulnerabilities. This is especially true, considering differences in flight crew training and experience levels.

There are several new operational concepts being implemented as well. These include increased use of Area Navigation (RNAV), airborne self-separation, and closely spaced parallel runway operations, among others. All of these advances in operations and technology have great promise, but human performance considerations will be important to achieve the benefits while minimizing the risks.

## Example: RNAV departures from multiple runways

Recent experience in implementing RNAV departure procedures at a large U.S. airport illustrates the importance of addressing error management and the associated layers of mitigation, and how it may differ for smaller operators. This particular airport has four parallel runways in sets of two pairs. The RNAV departure procedures were implemented so that two aircraft could depart simultaneously from one of the runways in each of the "pairs." This implementation is showing significant operational benefits (e.g., reduced time and fuel) and safety benefits (e.g., reduced workload and communication requirements).

However, a very small number of errors have occurred where the pilots had the incorrect runway in their flight management system (FMS), although they took off on the correct runway. For example, the correct runway was 9L and the pilot had 8R programmed in the FMS. The aircraft took off on 9L but the aircraft turned toward the first waypoint for the departure procedure from 8R. This raises the potential for a conflict if there is an aircraft departing from 8R.

Although very few errors have occurred during a very large number of operations, the potential severity of consequences make it important to address. The operation has been changed so that the takeoff clearance gives the aircraft headings to the first waypoint of the RNAV departure procedure, to ensure that the correct procedure is being followed.

Other mitigations are being developed to provide layers of defense so that operations can resume to using RNAV off the runway, rather than being vectored as they are now. These mitigations recognize that it is impossible to prevent all errors, although preventing as many errors as possible is important. Examples of recommendations that provide multiple layers of defense against the errors include:

1. Provide enhanced pilot training/familiarity/awareness. This may be done through one or more of the items below:
• *Implement a SID (Standard Instrument Departure) Ops departure page* to address general RNAV issues related to simultaneous RNAV departures from multiple runways.
• *Publish a safety alert notice or local notice to airmen* (this is intended to provide the information to non-airline operators).
• *Pilot bulletins from the operator or the pilot unions.*

2. Give the pilots the best chance of loading the correct runway in the FMS at the gate (although they need to be aware that they may be assigned a different runway based on air traffic needs). This may be done through ATIS (Automatic Terminal Information Service), PDC (Pre Departure Clearance) Departure Clearance, a matrix on the SID Ops page, or a combination of these methods.
• *ATIS* should provide information to flight crews on which runways are in use.
• *PDC*—This may be a useful tool to provide information about the expected runway; however, there is some concern about the possible misperception by the pilots that this represents a final runway assignment as opposed to a "best guess." In addition, many operators do not use PDC.

3. Detect and correct the error of having a different runway in the FMS from the one assigned:
• *Flight crew procedures*—Provide procedural means for verifying that the correct runway is entered into the FMS, e.g., have a performance-based checklist that directs pilots to detect and correct FMS errors through challenge-response. Many of the larger operators are implementing this into checklists. Other operators do not have a formal means of implementing this mitigation into checklists.
• *ATC RNAV procedure verification*—Just prior to transferring communication to the tower, ATC will ask for FMS runway and first waypoint. If the pilot responds incorrectly, it is expected that ATC will correct them. This is intended to actively ensure that flight crews have loaded the correct procedure and runway.
• *Runway Signage to remind pilots to verify runway in the FMS*—Signage may be more helpful for non-air-carrier flight crews.

4. Conduct an ongoing review of in-service experience during the initial implementation of the departure procedures. This review of in-service experience should involve multiple areas of expertise, including flight operations, air traffic operations, flight crew and air traffic training, human factors, avionics, procedure design, and other areas as needed.

This is not a complete list, but the items illustrate some of the layers of error mitigation. They also illustrate that smaller operators may need different mechanisms for informing their pilots or for accessing information about important operational and safety issues for a particular operation.

## Concluding remarks

Larger operators have employed many safety improvements, many of which address human performance concerns. These improvements provide layers of defense for human errors and for threats and are an important part of the safety net that has led to the excellent safety record that exists today.

Widespread application of these improvements to smaller operators has the potential to improve overall safety. This may be especially important, given the acceleration of introduction of new technologies and the potential changes to aircraft fleets and operations. ◆

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## Endnotes

1 This does not apply to all smaller operators. It should be noted that the accident rates of the corporate/executive segment (business aircraft flown by professional pilots) are comparable to, or better than, the Part 121 air carrier accident rates.

2 This category of errors is sometimes called "violation," but it should be mentioned that a "violation" error might not necessarily be in violation of a regulation or other legal requirement.

# Bringing Proactive Safety Methods And Tools to Smaller Operators

By Capt. John M. Cox (M03291), FRAeS, President, Safety Operating Systems

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This paper will describe how proactive safety tools used by large operators can be implemented into smaller flight operations to help investigations of incidents and accidents and to improve the safety of daily flight operations.

Many large airlines have developed systems and processes that allow the confidential collection of routine flight data. These data can be collected from the airplane and flight crews by programs such as Flight Operations Quality Assurance (FOQA) programs and/or by confidential reports in the Aviation Safety Action Program (ASAP) and the Line Operational Safety Audit (LOSA). Data collection programs such as these provide a real-time review of current safety issues in the flight operations department. Real-time data review facilitates the identification of areas where modifications to training programs or standard operating procedures (SOPs) or other areas might be appropriate. Such training program modification might prevent the occurrence of future safety events (incidents or accidents) and reduce costs as well.

FOQA programs, which evaluate various aircraft parameters recorded in normal flight, are a primary source of objective safety data. However, FOQA (which is by nature quantitative) cannot supply subjective—or qualitative—data. Subjective data, which help explain *why* a situation occurred, are gleaned by operations personnel through confidential safety reporting systems like ASAP. The independent observations from LOSA add a more objective "snapshot" to determine the effectiveness of SOPs, checklists, procedures, and other safety mitigations applied to the operation. These three data sources provide the safety department with a significantly improved ability to communicate the real needs of a specific area of flight operations to the appropriate level of flight operations management. This is a holistic approach allowing the constituent elements of ASAP, FOQA, and LOSA to become more than the sum of the parts, further benefiting the operator.

Until recently, smaller operators were unable to take advantage of these proactive methods and tools due to the substantial infrastructure required. The cost of this infrastructure was too high for many operators. Budget constraints, unfortunately, resulted in missed opportunities for safety enhancement.

Today, however, there are new marketplace strategies that allow small operators to have the same proactive safety programs that the large airlines enjoy. This paper will describe how these proactive safety methods and tools, used successfully by large operators, can be implemented by smaller flight operations. The utilization of proactive safety methodology can facilitate investigations and improve the safety of daily flight operations.

## Proactive safety

Accident data (both hull loss and accidents with fatal injuries) show that aircraft accident rates are declining. These data are collected from several sources; this paper will use the Flight Safety Foundation recitation of Boeing data where possible (cited at the IASS Conference 2004).

A gap remains between the accident rate for smaller jet and turboprop aircraft and the accident rate for larger jet transports (greater than 60,000 lbs). This gap, well-known and well-documented, exists even when the data are adjusted for different exposure levels of different fleets.

Are differences in equipment part of the reason for the accident rate gap? Terrain Awareness Warning Systems (TAWS) have significantly reduced (some would argue have eliminated) Controlled Flight Into Terrain (CFIT) accidents in aircraft equipped with TAWS. The TAWS example suggests that differences in equipage might be a partial explanation for differences in accident rates between the communities of larger and smaller aircraft. However, other factors come into play when analyzing the accident rate gap. For example, another factor contributing to the gap in accident rates might be airport facilities. Significant additional infrastructure is available to a large, intercontinental jet operator landing at a big international airport, compared to that available to the small turboprop operator landing at a tiny, remote airport.

Economies of scale (size and infrastructure) often allow a large operator to enjoy significant operational advantages. Dedicated in-house safety departments, highly qualified technical writers, well-developed cultures of SOP usage, and extensive reporting systems are demonstrably advantageous.

Safety reporting systems (such as ASAP, FOQA, and LOSA) allow the large operator to harvest reams of data, upon which a keener understanding of the realities of the operation can be based. These data-rich environments, which facilitate a proactive approach to problem solving, have paid off in appreciable improvements to safety and operational efficiency. For example, adjustments and enhancements in training programs, revisions to SOPs, and modifications to checklists can be facilitated before an accident or incident occurs. Thus the cost of an incident or accident may be avoided (and the overall risks lowered) by the proper and timely use of the information extracted from these reporting systems.

These same highly successful data analysis tools have the potential to improve the accident rate gap between smaller jets/turboprops and large jets. Unfortunately, most small jet/turboprop operators, as well as some small operators of large jets and some large operators of large jets, do not gather FOQA data. Older aircraft with low-tech flight data recorders (FDRs) make gathering these data very difficult and expensive. How can smaller operators gain the same benefits from safety reporting systems that large operators enjoy? How can these needed data be gathered, evaluated, and used by a smaller operator at a reasonable cost?

### Virtual safety departments

The cost of a large, extensive, and dedicated aviation safety department is high. Those that shoulder this high cost usually see a quantifiable reduction in risk. Large operators around the world have found this to be a good investment. The payback on the outlay has been considerable. With a large fleet there is direct contribution to the profitability of the company by FOQA, ASAP, and LOSA data-reporting programs. Millions of dollars have been saved by information obtained from FOQA, ASAP, and LOSA. One U.S. airline saved over one hundred million dollars in a single year by using FOQA data to explain the causes of engine exhaust gas temperature (EGT) exceedances. This allowed the engine to stay on wing, in service, for a longer time. This same operator was able to use combined FOQA and ASAP data to show the FAA of the need to redesign an instrument approach to reduce excessive descent rates. LOSA subsequently verified the effectiveness of the improved approach. For the smaller operator to reap similar advantages, the barrier of high initial cost must be addressed.

Cost of operation is a major concern to most aircraft operators nowadays. Fuel prices have climbed faster than a high-performance jet, and revenue is as hard to find as affordable fuel. As a result, outsourcing has become the standard. For example, large operators once had their maintenance performed "in house." Today it is often performed "off shore" on a "bid-for-contract" basis. The drive to lower operating costs has become an integral part of today's flight operation.

So the question arises: Can a smaller operator gain the benefit of data-gathering programs without having the high costs of a dedicated safety department? The answer is "maybe." That answer, too, depends on the exact requirements of the small operators. Germane questions could include Does the operator fly charters? Does the operator fly internationally? Can the small operator define what aspects of the operation could be improved? Is the operator willing to seek solutions from outside the company?

An operator might hire an outside source to compile the aviation safety reports. That independent contractor would then evaluate the safety reports and provide recommendations (e.g., training, SOPs, and checklists) if appropriate. The small operator could benefit from the arrangement. There are, however, important issues that must be clearly identified before "outsourcing" is initiated. What are the characteristics of a successful outside consulting firm? The arrangement with an outside source should add value to the operator's business. To enhance the operation, the outside consulting firm might provide cost savings and/or a significant level of expertise otherwise unobtainable by the aircraft operator. Any other additional expertise of the consultant to potentially enhance the operation should be considered.

The proper handling of aviation safety reports is critical. How the data and the reports are to be transmitted to the outside safety company must be determined. In today's electronic age (identity theft, hacking), the encryption of data is essential to maintain confidentiality and security. It is imperative that the security of this sensitive information be ensured from the beginning of the project. There must be a non-punitive reporting environment so that reports can be filed without fear of disciplinary or certificate action. The non-punitive aspects of an aviation safety reporting program apply only to sole-source, non-criminal, and non-deliberate actions.

Ownership of the information is a difficult question. Are the provided data the property of the operator or the outside safety contractor? Clear definitions of data ownership and authority to access information are fundamental. All parties must agree upon how the data will be stored, as well as when and how it will be de-identified and finally destroyed.

What reports the safety company will provide to the operator? How often? What will the reports contain exactly? Will the operator indemnify the safety company for the content of the reports? These are a few of the many issues that require agreement before an outside safety contractor can begin to use data gathered or reported by an operator's pilots. The outside safety company must keep all data it receives isolated and confidential. However, the outside contractor might request, for the purpose of enhanced statistical validity, that an operator's data be compared in the blind to like data from similar operators.

Data analysis, in this case, requires a standard of comparison, or it is of very limited value. Pooling sanitized data enhances the overall base of information. Comparing like-operators with similar data provides a much better understanding of the real world flight operation. A safety company with several similar operator-clients can observe and track trends and report to an operator without any loss of confidentially. By compiling data into trends over time and comparison to other similar operators, the maximum benefit for the collective few can be achieved.

### Achieving consensus

There must be agreement between the operator, the regulator, the pilot representative organization (if applicable), and the safety company. This agreement will result in a memorandum of understanding (MOU or similar written document). The specifics of how the data and reports can be used will be clearly stated in this document. The MOU becomes the backbone of the relationship among the operator, the regulator, the pilot representative body (if applicable), and the outside safety contractor. Successes at larger operators have proven that achieving a good, solid MOU is a good predictor of notable safety enhancements from the safety reporting program.

Guidance material from the FAA provides standard recommendations on the construction of MOUs for large operators. These templates can be downloaded from the FAA website. Additionally, the outside safety company should have access to other approved MOUs. These recommendations and examples from other operators can provide the framework for a virtual safety department. The cost of the virtual safety department is usually defrayed for individual operators when the independent safety company contracts with a number of operator-clients. In numbers, it becomes a symbiotic, win-win relationship.

### A theoretical example

The following is a purely fictional example of the benefits gained by a virtual safety department. Any resemblance to a real event, person, or company is purely coincidental.

Tiny Air, a small jet airline with 10 aircraft and 85 pilots, accepts a bid from "Safety R Us," an aviation safety firm, to provide FOQA and ASAP reports. A meeting is held between Tiny Air and Safety R Us officials and the exact requirements are specified. The senior flight management of Tiny Air, the regulating authority's Principle Operations Inspector, the chairman of Tiny Air's pilot association, and the senior management of Safety R Us meet to detail exactly how safety data will be gathered, evaluated, held, and reported.

There is agreement by all parties that de-identified reports will be presented to an Event Review Committee (ERC), made up of a representative from flight operations management, the regulator, and the pilot association, who will meet once a month to accept or decline reports into the program. The reports reviewed by the multi-party ERC are referenced only by number, so that "Safety R Us" is the only party with the ability to identify a flight crew. Should the ERC determine that it is imperative that the flight crew submitting a report be contacted, the ERC will submit, in writing, a request that the pilot association representative be given the name(s) of the flight crew. The pilot association representative will then call the flightcrew members for clarification of their report. The representative of the pilot association will then report the results of the call to the ERC.

Once the ERC has determined that a reports meets the criteria for admission into the program (sole source, non-criminal, not a deliberate act, etc.), it is logged into the system for evaluation. No disciplinary action or certificate action will be taken against the flight crew once the report is accepted into the program.

Safety R Us evaluates the report and compares it against other similar reports. If a trend is evident, Safety R Us will advise Tiny Air that an undesirable trend is developing. Any trend report generated by the outside safety company will include recommendations for mitigation of the problem.

Reports are de-identified after 2 weeks after the ERC meeting so that only a reference number is maintained. The reports can be used to make up month-over-month and year-over-year trend evaluations so that training effectiveness, SOP changes, and other items of emphasis can be observed, evaluated, and quantified.

This fictitious airline now has the ability to take a realistic look at its flight operation. Tiny Air can now learn of operational "near misses" that would have gone undetected previously. For the first time, Tiny Air can make safety improvements before an incident or accident occurs. Tiny Air is in the proactive league. The little airline has made a significant improvement in safety at a fraction of the cost of doing it "in house."

The regulator now has a means to monitor safety issues without waiting for an incident or accident. These data allow the regulator to work with the airline to resolve potential safety problems much earlier than previously possible. Additionally, the regulator can compare the airline to other similar airlines with similar programs to better understand how effectively the safety programs are working.

The pilot association now has a means to submit safety reports with the necessary protections from self-incrimination in place. NASA's highly successful Aviation Safety Reporting System has clearly demonstrated the value of confidential aviation safety reports. Through its non-incriminatory reporting system, NASA was informed of many, many near-miss events that otherwise might have gone unreported.

The ERC group members each become a part of the solution to the reported problems or issues. Not only do the ERC members accept a report into the program, they recommend corrective action so that the likelihood of recurrence is reduced or eliminated. The combination of the airline, regulator, pilot association (if applicable), and the outside safety company brings together a team to recognize, evaluate, and solve safety issues facing the airline.

The process is similar for FOQA data. The data are harvested from Tiny Air's fleet of aircraft and sent to Safety R Us where it is evaluated for "exceedances." Should an exceedance be observed, it is plotted, and a monthly trend report is provided to Tiny Air. This objective data, when combined with the ASAP reports, provide a comprehensive evaluation of the performance of the flight operation. The same process of data protection and reporting used in the ASAP program is used with FOQA data. Over time, maintenance cost alone can pay for this type of program. For example, careful monitoring of fuel burns can identify specific aircraft that may need rig adjustment.

LOSA data are never identified, so the confidentiality issues are slightly different. The flight deck observations and recordings during normal line operations result in the tabulation and classification of observed problem areas. Specially trained LOSA auditors, like the ERC members, should come from company flight operations, the regulator, the pilot association, and the outside safety company. The uniquely qualified LOSA auditor/pilots mark a form that classifies errors made by the flight crew. This data is then compiled by the outside safety company and presented to the other participant groups for a consensus-based solution.

### Limited resources and increased expectations

As the news media widely reports the airline industry's ever-improving safety record, airline customer's expectations of safer flights rise accordingly. Paradoxically, the flying public expects the airline industry to continue to improve flight safety while offering low-fare tickets, all in the face of record-high fuel prices.

The current economic squeeze is affecting some tangential aspects of the airline industry, too. Regulatory agencies (the FAA in the U.S.) face increased pressure on budgets. Those agencies must often do more work with fewer personnel. Regulatory oversight, while still mandated to improve aviation safety, is under significant fiscal pressure. New tools are needed to facilitate the administration of regulatory agencies and enhance aviation safety—concurrently.

One way to meet the emerging safety needs of the airline industry is to take big-airline proactive safety methods to the small operators. These methods of improving and enhancing operational safety are well-understood and proven. Since small operators are held to the same standards as large operators and the virtual safety department is a reality, *cost* is no longer a viable excuse for not having a dedicated safety department using all available safety tools. The virtual safety department offers the best of both worlds: the services and benefits enjoyed by the larger operators at a very affordable price.

All operators can now enjoy the benefit of reduced risks and improved efficiencies. Early detection and reporting of safety issues, followed by proper mitigation of those issues, is a time-honored methodology to achieve continuous improvement of aviation safety. That continuous improvement in operational safety will result in cost efficiencies throughout the airline.

A safer airline has fewer on-the-job injuries, often has lower insurance costs, has fewer passenger injuries (and resulting litigation), and can expect better resale price for equipment. The safer airline, too, may enjoy better relationships with the news media and the regulator.

The aviation industry has historically been a leader in safety. Our industry has the most enviable safety record in all of public transportation. Our accident rates have declined sharply over the years. This trend must continue. One method to help keep the safety trend going in the right direction is the utilization of all the means available for the early detection and mitigation of safety deficiencies. The methodology to improve safety at the small operator exists at the large operator. Those successful safety solutions from the greater part of the industry must now be applied at the lesser part. The virtual safety department brings proactive safety methods and tools to smaller operators efficiently and at an affordable price. ◆

# The Use of Operational Risk Management in the Royal Netherlands Air Force Applied to Apache Helicopter Operations in Afghanistan

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## Abstract

Operational risk management (ORM) is a continuous and systematic process for proactively identifying, assessing, and controlling hazards and associated risks related to a planned activity. The objective of ORM is accident and incident prevention. It is a generic tool that can be used by anyone involved in risk assessment and management, such as flight safety investigators and safety managers. The ORM process consists of six steps, which have to be performed in order. First, the activity under review (an operation, for instance) has to be defined and the associated hazards need to be identified. Next, each hazard is assessed to determine the risk level of the hazard. The severity level of the consequence(s) of a hazard has to be determined, followed by the assessment of the probability of occurrence of the consequence(s). The risk matrix is used to determine the risk level of a particular hazard based on the combination of the probability and severity level of that hazard. Subsequently, risk control measures have to be identified and their effect on the risk level and the operation has to be determined. When deciding which controls to select and implement, the cost of risk control measures, the reduction in risk, the impact of the risk control measures on the operation, and the benefit of the operation have to be weighed. Finally, the entire process should be supervised and reviewed to establish whether the risk control measures are effective and to identify which hazards are still present and/or whether new hazards have developed.

The implementation of ORM within the Royal Netherlands Air Force (RNLAF) started in 2002 with the objective to improve the risk assessment and management of operations. The Royal Netherlands Air Force uses ORM

- to support management decisions, e.g., during planning and preparation of out-of-area operations.
- to ensure that operational risks are tolerable and that they have been weighed against the benefits of the operation.
- to ensure that the risk decision is taken at the appropriate command level, with an explanation to commanding officers and politicians about risks that are managed, can not be further controlled, or are deemed intolerable.

The surplus value of using ORM is the structured approach of risk assessment and management instead of an intuitive one. Another major advantage is the ORM worksheet and database, which provide accountability and explanation to officers of all ranks and politicians.

This paper explains the use of ORM by the RNLAF during the deployment and operations of a squadron of AH64D Apache combat helicopters with the NATO International Security Assistance Force in Afghanistan in 2004. The RNLAF staff and Operations Planning Center used ORM to identify and manage risks pertaining to this particular deployment. This paper gives an example of this ORM case and describes the associated organizational process and lessons learned after the use of ORM in preparation of the operation in Afghanistan.


## 1. Introduction

1.1. *Background of operational risk management in the Royal Netherlands Air Force*

Operational risk management (ORM) is a continuous and systematic process for proactively identifying, assessing and controlling hazards and associated risks related to a (planned) activity. The objective of ORM is accident and incident prevention. It is a generic tool that can be used by anyone involved in risk assessment and management, such as flight safety investigators and safety managers.

The initiative to introduce ORM in the Royal Netherlands Air Force (RNLAF) was triggered by cooperation between the RNLAF and the Singapore Air Force, the Swiss Air Force, and the United States Air Force. The RNLAF started with the implementation of the ORM process at squadron level in 2002. In the demonstration project three squadrons were assigned to implement ORM in their daily flight operations and training missions. The ORM policy of the RNLAF required pilots to go through a checklist or risk assessment matrix in order to determine the risk level of their (training) mission during mission planning. After the evaluation of the demonstration project, the RNLAF staff concluded that the application of ORM at squadron level was not beneficial to the operations and susceptible to "tweaking" (to come to certain favorable results). Moreover, standard operating procedures already in place were deemed to cover day-to-day flight risks well.

At the same time the RNLAF staff, in particular the Safety

Division and the Operations Center (1), became interested in using ORM to assess and control risks related to operations in support of decision-making during the planning and execution of operations. Till then, risk management was done based on experience and gut feeling, and the process and its results were not documented. The aim of the RNLAF staff was to have a structured and documented method (by means of the ORM process) to carry out risk assessment and management.

The National Aerospace Laboratory NLR (2) has experience in safety assessment methodologies and has performed safety assessments of flight operations for years. In the framework of the research program, which NLR carries out in support of the RNLAF, NLR was commissioned to support the implementation of ORM in the RNLAF organization. After a feasibility study, NLR concluded that ORM would have a surplus value and would be beneficial in the planning and preparation of operations from the beginning of the high-level political and military decision-making through the actual execution of the operation. Hence, from the start of the implementation of ORM in the RNLAF organization, the Operations Center (1) has been closely involved in the project. First, the ORM process was tailored to the *Operation Decision-making and Planning* process used in the RNLAF during the preparation and planning of operations. Subsequently, severity and frequency classification schemes and a risk matrix to be used in risk assessments were defined. In addition, an ORM handbook was written, serving as a guideline for personnel conducting ORM, and workshops were organized at staff and squadron level to instruct officers in the use of ORM. Via this process, ORM has become an integral part of the planning, preparation and execution of RNLAF operations and deployments.

### 1.2. Paper outline

The set-up of this paper is as follows. Section 2 describes the general ORM process and its role in the planning process of the RNLAF. It deals with the steps in the ORM process and explains the activities to be done in each step. Section 3 addresses the application of ORM in the preparation of the deployment of an Apache helicopter detachment to Afghanistan. Conclusions are presented in Section 4.

## 2. The operational risk management process

### 2.1. ORM and its purpose

Operational risk management (ORM) is a continuous and systematic process to identify potential hazards, to assess the associated risk level, and to control the risks. It is a tool that can be used by everybody, irrespective of rank and experience, throughout the entire organization. In a perfect world, it should be used for every action involving risks (see Figure 1).

Every operation, in peace and in wartime, will inherently expose personnel and equipment to a certain level of risk. ORM is a method to identify those risks, and to control them as best as possible in a structured, transparent, and logical process. ORM is not regarded as a new trick or "rocket science." Obviously, risk assessment and management have been conducted for years by the RNLAF. This was done based on experience and intuition, although the process was not clearly defined and the results were not documented. The introduction of ORM aims to improve the risk assessment and management by combining experience, knowledge, and expert judgment in a systematic approach to control risks.

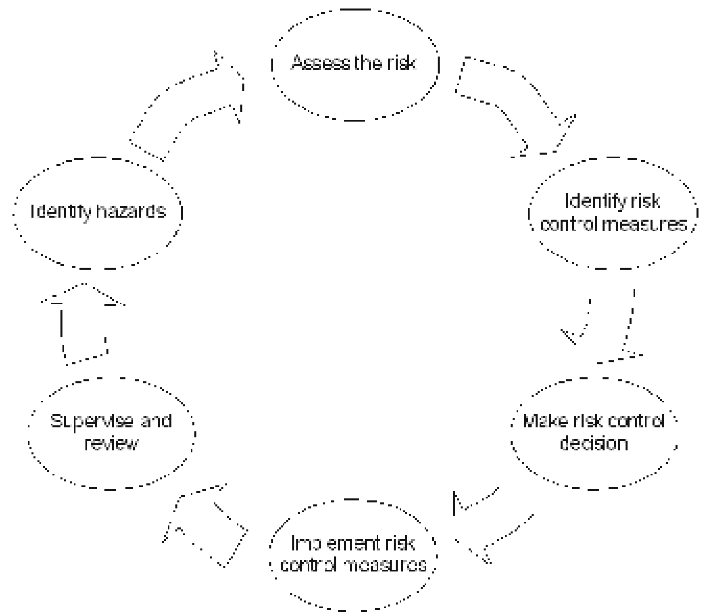


***Figure 1. The steps of the ORM process.***

ORM aims at the prevention of accidents and incidents by proactively identifying and managing potentially hazardous situations. The RNLAF uses ORM

- to define clearly the risks at hand.
- to ensure that operational risks are tolerable and to ensure that the risks have been weighed against the benefit of the operation.
- to support management decisions by providing an overview of potential hazards, with the associated risk level, risk control measures, and remaining risk level (i.e., risk level remaining after risk control measures have been implemented).
- to make clear at which level in the organization the risk management decisions (on the acceptance of risk) have to be taken.
- to explain to supervisors and to politicians which risks can be controlled, which risks are not yet controlled, which risks are to be accepted, and which are not. Clearly, acceptance, rejection, or management of risks has consequences with respect to costs, resources, operational readiness, and feasibility of tasks.

### 2.2. Starting an ORM case

An ORM case is defined as the use of ORM for a particular operation. For instance, the planning and preparation of an out-of-area deployment requires an "ORM case." Meetings, which are held in the framework of the ORM case, are defined as "ORM sessions." Examples of such meetings are brainstorm sessions to identify hazards and risk assessment meetings.

ORM can be carried out in various forms and at different commanding levels, depending on the available resources, time, and the user's needs. Time-critical ORM can be performed in situations that require quick decision-making and (immediate) controlling of hazardous situations. For example, at this level an ORM case involves a few people, takes less than an hour, and concludes with a documented and founded risk decision.

Tactical ORM is done in circumstances that allow more resources, time, and effort in order to assess and control risk in, for instance, the planning and execution phase of operations or the preparation of deployments. Typically, at this level brainstorm sessions and risk assessment meetings are organized and documented. The hazard identification, risk assessments, and risk control measures are generally at a larger scale and encompass the entire or a large part of the operation (whereas time-critical ORM typically involves a particular hazard).

Finally, strategic ORM tackles long-term, strategic hazards for high-level decision-making.

Before starting the ORM case, it is important to define its purpose, context, scope, and level of detail in order to set a common goal and direction of the ORM case for all participants. The purpose of ORM in the framework of operation planning is the identification and control of risks pertaining to a particular operation. The context of the ORM case must be defined. For instance, it must be determined if only risks to one's own detachment are considered or that risks to third parties are also included in the assessment. Likewise, it has to be decided whether to ignore risks that are encountered in daily operations, that are already covered in standard operating procedures, or that are rather obvious. Additionally, it should be established who (i.e., which expertise areas) should be involved in the ORM sessions. Expert judgment, experience, and common sense are widely used throughout the ORM process. Finally, an ORM coordinator has to be assigned, for example, a planning officer in the Operations Center.

### 2.3. The RNLAF ORM database

An ORM database has been prepared by the RNLAF to record ORM data during the planning of an operation. General information on the operation such as the date, location, weapon system, and detachment can be stored. Each record in the database refers to an identified hazard, containing information on the assessed risk level of the hazard, the suggested risk control measures, the implementation plan of the measures, the persons responsible for the measures, etc.

During the planning and execution of a particular operation, the planning team uses this database to keep track of the progress of the ORM sessions during planning of the operation. An extra benefit of the database is its potential to secure lessons learned of past operations and the associated ORM session data. The planning team can, for instance, query the ORM database to see which risks were identified in previous operations and which risk-control measures were then applied. This helps them to identify risks they may have overlooked in the ORM brainstorm sessions, and to learn which measures have been used in the past. The ORM database generates ORM worksheets presenting an overview of the hazards, risk level, risk-control measures, details of the measures, responsibilities, etc. After review and a final approval by the "boss" the sheets are signed and become part of the operation order. Lessons learned and the results of the review of the implemented risk-control measures by the Detachment Commander during the actual operation are stored in the database as well. The data are also an important tool to assist a recce team (a reconnaissance team is deployed to the area of operation in the beginning of the planning phase of an operation). By reviewing the database with respect to specific areas and/or weapon systems, the recce team can focus on potential problems discovered in the past.

### 2.4. The ORM process steps

#### 2.4.1. General

The ORM process consists of six steps, as is shown in Figure 1. The process can only be effective when all steps are executed in a chronological order. Depending on the available time and resources, some steps may be done more elaborately, or, on the contrary, in less detail and quickly.

#### 2.4.2. Step 1: Identify hazards

The ORM process starts with the definition of the operation under review. It is clear that the participants in the ORM case should have a clear picture of the planned operation in order to be able to identify hazards. The operation description can generally include

- The objective(s) of the operation and the resulting operation requirements.
- The operational context, i.e., the environment, the specifics on command and control, the political background, etc.
- The responsibilities and tasks of personnel.
- The applicable procedures (international, national, organizational).
- The technical systems involved.

The identification of potential hazards in the operation is done in the first step of the ORM process. A hazard is defined as an event that may lead to a dangerous situation or an event that may hamper the resolution of such situations. One needs to identify as many relevant potential hazards as possible, while these hazards are related to as many different aspects of the reviewed operation as possible. For example, hazards related to operations, medical issues, logistics, force protection, maintenance, ammunition, accommodation, personnel, etc., have to be considered. Identified hazards should be clearly defined in order to avoid misunderstanding. Hazards should also fall within the scope of the operation (which was defined before the start of the ORM case).

Usually, brainstorm sessions are the primary means to identify hazards. In order to cover as many relevant hazards as possible, experts from various working areas should take part in the hazard identification (e.g., pilots, doctors, maintainers, explosives experts, experts on the specific location of the operation). In addition, databases of hazards identified in previous operations can be searched for hazards that may have been overlooked.

#### 2.4.3. Step 2: Assess the risk

The risk of a hazard is defined as the combination of the severity and the frequency of that hazard. The RNLAF and NLR have established a severity and frequency classification scheme (3) and a risk matrix to determine the risk level of hazards in the framework of an ORM case (see Figure 2, page 143).

Four severity categories have been defined qualitatively: catastrophic, hazardous, major, and minor. In the assessment of the severity outcome of a hazard, the following issues have to be considered: damage to personnel, equipment, and the operation; political damage and loss of goodwill or support; collateral damage; and environmental damage. Eight frequency categories have been defined qualitatively: very frequent, frequent, now and then, sporadic, very sporadic, seldom, very seldom, and almost unimaginable. Each category has a quantitative definition in terms of frequency in time (e.g., very frequent corresponds to more than once per two weeks). Finally, a risk matrix has been established, which gives the risk level for each combination of frequency and severity level. The risk levels are classified as "high," "medium-high," "medium," "medium-low," and "low."

The severity assessment will determine the severity level of the outcome(s) of the hazard. Using expert judgment, one can quali-

| | *Catastrophic* | *Hazardous* | *Major* | *Minor* |
|---|---|---|---|---|
| **Very frequent** | H | H | H | H |
| **Frequent** | H | H | H | MH |
| **Now and then** | H | H | MH | M |
| **Sporadic** | H | MH | M | ML |
| **Very sporadic** | MH | M | ML | L |
| **Seldom** | M | ML | L | L |
| **Very seldom** | ML | L | L | L |
| **Almost unimaginable** | L | L | L | L |

*Figure 2. The risk matrix.*

tatively classify the severity level of the outcome(s). The frequency of occurrence of each outcome of a particular hazard is estimated based on a combination of data, expert judgment, and experience. To assess the frequency of an event, qualitative and quantitative guidelines are available in the frequency classification. Moreover, incident databases or flight data monitoring systems could be used to derive frequencies of particular events. The risk level of a hazard follows from the combination of the severity and frequency level of the hazard according to the risk matrix in Figure 2.

The risk assessment of the hazards does not judge on the acceptability of the hazards. A certain level of risk may be acceptable compared the benefit of the operation. The point is that a particular risk of a certain level can be acceptable in one operation, but not in another operation, because the benefits of the operations are different. The weighing of risks, costs, and benefits should not be done in this step of the ORM process, but later on.

The risk level is a means to prioritize hazards, so that the hazards with the highest risks can be managed first. Time and resources are usually limited, so the highest risks should be covered first to control risk effectively and efficiently.

#### 2.4.4. Step 3: Identify risk control measures

The outcome of the risk assessment is a list of hazards, which are ranked in priority, based on the corresponding risk level. Step 3 in the ORM process identifies risk-control measures that can be implemented to mitigate the risk of a hazard. These risk control measures should reduce the severity and/or frequency of the outcome of the hazard. Besides the reduction in risk that can be achieved with the measure, the costs, and effects of the risk-control measures on the operation are assessed. Before selecting risk-control measures, it is necessary to reassess the entire operation with the proposed risk-control measures in place to ensure that the measures do not introduce new hazards in the operation and do not increase the risk level of the identified hazards. The identified hazards and associated (remaining) risk level, risk control measures, and an implementation plan are entered in the ORM database. The ORM worksheet presents an overview of the aforementioned items for the entire operation (the worksheet can be generated by the database). The ORM database is used to keep track of the ORM process and to store the results of the ORM sessions. It can also be used as reference in future ORM cases.

#### 2.4.5. Step 4: Make risk control decisions

The next step is the risk-control decision, i.e., the risk control measures and associated costs, the cost of risk, the impact of the measures on the operation, and the benefit of the operation have to be weighed. This decision possibly results in the selection of a set of risk-control measures to control the risk with the acceptance of the remaining risk level, or a rejection of unacceptable risks and associated parts of the operation. In the latter situation, one could decide to implement extra risk control measures to further reduce risk or to change parts of the operation (which requires a new cycle of the ORM process).

#### 2.4.6. Step 5: Implement the risk-control measures

This step defines and accomplishes the implementation of risk-control measures, the tasks and responsibilities of personnel, time line of implementation, and so on. Some risk-control measures may be recurring, such as safety briefings or at times when personnel changes occur. Other measures may be "once only," such as the installation of equipment in aircraft.

#### 2.4.7. Step 6: Supervision and review

Finally, a review is performed to check whether the risk assessment conducted "behind the desk" is realistic and in accordance with the actual operation in the field. In addition, the review determines whether risk control measures are effective and in place. This review can be conducted by an audit team or a (Detachment) Commander. Additionally, it must be determined whether the operation or circumstances have changed, and if so, whether such changes require an additional risk assessment and management. This means that the entire ORM process will be repeated for the newly identified hazards, i.e., this is a new cycle of the continuous ORM process.

## 3. Application of ORM in the RNLAF deployment to Afghanistan

### 3.1. Introduction

This section explains the use of ORM by the RNLAF during the deployment and operations of a squadron of AH64D Apache combat helicopters with the NATO International Security Assistance Force in Afghanistan. The RNLAF detachment operated in Afghanistan from March 2004 till March 2005 with six Apache helicopters. The task of the detachment was to serve as a Quick Reaction Force in the area of operations (Kabul and surroundings).

The International Security Assistance Force (ISAF) is mandated under Chapter VII of the United Nations (UN) Charter (Peace Enforcing) by UN Security Resolutions 1386, 1413, and 1444. ISAF exists to help the Afghan people, not to govern them. Additionally, under the UN mandate, the role of ISAF is to assist in the maintenance of security to help the Islamic Republic of Afghanistan and the UN in Kabul and its environs. ISAF exists in accordance with the Bonn Agreement of Dec. 6, 2001. A detailed Military Technical Agreement between the ISAF Commander and the Islamic Republic of Afghanistan provides additional guidance on ISAF operations. Following these provisions, ISAF will be in existence at least until the successful closure of the Bonn process, that is, the general elections. ISAF's mission is to assist the Islamic Republic of Afghanistan in creating a stable and secure environment in Kabul and its vicinity.

The primary role of ISAF is to assist the Islamic Republic of Afghanistan in providing a safe and secure environment within Kabul and its surrounding areas, which will assist in the reconstruction of a new Afghanistan. In carrying out this mission, ISAF conducts patrols throughout the 16 different police districts in Kabul and its surrounding areas. Over a third of these patrols are carried out jointly with the Kabul city police. On a political level, ISAF works closely with the Afghan authorities, United Nations Assistance Mission to Afghanistan (UNAMA), UN agencies, international organizations, and non-governmental organizations. As part of this process, ISAF has established liaison teams in all departments of both the Islamic Republic of Afghanistan and UNAMA. ISAF currently runs Civil Military Cooperation (CIMIC) projects throughout the city, focusing on the assessment of the provision of basic human needs such as fresh water, electric, power, and shelter, and by improving the existing infrastructure destroyed by more than 20 years of conflict. CIMIC is also involved in rebuilding medical facilities and the renovation of schools. (Source: NATO)

### 3.2. The preparation of the deployment

In preparation of the decision-making and planning of the deployment a fact-finding mission was carried out. Later, a reconnaissance (recce) team was deployed to Kabul, Afghanistan, to prepare the deployment in more detail. During this recce, a first ORM brainstorm session was organized to identify hazards. The recce team consisted of the upcoming Detachment Commander (Detco) and personnel from various expertise areas such as logistics, medicine, force protection, flight safety, and intelligence. After the initial hazard identification, the team further assessed the risks together with planners from the RNLAF Operations Planning Center at headquarters. In this process, risk levels of hazards were determined, risk control measures were identified, and their implementation was prepared. Review sessions with the Deputy Commander Operations and Commander Tactical Air Force were part of the ORM process. Finally, the hazards, with associated risk level, risk-control measures, persons responsible for the measures, the implementation plan, and the remaining risk level were entered in the ORM database. The ORM worksheets were reviewed and signed by the Commander Tactical Air Force and were part of the operation order. Figure 3 shows an example of an ORM worksheet.

### 3.3. The role of the Detco in the ORM sessions

The Detco is part of the ORM sessions from the start. This enhances the acceptance of the decisions made during the planning of the operation. Furthermore, including the Detco in the sessions guarantees that the most up-to-date procedures are used for decision-making and that the issues specific for his detachment are addressed. For example, specific discussions that take place at the squadron after the return of the recce party become part of the ORM sessions and are solved before deployment. Although these topics may not be an item at staff level, they need to be addressed if they are an actual discussion within the future detachment. Another reason to consider the Detco as an integral part of the ORM sessions is to close the (possible) gap between the staff and the operational detachment. If questions arise about specific decisions in the detachments during the deployment, the Detco can give more inside information, which leads to a better understanding and acceptation of the decisions. And last, but not least, the Detco is committed to the decisions made for his detachment and is very well able to explain to his detachment the "thought process" behind the decisions.

### 3.4. Example

One of the identified hazards was a possible forced landing in a hostile environment, which was new to the Apache detachment. This hazard was not only related to the safety of the crew and the aircraft, but also to the possibility that a weapon platform (including secret subsystems) would get into enemy hands after a forced landing.

This hazard was assessed as follows. First, the severity level of a forced landing was determined, based on experience and common sense. Aspects like damage to the aircraft, damage to the crew, damage to the operation, etc., were considered. The hazard was classified as "*hazardous.*" Next, the ORM team determined the planned amount of hours to be flown during the operation in combination with the known frequency of forced landings per flying hour (from flight safety data) in order to get an estimate of the frequency of this type of occurrence (estimated as "*sporadic*"). The resulting risk level of this hazard was thus estimated as "*medium/high*" (see risk matrix in Figure 2). The next step dealt with the identification of risk-control measures. It was judged that the best way to reduce this particular risk would be to try to reduce the rate (per hour) of forced landings. In order to do so, it was necessary to review the possible emergencies that would lead to a forced lading and to differentiate between situations that would be dangerous to the crew and those situations that would be "just" dangerous to the aircraft. For instance, an engine failure will normally (in peace time) lead to a forced landing in order to reduce the possibility of aircraft and engine damage. It was decided that during the ISAF operations it would be safer to continue flying in such emergencies, with the possibility and cost of damaging an engine, than to get stranded in hostile territory and lose the Apache and/or the crew. This is an example of a risk-control decision, i.e., weighing the benefits (reducing the "exposures" of the crew and the aircraft to a hostile environment), the costs (degree of engine damage, losing the crew and the aircraft, secrets falling into enemy hands) and risks. The mitigating measure consisted of not carrying out a forced landing under certain circumstance, whereas in peacetime a forced landing would have been appropriate. Next, actions were defined that would be taken in case a forced landing was unavoidable. Issues that were considered included: classified items in the Apache, crew safety in relation to guarding the aircraft, and recovery of the aircrew and aircraft. The procedures were developed before the deployment and briefed on a regular basis to the crews and newcomers. At the end, the remaining risk level was classified as medium. A well-defined "game plan," including the mitigating measures, implementation plan, and responsibilities, was presented to the Commander Tactical Air Force for approval.

### 3.5. Lessons learned

The following lessons learnt were identified from the application of ORM in the Apache deployment.

- The most important benefit of ORM is that the risks are clearly

***Figure 3. Example Operational Risk Management Worksheet***

**Name operation:** ISAF Apache
**Expertise Area:** Divers (example only) **Detachment** 1 (NL) Helo Detachment Afghanistan

| Identified hazard | Level | Risk control | Implementation | Responsible measure | Repeat | Rest risk | Decision CATF | Reviewed |
|---|---|---|---|---|---|---|---|---|
| Personnel affected by high temperatures in summer period, resulting in x% availability | Medium-Low | Rest-work scheme adapted, water balance regime, buddy system | Personal hygiene game plan | Detco, Doctor | Continuous | Medium-Low | Ok | |
| Forced landing with potential hostile intent | Medium-High | Procedures for forced landings outside Kabul International Airport and declassification heli adapted | Procedures in operations order and LOP | OPCEN, Detco | Implementation before deployment, aircrew briefing regularly | Medium | Ok | |

**Signed decision-making authority: Commander Tactical Air Force**

described and written down before the discussion on risk acceptance starts (Step 4: the risk decision). This largely reduces miscommunication during the discussion, which is not uncommon if the subject is not clearly defined.

- The fact that high-ranking officers are involved in the ORM process as reviewers and that the Commander Tactical Air Force has to sign the ORM worksheets improve their awareness of the risks at hand, and the measures to be taken to reduce and control risks.
- The ORM worksheets are attached to the operation order so that the information and reasoning are always available, even after multiple changes of detachments. Personnel know that their higher ranking staff members have been working to decrease the risk level to a tolerable level. Before ORM was used, it was not always clear to the detachment that headquarters had addressed all important issues or what issues had been addressed.

## 4. Conclusions

The following conclusions are drawn:

- The ORM process helps to identify in structured and explicit manner as many and as diverse hazards as possible.
- The ORM process enables RNLAF officers to perform risk assessment and management in a structured and logical process, while using expert judgment, experience, and common sense.
- By using ORM officers and decision-makers obtain a documented assessment of hazards, associated risk levels, and risk-control measures with respect to a particular operation. In this respect, ORM supports staff level decision-making.
- The most important benefit of ORM in the RNLAF is that the risks are clearly described and written down before the discussion on risk acceptance starts.
- In order to take rational decisions based on objective assessments, it is of uttermost importance that the same criteria are used to judge different operations and that the interpretation of these criteria does not change. ◆

## Notes

(1) The Operations Center (OPCEN) is a staff division responsible for the planning and preparation of future operations and the support of current operations of the RNLAF.

(2) The Dutch National Aerospace Laboratory (NLR) is an independent technological institute that carries out applied research on behalf of the aviation and space industry.

(3) The severity and frequency classifications were designed by the NRLAF and NLR so that the classification is

- generic: it can be applied to different ORM cases, different types of hazards (e.g., medical, logistic and operational hazards), and different types of operations.
- transparent: the severity and frequency categories have been defined, making clear which combination of severity and frequency corresponds to which risk level.
- standard: everyone will use the same classification and risk levels in the risk assessments, which helps to assess each operation equally.

# The Unified Field Theory

By Michael Huhn (MO3689) and Mark Solper (MO4670)

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***Mark Solper*** *is a first officer for America West on the B-757. He is the Chairman of the Air Line Pilots Association Accident Investigation Board, and also the Chief Accident Investigator for America West ALPA. He was also the Manager of Training and Safety for America West. Prior to joining America West, Solper held multiple positions with the FAA. Prior to that, he was a fleet manager and check airman for Simmons Airlines. (Photo not available.)*

## Introduction

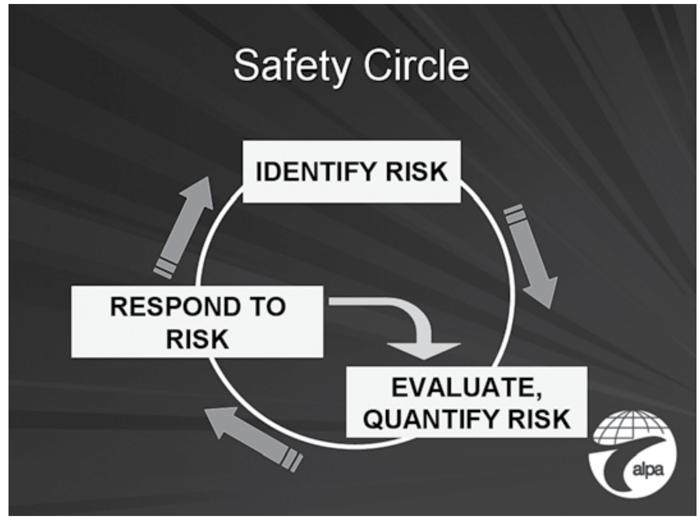
What in the world does the title of this paper, "The Unified Field Theory," have to do with air safety investigation? After all, unified field theory is associated with the domain of physics, not aviation. The term "unified field theory" was coined by Albert Einstein and denotes the long-sought means of tying together and explaining the nature and behavior of all matter and energy. Not surprisingly, it is sometimes called the "Theory of Everything," and the current quest for a unified field theory is frequently referred to as the "holy grail of physicists." We propose that a parallel concept applies to the commercial air transportation safety scheme.

## Background information

The safety landscape is changing. The most obvious shift is from reactive tinkicking to proactive data mining. While the U.S. Department of Transportation's "zero accidents" goal may never be achieved, commercial air transportation is moving in that direction, and the means to accelerate that progress are more prevalent than ever. As safety investigators, we are some of the users of safety data and mechanisms. The information is available. The tools exist. So what are we doing, and what do we need? The answer appears to be "a proactive, integrated approach." This prompts the question, "What are we, as air safety investigators, doing to cultivate and orchestrate the uniform and effective application of these tools and information?"

At this stage, it would be useful to briefly discuss some key aspects of the safety improvement process, which can also be called risk management. Ideally, risk management is a closed-loop process that consists of the following three principal steps:

1. Identify the risk.
2. Evaluate and quantify the risk.
3. Respond to the risk (take action, quantify, and communicate results).

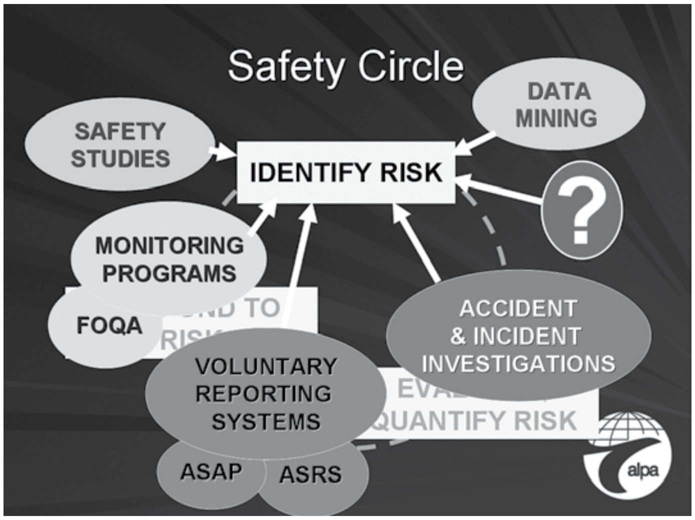


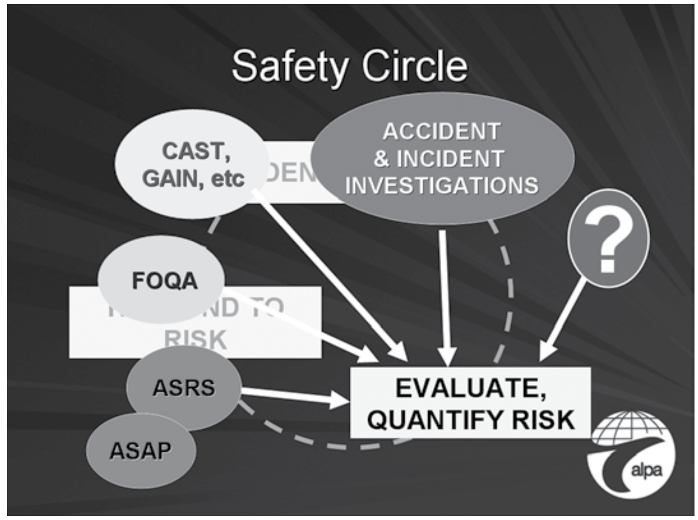

As the name implies, this "Safety Circle" is a continuous iterative process, and it can be as localized or as global as needs dictate, and as resources permit.

At this point, it is necessary to introduce the concepts of "systems" and "systems approach." Definitions of a system include "a combination of related parts organized into a complex whole" and "a method or set of procedures for achieving something." So it is not a stretch to say that a system is a thing or process that utilizes or performs actions on inputs to produce an output. In a sense, any system boundary is arbitrary and user defined, and based on one's perspective or needs. Perhaps the easiest way to illustrate this is to consider a series of concentric squares, with each square representing a system. These systems are related and interact with one another; but for analysis purposes, the boundaries will vary as a function of the scope of the observer or analyst. A helpful way to look at the boundary is that it is a dividing line between the system itself and its environment.

So just what is a "systems approach" then? Based on the definitions and discussions above, it would be something akin to "analyzing or evaluating an event or situation with emphasis on the various levels and interactions, as well as their overall context(s)." Pursuit of the Safety Circle in accordance with a systems approach would dictate that each of the three process elements be practiced and implemented to their maximum limits, and that their interactions also be considered.

Now switch gears. It is fair to say that air safety investigation is intended to accomplish some or all of the following tangible results: prevent incidents and accidents, prevent injuries and loss of life, and prevent damage or loss of equipment. In broader terms, the process of air safety investigation identifies hazards, and then strives to reduce risk. In a more encompassing perspective, air safety investigation could be considered one particular method of risk management. The scope and extent of any par-




ticular risk-reduction effort is user driven, but in a perfect world would always be promulgated globally.

It is appropriate that the reader be reminded what the acronym ISASI stands for—the International Society of Air Safety Investigators. Let's look at this acronym, and in particular, just what it says we are investigators of "air safety." It doesn't say "accident," or even "incident." It's much less prescriptive than that. Yet when we think of improving aviation safety, particularly in the "investigation" context, we immediately think of accident and incident investigation. And history strongly supports this perception. The government investigative agencies (NTSB, TSBC, AAIB, BEA, etc.) and the rest of industry still rely heavily on this method, conducting "accident," instead of "transportation" or "air safety," investigations.

What are the differences, and are they important? For starters, accident and incident investigations are reactive, not proactive. The efforts to improve air safety have their roots in the crash-fix-fly scheme, and, for the most part, in many countries (and minds), it is still the predominant approach. Second, accident, and particularly incident, investigations tend to be highly non-uniform in terms of their conduct and information dissemination. Similar events receive different levels of investigation by the same State, or in different States, and the information gleaned, lessons learned, or improvements proposed do not get the broadest promulgation.

If we investigate a situation involving aircraft A with airline B in country C, ideally the entire industry, not just country C, or airline B, or the manufacturer of aircraft A, should benefit. But to a fair extent, that isn't the case. And this is at least partially due to a lack of information sharing and dissemination. Real Levasseur (Chief of Air Investigations Operations, TSBC) intimated at this last aspect a year ago in his ISASI paper on investigation communication when he stated, "Our challenge is clear: each safety deficiency that we identify and validate during the course of our investigations must be addressed.... It is imperative that [safety communications] be targeted at the appropriate audience." It is a reality that barriers to communication and information sharing exist. Some are intentional, some are known, and some are significant. Many others are completely opposite, or some combination of those conditions.

In short, for the above reasons and more, by expending the bulk of our air safety resources conducting accident or incident investigations, we are not expanding the boundaries far enough to legitimately consider it a systems approach to air safety. This implies that we are not necessarily capitalizing on all opportunities, or making the most efficient or effective use of our resources. Thus, the question starts to become an issue of how we can derive the most, and most widespread, benefit for any given event or action. Just as the title theme for this year's seminar states, we need to investigate new frontiers in safety.

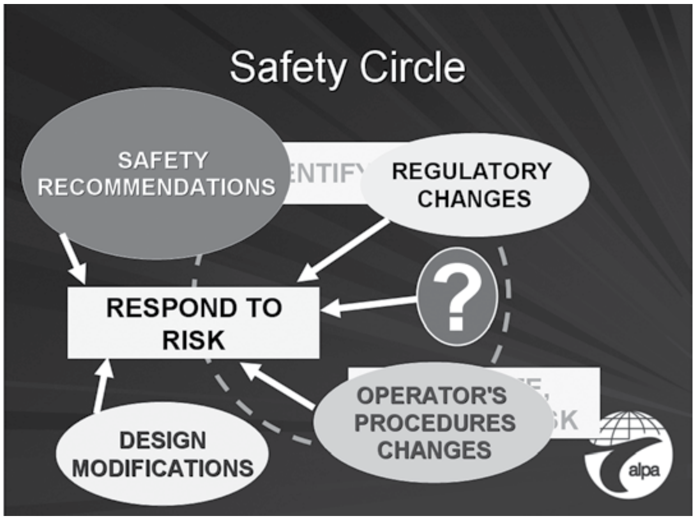
Therefore, it appears to the authors that the time is right for the collective "we" to more sharply focus on and more strongly advocate taking a systems approach to air safety. We need to take a look from several steps back, and map out the tools, elements, and processes that are, or can be, used to improve air safety, and to identify the weak or nonexistent efforts as well. We need to identify additional opportunities. It is time for a holistic approach, something akin to developing a sort of "unified field theory" for air safety. To that end, this paper will examine the historic and evolving methods of hazard identification and risk reduction, and attempt to point the way toward integrating the developing wealth of new tools, knowledge, and information into a coherent and effective safety strategy.

## Motivating factors and stakeholders

Now let's consider accident and incident investigations. We have to look at why most societies invest the majority of their investigative resources in efforts that arguably yield relatively small paybacks. What are their motivations; what are the perceived benefits to be derived?

What's the goal of accident investigation? This seemingly simple question has a perhaps not-so-simple answer. From an audience of investigators, the reflexive response would likely be the oft-repeated statement "to prevent future similar occurrences." That might be the most obvious and immediate goal, but there's more to it than that. A more sweeping and altruistic characterization might be something like "to improve safety and save lives." And yes, that is true, but there's more to this story. There are multiple forces in effect, and improved safety has numerous direct and indirect benefits aside from the altruistic one. These benefits can and do include several less-than-altruistic ones such as reducing costs, improving public perception, improving public confidence, improving profitability, etc.

In our context, a "hazard" is considered to be any condition that has the potential to lead to an undesired outcome, and "risk" is




defined as the product of that hazard and its probability of occurrence. Conversely, "safety" can be defined as the freedom from risk. In the air transportation system, risk is usually associated with incidents or accidents that result in injuries or death, or damage to or loss of equipment. But in reality, risk is far more sweeping than that: it can include not only these human or equipment risks, but also economic, political, and environmental risks as well. Accident and incident investigation can be considered as one manifestation of a risk-management strategy. This means that accident investigators, along with other aviation safety personnel, can be considered to be conducting some form of risk management.

Simple logic should lead one to the conclusion that it is far preferable to prevent experiencing the results of a hazard or risk in the first place, and that the means to accomplish this is to diligently work to identify, analyze, and mitigate hazards and risks *before* they are experienced. It should be equally apparent that accident and incident investigation is the exact antithesis to this strategy. This raises an obvious question: How did it come to pass that we operate like this? But perhaps a better question might be: Are we really using accidents and incidents as our primary means of identifying risk, or does investigation serve only to fill in the relatively small "gaps" that have been missed by other, more dominant risk identification and analysis efforts?

The safety payoff of an accident investigation is a function of many factors, including the effort and resources expended, the efficiency and focus (targeting) of the investigation, the characteristics of the participants, the existing state of relevant knowledge, and the myriad of biasing factors and competing priorities. We have all witnessed the occasional imbalance between the resources expended and the benefits obtained; we know that the "newsworthiness profile" of an accident is not necessarily proportional to its potential safety benefits, or vice versa. But there may even be a larger imbalance present. Is our overall approach to improving safety proactive and methodical, or more reactive and random? Are our pre-event (accident or incident) risk identification and analysis processes sufficiently robust? Do we place sufficient emphasis and attention on these efforts? Are they satisfactorily resourced?

To better answer the question as to why society expends significant resources on accident investigation, we should examine the drivers in the air safety process, the various stakeholders. Who are they? In the broadest sense, "stakeholders" are those persons and organizations with an interest in the outcome. There are actually multiple groups of stakeholders, and these groups can be differentiated by their respective roles in the air transportation system. In one (but not the only) arbitrary scheme, there are three distinct sets of stakeholders—the "providers," the "customers," and those who indirectly affect the safety of the industry. The providers would include the entities directly responsible for providing the safety in the air transportation industry. In our case, these would include such entities as aircraft and component manufacturers, the airlines, as well as their individual employees. The customers would include the traveling public, as well as those elements of society affected by an accident or incident. Those who can only indirectly affect the level of safety attained in a particular operation or State, by virtue of the fact that they are one step removed from the process, would include the regulators, the government (e.g., Congress), and the investigative agencies.

A closer look at some other influencing factors that differentiate the stakeholders, aside from the above-listed broad functional distinctions, is also warranted. Some of these are a result of national characteristics including culture, economics, national priorities, national prestige, international relations, and geographic location. Others might include more technologically based factors such as organizational or proprietary issues, military vs. civilian responsibilities, etc. Clearly, some of these differentiators are also barriers, and just as clearly, some are avoidable while others are not. Some are rather localized, and some are much more global in nature. Given all these influences, it is no surprise that from a worldwide standpoint, the safety situation is less than homogeneous.

So the stakeholders, the ones who drive the air safety process, are both numerous and diverse. This means that they will most probably have different motivations, have different perspectives, and be subject to different influences when it comes to managing risk. Certainly they will also have differing abilities to decrease the hazards. And that suggests that there is very likely no one-size-fits-all approach to improving air safety.

The issues and questions above should not preclude us from trying to map out a macro-scale view of potential safety improvement strategies. In fact, they should provide a greater impetus for initiating such an effort. Only after we complete a systems approach analysis of the overall safety effort will we be in the best position to chart the way forward. Accident investigations are the most conspicuous form of advancing safety, and certainly one effective means of doing so. But they are not the only, and likely not the best, means of advancing safety. We advocate that we get away from the historically reflexive, random, and opportunistic approach to safety and move toward a more methodical, measured approach in order to make the most effective and efficient use of our resources.

## Metrics and processes

Now that we have established that the motivations, resources, and other factors that drive air safety efforts are not homogeneously applied, it is appropriate to discuss the common factors that are used in, or affect, air safety efforts. In particular, we will look at the more prevalent metrics and processes in the industry.

In our attempt to develop the overall picture of the safety and safety efforts of the air transportation system, we recognize that this is an ambitious project, and beyond the authors' resources.

So instead, our goal is to develop the framework and course that would be necessary to do this. In that regard, we will necessarily present more questions than answers.

Establishing a baseline is an excellent practice in most endeavors, and this one is no different. So it follows that the first step should be to ascertain the current situation, primarily by determining the existing level(s) of safety with respect to a variety of "index variables." These index variables would be the denominators in any safety rate calculations, and would include such items as flight hours, number of departures, geographic locale, phase of operation, etc. Of course, these index variables could be combined with one another for more specific or focused studies, in an effort to determine the distribution of safety levels and to help locate areas of deficiency.

It is also necessary to quantify the means available and employed (or conversely, ignored) to improve safety. These would include the methods and tools, as well as the processes, organizations, and preferences that induce their respective use or non-use. The determination of the safety levels and safety means are not sequence-dependent, and these determinations can be done serially or concurrently. However, once both of these tasks have been accomplished, a correlation of the two sets of results should prove to be revealing. Deficiencies in safety levels or efforts, or reasons for those deficiencies, that otherwise might not be discernible in either study could be revealed by their correlation.

In the course of conducting these two baseline studies, there are a number of pertinent questions that would have to be answered in order to develop the most complete picture. In no particular order, these questions could include but are not be limited to the following:

- How do we define "safety"?
- What are the specific levels of safety?
- Who is measuring safety? Who should measure safety?
- What are the best denominators for the level of safety? Is it airline, State, global, or...?
- What is an acceptable level of safety? What is an unacceptable level of safety?
- Who is paying to improve safety? Who should?
- Who is benefiting from improved safety? Who should?
- Who cares if safety degrades, stays the same, or improves? Who should?
- Is safety a commodity, or a sales tool, or a business tool? Should it be any of those?

We have previously defined safety as "freedom from risk," and have discussed some of the means of developing safety indices, so it is appropriate to identify the methods that are used to measure and track safety levels. As a minimum, the safety measurement process requires the collection of information, analysis of that information, and conclusions from that analysis. Although dissemination of the conclusions is desirable, it is not mandatory for this part of the process. The collection of safety-related information is accomplished in a multitude of ways, but the raw information can always be readily placed into one of two basic categories—parametric or narrative. Obviously, when it comes to collection and analysis, parametric information is typically far superior. But until recently, raw parametric information was a relative rarity. The actual collection effort modes can be characterized using some of the following terms, many of which are not necessarily mutually exclusive.

**Examples of Information Collection Modes**

| | |
|---|---|
| Parametric/Numerical | Narrative/Perceptual |
| Dedicated | Ancillary |
| Voluntary | Mandatory |
| Regimented (controlled sample population) | Random (uncontrolled sample population) |
| Reactive | Proactive |
| Targeted | Event-precipitated |

Likewise, although there are many systems and methods used to collect, analyze, and disseminate safety information, they fall into just a few major categories. Several main categories, plus the responsible organizations and some specific examples of the programs and products (the means to disseminate the relevant conclusions or corrective actions), are presented (in approximate historical sequence) in the table below. To readers familiar with the subject, it should be obvious that these programs are not uniformly applied within or across any given entity (airline, State, etc.), or even over time, for that matter.

In the early period of aviation, accident investigation had served well to identify hazards and risks. Eventually it was recognized that accidents were not the sole means of gathering safety information, and the collection of incident information was begun.

The underlying concept for collecting incident data is best explained by Heinrich's Pyramid. This hazard model states that for every major accident there are a larger number of incidents, and a much larger number of unreported "occurrences" that in and of themselves are seemingly innocuous. While the exact ratios will vary, representative values indicate that there may be 10-15 incidents per accident, and possibly hundreds of "occurrences" per accident. In this context, accidents are considered to be events that result in hull losses or fatalities; incidents are events that result in injuries or damage; and occurrences are mistakes and/or failures that could have, but did not, result in incidents or accidents. Accidents are rarely the result of a single failure or mistake; it typically requires a series of events and circumstances to result in an accident, and indeed this is frequently referred to as the "accident chain." While these events may or may not be related to one another, they do enable the accident to occur, and, therefore, can be considered the precursors to the accident. Logic then dictates that if any of these precursors are removed, the accident chain will be broken, and the accident should not occur. From Heinrich's Pyramid model, we see that there should potentially be hundreds of opportunities to break the accident chain by identifying and removing the precursors. This underscores the utility and significance of collecting and analyzing incident data.

The information collection scheme was again modified to implement voluntary, non-punitive reporting systems in order to encourage more input. The FAA explicitly states this thought in its ASAP Advisory Circular, stating that the "focus is to encourage voluntary reporting of safety issues and events that come to the attention of employees of certain certificate holders. The program provides for the collection, analysis, and retention of safety data that would *otherwise be unobtainable*." [Emphasis added]

The primary weakness of incident reporting programs (BA-

**Selected Safety Information Paths**

| Risk Identification | Risk Identification, Analysis, and Response | | Risk Response |
|---|---|---|---|
| **Category** | **Responsible Organization(s)** | **Program Examples** | **Product Examples** |
| Accident and incident investigations | Investigative agencies, operator, manufacturer, association, private organizations | N/A | Safety recommendations, advisory circulars |
| Accident and incident databases | Operator, manufacturer, association, private organizations | ICAO ADREP, BASIS, CADORS, NTSB, FAA | ICAO ADREP, BASIS, CADORS, websites |
| In-service reporting systems | Operator, manufacturer, regulator | FAA SDR | Service bulletins, airworthiness directives |
| Administrative action database | Regulator | FAA Enforcement Information System | FAR interpretations |
| Mandatory incident reporting systems | Operator, NTSB | Operator event reporting systems | Operator safety bulletins |
| Voluntary incident reporting programs | Operator, manufacturer, regulator, association | NASA ASRS, ASAP | NASA Callback, Operator bulletins, etc. |
| Automated parametric | Operator-regulator collaboration | FOQA | Procedure changes (operator, ATC, etc.) |
| Industry collaborations | Operator, manufacturer, regulator, association | GAIN, CAST | Training curricula and materials |

SIS, ASRS, ASAP, etc.) is that they can only capture known, operational anomalies. If an anomaly is not detected by an individual, it is not reported; it is invisible or latent. Furthermore, these anomalies are predominantly procedural irregularities or failures, and they represent the exceptions rather than the norms. This data capture scheme reveals a loophole in the risk identification scheme: How do we capture all the precursors that are not detected by individuals as operating anomalies, or those that are "transparent to the user" because they either represent the status quo, or are not deemed to be hazardous? The answer is to look at normal operations, in order to detect the "transparent" events and conditions. But as little as a decade ago, this answer was not so obvious.

## Proactive safety programs

The last two rows in the Safety Information Path table contain the beginnings of the move away from accident and incident investigation and more toward proactive, global efforts to cull existing information for the purposes of identifying previously unknown or unaddressed risks. Several of these efforts are briefly discussed below.

One tool in this effort is referred to as Flight Operational Quality Assurance (FOQA). According to the FAA, "FOQA is a program for the routine collection and analysis of digital flight data generated during normal line operations. FOQA programs provide more information about, and greater insight into, the total flight operations environment. FOQA data is unique because it can provide objective information that is not available through other methods."

From this description it can be seen that FOQA is designed to complement incident reporting systems by capturing the information regarded as "normal" (i.e., non-anomalous). The primary information source for FOQA is the aircraft flight data recorder, and this information is quantitative, as opposed to the qualitative nature of ASAP. Like ASAP, FOQA programs are approved by the FAA on an individual carrier basis. It is the FAA's intent that the "information and insights provided by FOQA can improve safety by significantly enhancing training effectiveness, operational procedures, maintenance and engineering procedures, and air traffic control procedures."

Unlike ASAP, FOQA is less of a "real time" problem-reporting program and relies heavily on data analysis to identify hazards and risks. In the FOQA program, the FAA envisions that the operators would collect deidentified flight data in order to routinely monitor line operations. Additionally, the FAA expects that each operator would establish provisions and procedures for detecting and correcting any unsafe conditions and practices. Finally, the FAA plans to collect such deidentified aggregate data from all FOQA participants for use in its own analysis and potential corrective action efforts.

The FAA's inability to quickly develop universal FOQA program policies, procedures, and formal contractual language that would satisfy the operators' data privacy and abuse concerns delayed the widespread implementation of FOQA for several years. In the latter part of 2001, the FAA and industry finally overcame the two above-noted impediments to FOQA, and in April 2004 the FAA issued its Advisory Circular 120-82 on FOQA.

It should be made clear that operator participation in FOQA is discretionary, not mandatory. However, it will be very interesting to observe how extensively and quickly industry implements FOQA. Until very recently, most operators considered a FOQA a liability because of their concerns regarding access and application. Now that the necessary protective framework is in place, it is possible that operators that do not choose to implement FOQA programs could be viewed less favorably by the FAA, the courts, the general public, and the news media. This would be due to the (perhaps inaccurate) perception that these operators are not devoting sufficient attention or resources to safety. Regardless of the timing and scope of FOQA implementation, it is clear that this program represents a significant paradigm shift with respect to safety. The industry is truly becoming proactive instead of reactive.

A look back at the success of the accident-reduction efforts will be helpful prior to discussing some other efforts. Accident rates, and the historical reductions in accident rates around the world, vary. In several countries, particularly the U.S.A. and western Europe, the resources and efforts devoted to accident investigation have significantly reduced the accident rates. But by the mid 1990s those rates had leveled off, and it was recognized that existing methods of identifying hazards (such as accident and incident investigation) were no longer continuing to decrease the accident rates, and a new approach was needed.

The Global Aviation Information Network (GAIN) had its inception in May of 1996. As the FAA puts it, GAIN was proposed as a "voluntary, privately owned and operated network of systems that collect and use aviation safety information about flight operations, air traffic control operations, and maintenance to improve aviation safety worldwide." GAIN is facilitated by the FAA's Office of System Safety, but is almost completely dependent upon industry participation (in terms of resources and data) for its functioning. Conceptually, GAIN is the overarching initiative designed to enable the capturing and sharing of accident precursor information. This program is ambitious in scope for two reasons. First, while the concept of data capture is not new, the scale and depth proposed by GAIN is far beyond the typical industry practices of the day. Second, GAIN's synergistic approach to maximizing safety benefits by sharing data among different companies, organizations, and regulators from around the globe was definitely new and revolutionary.

GAIN differs from BASIS and the NASA ASRS program in some key ways. Unlike BASIS and ASRS, GAIN is not a database. Nor is GAIN intended to replace either of these programs, or any other similar ones. GAIN's widespread inclusion of, and reliance upon, many different facets of industry from many countries further differentiates it from these programs. GAIN's success is predicated on its ability to capture and share accurate and adequate information. Like BASIS and ASRS, GAIN is reliant upon deidentified data, but since GAIN crosses many boundaries, it is subject to many more obstacles than the other two programs. GAIN is intended to obtain its information from a variety of data sources, and here in the U.S.A., implementing these data-gathering concepts has proven to be significantly more difficult than anticipated.

Also in 1996, due to a series of high-profile fatal commercial aircraft accidents, the air transportation system came under scrutiny from the U.S. government and industry. Two government efforts (Commission on Aviation Safety and Security and the National Civil Aviation Review Commission) were chartered with examining the U.S. air transportation system and developing recommendations to significantly reduce the accident rates. Both recommended a fivefold reduction in accidents by 2007. In addition, the NCARC recommended that the FAA and industry work jointly on safety data analysis, and the FAA Administrator committed to developing a 5-year plan designed to focus FAA resources on the most promising accident prevention steps. In April 1998, the FAA publicly unveiled its new program "Safer Skies" to accomplish this.

Like FOQA, one underlying concept of Safer Skies is the approach of using historical data to detect and eliminate accident precursors. Unlike FOQA, Safer Skies is much broader in terms of scope and data sources. Although the bulk of the resources and effort are concentrated on commercial air transportation, Safer Skies was designed with three separate and distinct areas of application; commercial aviation, general aviation, and cabin safety. As the FAA noted in its original Safer Skies announcement, these were broken out as follows: "The commercial aviation initiative will focus on controlled flight into terrain (CFIT), loss of control, uncontained engine failures, runway incursions, approach and landing, and weather. The general aviation initiative will focus on pilot decision-making, loss of control, weather, CFIT, survivability, and runway incursions. The cabin safety initiative will focus on passenger seat belt use, carry-on baggage, child restraints, and passenger interference issues."

The Safer Skies functional concept involves assembling teams, comprised of individuals from various industry areas of expertise (e.g., propulsion, design, operations, etc.) that will then develop and utilize their own methodologies to achieve the stated goal(s). A principal element of this approach is that the teams are to first identify the leading causes of accidents, and then again apply the Pareto Principle to determine the most prominent causes and factors. Once this is accomplished, the teams will develop "intervention strategies" designed to prevent these causes and factors from leading to accidents. In this manner, the various segments of industry will engage in a coordinated, complementary effort with mutual goals, as opposed to working on possibly conflicting goals and competing with each other for relatively scarce resources.

Safer Skies is frequently referred to as a "data driven" approach, and the prioritization and coordination discipline used to obtain and evaluate the precursor data is also applied throughout the continuation of the process. Once the intervention strategies are developed, they must still be implemented in order to be effective. Once implemented, they need to be tracked to enable an assessment of their effectiveness, and information regarding this would then be fed back to the appropriate organizations in order to fine-tune the results. In theory, this highly disciplined approach minimizes wasted efforts and resources and maximizes beneficial results.

The Safer Skies teams were given essentially free reign to "mine" as much historical data as they could in order to ensure that they were not initially biased during their preliminary surveys and work program definition. To that end, the FAA provided a significant amount of resources and personnel. In addition, it was recognized early on that Safer Skies would be very reliant on accessing information from the data sharing "partnership programs" such as ASAP and FOQA, described above.

As of this writing, both the general aviation (GA) and cabin safety teams are quite far along in their efforts. The activities of the GA team are beyond the scope of this paper. The cabin safety team has relied heavily on FAA and NTSB databases, and employed a team primarily comprised of experts from the FAA, NTSB, and cabin attendant organizations. The efforts of this team are nearly complete. To date, their products include several public-awareness brochures and associated educational campaigns, some significant changes to and standardization of airline operating practices (e.g., seat belt use, carry-on baggage size limits), and at least one notice of proposed rulemaking (NPRM).

By far the most complex and extensive Safer Skies efforts are being conducted by the Commercial Aviation Safety Team (CAST). CAST focused on six separate categories of accident precursors, based primarily on accident type (CFIT, ALAR, LOC, UCEF, runway incursions, and weather). CAST is comprised of three types of working groups: Joint Safety Analysis Teams (JSAT), Joint Safety Implementation Teams (JSIT), and Joint Implementation Monitoring Data Analysis Teams (JIMDAT). CAST participants include representatives from government (e.g., FAA, NASA, ICAO, etc.), manufacturers, operator associations (e.g., RAA, FSF, ATA, etc.), and employee associations (e.g., ALPA, NATCA, etc.).

The CAST process is as follows: The JSAT effort comes first, with one JSAT assigned to each of the six each accident categories, and uses a predetermined methodology to analyze the accident data in order to determine the accident precursors and intervention strategies. In addition, the JSAT is charged with evaluating the expected effectiveness of these intervention strategies. Once the JSAT has developed proposed intervention strategies, these are handed off to the JSIT. The tasks of the JSIT include determining the feasibility of the intervention strategies, as well as developing and recommending the means to implement these strategies. Finally, the JIMT is responsible for monitoring the implementation of the intervention strategies, for evaluating their effectiveness, and for suggesting modifications to the overall CAST safety strategy.

Currently, the implementation and tracking phases are active in the CAST process. Remember that the goal was a fivefold (80%) decrease in the risk of a fatal accident by 2007, using 1997 as the baseline; the current CAST prediction is that we can expect to see an approximately 73% reduction if we remain on the current course and all planned interventions are implemented. In addition to this encouraging news, two other items are worth noting. First, the CAST tools, findings, and recommendations (interventions) are being passed to the other international safety groups such as ICAO, the Association of Asia Pacific Airlines, the African Safety Enhancement Team (ASET), etc. Several of these groups report that the interventions are sometimes being quickly implemented due to the relative lack of existing infrastructure or processes. Second, CAST has nearly completed its work of identifying risk-reduction strategies based on analysis of accident data, and has started the development of processes that will use incident and other information to identify emerging and changing risks. This effort is expected to further improve the risk-reduction benefits of CAST.

One question that has not yet been addressed is "who is doing all this data mining, and what are their qualifications?" In too many organizations, FOQA and other flight safety data analyses are conducted by interns, engineers, or others with little or no investigative experience or skills. This seems to be an accepted weakness in an otherwise robust concept and program. As air safety investigators, we are well-equipped to bring a new perspective and greater value to these efforts. Our investigative skills should not go unutilized until they are needed to investigate the next "smoking hole"; instead we should begin our integration into these proactive and data mining programs.

These programs and efforts represent a significant change to the U.S. air transportation industry's approach to safety. We are availing ourselves to enormous amounts of historical data in an effort to proactively eliminate accidents, instead of waiting to reactively investigate the next hull loss or fatal accident. It is difficult to see how GAIN, CAST, and other similar programs will not dramatically improve the overall safety of commercial air travel in the U.S.A. and throughout the world if widely pursued and applied.

### Additional aspects and influences

In addition to the methods and programs discussed above, there have been several other efforts and factors influencing the course of air safety. Some are dedicated and aimed at risk reduction, while others are peripheral or incidental. It is possible that we, as professional safety investigators, do not invest sufficient consideration, resources, or effort in exploring the potential impact (either positive or negative) that these factors may have on the overall safety environment.

Several examples of these would include:

- News media
- Passenger advocacy groups
- Information age
- National priorities and prestige
- Technologically advanced aircraft
- National and corporate economies
- Division of responsibilities between private and public sectors
- Proprietary considerations
- Cultural norms
- Communications

As we established previously, a systems approach considers the broadest view possible. Since any system is influenced by its environment, and all these factors represent segments of the air transportation system environment, we fall short of a thorough systems approach by failing to consider issues such as those above.

### The way forward

As we can see, the tools available to the air safety investigator have greatly improved over the last several years. Similarly, the expectations of the traveling public have been raised; they expect safer travel with fewer accidents, incident, and events. Therefore, it is fair to say that the role of the safety investigator also has to change from one of reactive (waiting for the incident or accident to happen), to proactive data-driven investigations that identify accident precursors before they result in accidents. In simple terms, we are replacing the "tinkicker's tin" with data, but it must be remembered that the goal (accident prevention) has not changed. Nor has our need to stay proficient in the art of tinkicking disappeared.

As the data-collection tools have advanced, so has our ability to analyze the data we have collected. The technologically advanced FOQA software, along with analysis programs and other data mining tools, are commercially available. Perhaps our greatest challenge is shifting our paradigms from the reactive to the proactive use of data. As safety investigators, we need to gain the comfort that is required to see beyond the numbers and use them to advance safety, as we have previously learned to do by investigating the tin.

Similarly, as a result of our communications networks and abilities, we can share, virtually instantaneously and globally, any lessons learned from any air safety investigation. Using existing resources and infrastructure that were not originally designed for safety applications, (such as the Internet) provides a critical element for improving our global aviation safety system in a timely fashion. This also has the significant but still relatively unrealized benefit of reducing the overall amount of resources required by eliminating duplication of investigative efforts.

Returning to the notion of the Safety Circle, we see that the three primary steps (collection, analysis, and response/communication) have all made significant advances in the recent past but are still not being utilized to their fullest potential. However, it does seem to us that we are on the right path, and what is really required is a greater appreciation of and investment in the many new proactive risk-reduction programs such as FOQA and CAST. We as air safety investigators need to become more involved in the day-to-day analysis of non incident/accident data. We as the tinkickers, along with our parent agencies, must begin to learn about and utilize these new tools and methods; our paradigm must begin to shift. We can not and should not wait around for the next accident. ◆

# GAIN Contribution to an Airline Safety Management System

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## Executive summary

This paper argues that we can only further improve aviation safety through the application of a system that addresses latent failures at an organizational level and manage safety risks as a vital component of corporate management through a safety management system (SMS). The SMS should be based on quality management principles and have as a goal the elimination and mitigation of safety risks that could cause or contribute to an aircraft accident or incident. For SMS to succeed, real-time information exchange between various industry groups is required to properly identify hazards and appropriately manage risks.

The GAIN initiative, launched a decade ago, aims at enhancing aviation safety through information sharing. It has been working since its inception to achieve that goal, and in doing so has contributed largely to the promotion of SMS through conferences and various freely available products that can help air carriers develop their own SMS and operate components of that system.

## Introduction

No doubt that the improvement in aviation safety through the years has made that industry one of the safest ways to travel nowadays. This has been mainly due to regulations and regulatory oversight, accident and incident investigations, prevention strategies including procedures, technological advancements, human factors studies, and safety management.

With deregulation and cheap travel, it also made aviation very economical, hence the continuous worldwide boom in the industry. Nevertheless, that boom is tightly linked to the public, well-founded perception of aviation as the safest and most efficient way to travel, as attested by the safety statistics.

However, the rising frequency of air travel and the "global" news network linking different parts of our planet and allowing the live transmission of events have increased the need to ensure that our skies become "accident free"; reducing the percentage of air accidents is not enough anymore, we have to address the gross number!

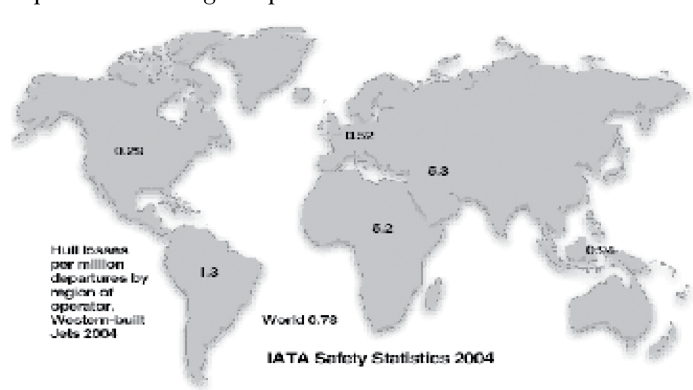
This paper will argue that we can only achieve that goal through a proper internal control and oversight system tailored to the need and requirements of every component of the aviation industry. Such a safety management system (SMS) is based on quality management principles and requires knowledge, data, data analysis, commitment, cooperation, and a corporate approach at an organizational level, in addition to smooth and on-time flow of information. The GAIN initiative, which aims to facilitate the on-time exchange of safety information, has largely contributed to that concept during the past decade, through various products and conferences.

## Safety and SMS

The developments of accident and incident investigation techniques have allowed us to identify on many occasions management failures that contributed to the disastrous end of many flights. It became essential to address those latent failures and manage all the safety risks associated with aircraft production, maintenance, or operation, bearing in mind that the risks being managed are those associated with causing or contributing to an aircraft accident or serious incident.

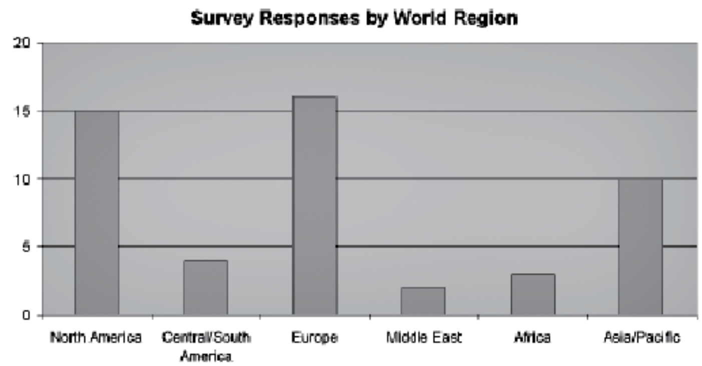
Therefore, aviation safety is becoming more and more a science, requiring extensive knowledge of the human element, technology, working environment, regulations, and, above all, business management. Management and decision-making at top managerial levels are where most latent failures lay and affect the outcome of air operations. This can only be addressed when we manage safety as an essential component of business and when we allow the safe and on-time exchange of essential safety information.

In June 2003, the GAIN GST published the result of its study entitled *Status of Safety Management Systems and Related Reporting Methodologies in GST Member Organizations.* That study has been based on a survey that aims at identifying those countries or organizations that have established safety management systems (SMS) that emphasize the importance of non-punitive collection, analysis, and sharing of safety information. An interesting comparison between the IATA safety statistics for 2004 and the responses to that survey will reveal that regions of the world where the accident statistics are the highest are the same regions where the least number of responses to the survey were received, reflecting either a lack of concern about SMS or the non-implementation of that concept. The following comparative table reflects that fact.



| *Region* | *Number of Responses* | *Accident Rate/ Million Departure* |
|---|---|---|
| North America | 15 | 0.29 |
| Central/South America | 4 | 1.3 |
| Europe | 16 | 0.52 |
| Asia/Pacific | 10 | 0.94 |
| Africa | 3 | 5.2 |
| Middle East | 2 | 5.3 |

It could also be interesting to notice that, while the global safety statistics are improving, the regional statistics in some of the above-mentioned region are deteriorating while the amount of air transport activity in those same region is increasing, making it an alarming safety issue. It must not be forgotten that any major air accident that occurs anywhere in the world is immediately transmitted through the "global" information news network worldwide, thus affecting the public perception of aviation as the safest way of transportation. The fact also remains that, either directly or through code-share, most air carriers cover most of the world regions, making it imperative to them to contribute in the enhancement of "global" aviation safety through the proper approach to safety management at an organizational level, a principle well-illustrated in the IATA IOSA program.




## SMS

In the above-mentioned study conducted by the GAIN GST, respondents were asked to provide their formal definition of SMS. Answers varied from "a process or approach to managing safety risks" (U.S.A. and Canada) to "a system requiring all parts in the aviation industry to take part in the safety work" (Sweden). The U.K.-CAA mentions in its CAP-712 Guide entitled *Safety Management Systems for Commercial Air Transport Operations* two definitions of SMS appropriate to commercial air transport operations:
"1) 'Safety Management' is defined as the systematic management of the risks associated with flight operations, related ground operations, and aircraft engineering or maintenance activities to achieve high levels of safety performance.
2) A 'safety management system' is an explicit element of the corporate management responsibility which sets out a company's safety policy and defines how it intends to manage safety as an integral part of its overall business."

An air carrier, being the process owner of an aviation service production system serving customers, must ensure continued revenue-generating operations as a purpose of its production system. For that, a well-defined financial management system (FMS) is implemented, where targets are set, budgets are prepared, levels of authority are established, a "checks and balances" component is included and monitoring elements are in place so that corrections can be made if performance falls short of set targets. The outputs from that system are usually felt across the organization and, though risks are still taken, the finance procedures should ensure that there are no "business surprises."

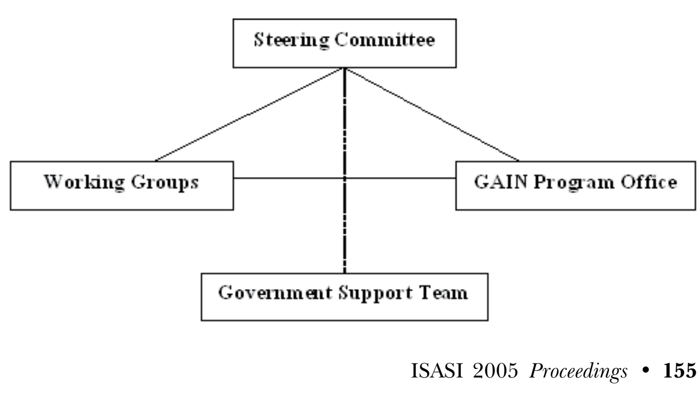
An air carrier, being the process owner of an aviation service production system serving customers, must also ensure as a purpose of its production system that risks associated with air operations are continuously eliminated or mitigated before they result in accidents or incidents. If there are, it can be disastrous for a small company and for the larger company; unwelcome news media attention usually follows an unexpected loss. Therefore, it should be apparent that the management of safety must attract the same focus as that of finance and result in an SMS that comprises at least the same system elements as an FMS. The output of an SMS should also be felt across the organization and, though risks are still taken, the safety procedures should ensure that there are no "safety surprises."

An air carrier SMS should be an open system that will respond to feedback from its specific environment to avoid hazards and mitigate risks. With aviation as a global and inter-dependent industry, that specific environment becomes wider and the associated hazards-identification process requires data sharing, collaboration, and open communication between various players in the industry to optimize the feedback processes. This is where the GAIN initiative comes in direct relation with SMS.

## GAIN

The Global Aviation Information Network (GAIN) was established a decade ago as "an industry and government initiative to promote and facilitate the voluntary collection and sharing of safety information by and among users in the international aviation community to improve safety." Since its establishment, GAIN has been working, in line with its driving motto "Enhancing Aviation Safety Through Sharing," to bring aviation theorists, regulators, and practitioners together to explore how better to procure, process, analyze, and share information that is vital to safety decision-making.

The fundamental organization of GAIN consists of a team of industry representatives grouped in a steering committee that "sets high-level GAIN policy, develops the GAIN Action Plan in collaboration with GAIN participants, and oversees the implementation of the Action Plan"; various working groups conduct tasks in various technical specialty areas and report to the steering committee; a Government Support Team (GST) formed from representatives of civil aviation authorities addresses the existing legal and regulatory environment that would inhibit implementation of advances in system safety, and the GAIN Program Of-



fice (GPO), funded and staffed by the FAA Office of System Safety, coordinates activities for all GAIN groups and conferences. The following figure illustrates the GAIN organization.

**GAIN working groups**

In order to understand the GAIN contribution to airline SMS, it is essential to review the working groups that were behind most of this contribution.

Working Group A, Air Operator Safety Practices, was formed with the objective of developing products to help operators obtain information on starting, improving, or expanding their internal aviation safety programs. The working group products included commonly accepted standards and best operating practices, methods, procedures, tools and guidelines for use by safety managers. This working group has been deactivated following the issue of the Operator Flight Safety Handbook and the Cabin Safety Compendium.

Working Group B, Analytical Methods and Tools, was formed with the objective of identifying and increasing awareness of existing analytical methods and tools by collecting, cataloging, and distributing resource materials. Requirements are usually solicited from the aviation community for additional analytical methods and tools and the development and validation of these methods and tools are promoted through the working group.

Working Group C, Global Information Sharing Systems, was formed with the objective of developing prototype systems to begin global sharing of aviation safety information. These prototype systems include sharing safety incident/event reports among airline safety managers in near real-time and effectively disseminating throughout the aviation community safety information that is "publicly" available.

The Government Support Team (GST) was formed with the overall objective to foster GAIN goals and to reduce impediments to sharing. Three focus areas supporting this objective are as identified as follows:

- "Promote and facilitate the non-punitive collection and sharing of safety among the worldwide aviation community;
- Help reduce legal and organizational barriers that discourage the collection and sharing of safety information; and
- Encourage government organizations to support the development and implementation of GAIN."

Working Group E, Flight Operations/ATC Safety Information Sharing, was formed with the objective of fostering increased collaboration on safety and operational information exchange between flight operations and air traffic control operations. This working group promotes a "just culture" and is also tasked to identify and document pilot/controller collaboration initiatives that improve safety and efficiency and promote such collaboration in training and education programs.

**SMS in practice**

The concept of SMS is based on closed loops in the information flow as well as actions within both small parts of the organizations and the outer loop involving the authorities and other organizations, such as IOSA or code-share partners. It rests on information collection systems and analysis, both on an ad-hoc basis and systematic trend analysis, where the output is a fact- risk-based safety surveillance methodology.

The three essential components of an SMS are

- a comprehensive corporate approach to safety.
- a structure that is organized to effectively achieve its safety objectives.
- systems to assess upon regulatory compliance and improve using industry "best practices."

So for an SMS to succeed, it requires the following elements to be implemented:

- management commitment and planning,
- data-collection procedures,
- hazard identification and risk management,
- occurrence and hazard reporting,
- incident analysis,
- safety management training requirements,
- emergency response plan, and
- documentation.

We shall now consider each of those elements and see where GAIN has contributed.

**Documentation**

Documentation is an essential component in any quality-based management system including SMS. While most documents published by GAIN contribute in some sort to elements of SMS, the *Operator Flight Safety Handbook* (OFSH) helps air carriers to develop their own safety manual or revise their existing one. It has been compiled using the expertise of various prominent members of the aviation industry and can easily be adapted to the requirements of various air operators.

This document has been revised since first published and includes in a generic way a description of an SMS, a management commitment statement by the CEO of the air carrier, human factors issues, organizational responsibilities, incident reporting, risk management and ERP. All of those topics are essential elements of SMS.

A Cabin Safety Compendium has also been compiled by a group of prominent experts from various aviation organizations and includes generic normal and emergency procedures related to cabin safety, hazard reporting and tracking, and internal audits.

**Management commitment**

The *CEO Statement on Corporate Safety Culture Commitment* at the beginning of the OFSH clearly demonstrates the terms in which an air carrier can outline its top management commitment to safety, where "safety excellence will be a component of our mission" and "senior leaders will hold line management and all employees accountable for safety performance and will demonstrate their continual commitment to safety."

The GST document *Status of Safety Management Systems and Related Reporting Methodologies in GST Member Organizations* reflects many SMS application experiences and shares related information gathered from ICAO, the U.S.A, Canada, the U.K., Scandinavia, New Zealand, Australia, and France. Throughout the document management commitment is emphasized.

In the *Roadmap to a Just Culture,* a GAIN document published in 2004, a just culture is defined as "a way of safety thinking that promotes a questioning attitude, is resistant to complacency, is committed to excellence, and fosters both personal accountability and corporate self-regulation in safety matters. A 'just' safety culture, then, is both attitudinal as well as structural, relating to both individuals and organizations. Personal attitudes and corporate style can enable or facilitate the unsafe acts and conditions that are the precursors to accidents and incidents. It requires not only actively identifying safety issues, but responding with appropriate action." The necessity of management commitment to implement a just culture as part of an SMS is thus well-established.

### Data collection and analysis procedures

In 2004, GAIN published a document entitled *The Status and Future Plans of FDM/FOQA in GST Countries.* The document is based on a survey sent to the nine GST member countries: Australia, Canada, France, Italy, Japan, New Zealand, Sweden (representing the Nordic Working Group), the United Kingdom, and the United States. They were asked to respond to a series of questions about the status and future plans of flight data monitoring and Flight Operations Quality Assurance (FDM/FOQA) programs in their countries. Among the questions asked was What FDM/FOQA guidance, direction, training, or assistance are you giving the following:

a) Your operators (letter of intent, CAP, etc.)
b) Your FDM/FOQA system suppliers
c) Your regulatory inspecting/audit staff

The answers provided allow air carriers and oversight authorities to develop, implement, and control that vital component of SMS within their organizations.

In another document published by GAIN in 2001 and revised in 2004 under the title of *Major Current or Planned Government Aviation Safety Information Collection Programs,* 38 fact sheets were published. They describe 38 different collection and sharing programs applied by various organizations within the GST countries and aim at facilitating "the creation or enhancement of similar reporting programs…worldwide," thus leading to improvements in the aviation safety management system and allowing those in the rest of the world to profit from those leading countries, experiences in order to fulfill that essential element of SMS.

The *Safety Event Descriptor Codes; International Standards Development* brochure published by GAIN in 2004 is an open invitation to the industry to participate in the "task to harmonize the existing event descriptor environment as used by safety event management systems to facilitate information sharing within the international airline community." The project is scheduled to end in September 2006 and should result in a completed documentation package containing framework specification, transition primer, and implementation guides. The advantage of a unified taxonomy is reduced time to prepare data for translation; therefore, direct reductions in cost of ownership can be realized in the analysis and sharing of safety information, which in turn should allow the airline safety office to derive additional benefits from their budgets, while at the same time getting more relevant safety information that allows them to manage their SMS in a better way.

It is also obvious that once data are collected, it is essential to analyze the data and share them in order to generate the benefits and be in a better position to manage associated risks. This is why GAIN has published many document to help air carriers achieve such objectives. The products include the *Guide to Methods and Tools for Airlines Flight Safety Analysis* prepared by Working Group B and published in 2003 "to provide information on existing analytical methods and tools that can help the airline community turn their data into valuable information to improve safety."

Another GAIN contribution in the field of SMS is the *Role of Analytical Tools in Airlines Flight SMS* first published in 2001 and further revised and reissued in 2004 to "examine the role of analytical tools in airline flight safety management systems and discuss some of the issues involved in the collection and analysis of flight safety data in support of airline safety management programs."

Examples of such activity have also been published by GAIN in the form of brochures such as the *Aviation Safety Analysis Tools in Action,* which reflects the experience of two major air carriers on both sides of the Atlantic, and seven other very elaborate reports published by GAIN between November 2000 and February 2005 including the 53-page report entitled *Application of Insightful Corporation's Data Mining Algorithms to FOQA Data at JetBlue Airways,* which resulted from a project funded by the FAA and supported by GAIN "to facilitate the application of advanced methods and tools in the analysis of aviation safety data with the goal of improving aviation safety industrywide." All those reports are published by GAIN and can be viewed and retrieved from the GAIN website, www.gainweb.org.

### Hazard identification and risk management

Section 7 of the GAIN OFSH is dedicated to risk management. That document was first published in 1999 and revised in 2001. In that section "risk" and "hazard" are defined and a description is included to explain how they can be "identified, analyzed, economically eliminated and controlled" in a commercial aviation enterprise in order to achieve "reasonable safety."

That section explains in a very simple way risk management, the true (direct and indirect) cost of risk, and the way hazards are translated into risks. Also explained is the fact that the risk management process is more comprehensive than an air carrier safety program, since it includes training and awareness, culture and attitudes, the ability of the operator to carry out self-assessment, loss prevention and control, in addition to auditing procedures—all essential components of an SMS.

In addition to that theoretical section published in the OFSH, GAIN addressed a very important component of risk management that might affect aviation safety through Working Group E devoted to pilot/controllers interaction. Many studies and documents have been issued by that Working Group to help the communication process between those two elements of air operations, identify hazards and manage associated risks. For that, documents have been developed such as *Pilot/Controller Collaboration Initiatives: Enhancing Safety and Efficiency, Evaluating the Benefits of a Pilot/Controller Collaboration Initiative, The Other End of the Radio: Identifying and Overcoming Common Pilot/Controller Misconceptions, and Roadmap to a Just Culture: Flight Operations/ATC Operations Safety Information Sharing.*

The GST objective of reducing impediments to the exchange of safety information has been published in 2001 in a document entitled *Reducing Legal Impediments to Collecting and Sharing Safety Information* where governments are invited to "become more effective in establishing and maintaining a non-punitive environment for the collection and sharing of information to improve aviation safety," thus facilitating the hazard-identification process and allowing air carriers to manage risks in a more comprehensive way.

### Occurrence and hazard reporting, incident analysis, and ERP

The OFSH deals in Section 5 with accident investigation and reports, in Section 6 with emergency response and crisis management, and includes in Appendix A example forms and reports.

The Cabin Safety Compendium published by GAIN in 2001 also includes in Section 5.1 a hazard tracking and reporting chapter dealing with issues related to cabin safety, such as the type of hazards to be reported by cabin crew, the way to report them, the processing and distribution of the report, and the report closure, thus generalizing that particular element of SMS and helping to generate the necessary data across the organization by involving all the persons concerned and enhancing the safety culture.

### Safety management training requirements

Safety management training requirements are also discussed in the OFSH Section 2.7 *Recruiting, Retention, Development of Safety Personnel* and in Section 2.8 *Safety Training and Awareness* where issues such as management safety awareness and training and the fundamentals of safety training are discussed. It describes the essential role played by training and development in SMS in the following conclusion: "effective resource management begins in initial training; it is strengthened by recurrent practice and feedback; and it is sustained by continuing reinforcement that is part of the corporate culture and embedded in every element of an employee's training."

All other GAIN documents also describe in detail the importance of training in the safety activities related to data collection, analyses, risk management, and other relevant issues discussed in each of those documents.

### GAIN conferences

GAIN held seven world conferences in various parts of the globe and a regional conference in Tokyo, Japan. Another GAIN regional conference was scheduled this year in Amman, Jordan, but was postponed due to administrative constraints related to the GAIN program.

The last world conference held in Montreal, Canada, in September 2004 was entirely dedicated to SMS. Regulatory authorities, air operators, and various industry groups shared their experience on the development, implementation, and operation of SMS within their organizations and the various GAIN working groups shared their accomplishments with the delegates.

The conference was a very successful melting ground where people from all over the world shared vital safety information and understood the necessity to implement SMS within their organizations. Ways for such implementation were exposed and tools were provided, thus adding enabling those organizations to develop their own SMS and make the "global" skies safer for aviation.

### Conclusion

For the past decade, GAIN has been contributing to the enhancement of aviation safety at a global level. That contribution couldn't have been achieved without the support and active involvement of various industry groups including the FAA, which provided the necessary administrative and financial support through the GAIN Program Office and the continuous assistance of the Office of System Safety (ASY).

The FY2005 Appropriations Act transferred that Office to the Associate Administrator for Regulation and Certification, renamed since as the Associate Administrator for Aviation Safety (AVS). The transfer included funding and staffing for the GAIN Program being assigned to AFS-900 FSAIC where it would be reorganized to better support the AVS mission: "to promote aviation safety in the interest of the American public and the millions of people who rely on the aviation industry for business, pleasure, and commerce."

That mission is best accomplished through protective safety/quality management systems that are "properly designed to control hazards by eliminating or mitigating associated risks before they result in accidents or incidents."

We can thus assume that GAIN will be further realigned with SMS and continue to contribute in very proactive, and probably more appropriate way, in the enhancement of the "global" aviation safety system.

We should always remember that aviation is a "global" business and that the more advanced we are, the more obligations we have to maintain the industry as the safest way of transportation and ensure that the public continues to perceive it as such. ◆

# An Analysis of Flight Crew Response To System Failures

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## Abstract

This exploratory study examined flight crew response to aircraft system malfunctions. The study sample consisted of 476 events of system malfunction for which good quality data were available. The data sample was limited to Western-built turboprop and jet aircraft operated by commercial operators. Only events that occurred between 1990 and 2000 were included in the sample. Failures of the following systems were included in the analysis: avionics and instruments, electrical systems, engine, flight controls, landing gear and hydraulic systems.

The results show that in 19% of the sample, crew response to system failures was inappropriate. The percentage of inappropriate flight crew response decreases from 25% for earlier generation aircraft to 4% for the newest generation. The percentage of inappropriate response shows differences when various systems are compared, the lowest percentage of inappropriate responses occurs for flight control system malfunctions (8%), the highest percentage for instrument failures (48%). Approximately 11% of the investigated cases of inappropriate flight crew response involved wrong detection, 38% involved wrong diagnosis/decision, and almost 51% involved wrong action. Annunciators have a pronounced effect on the probability of failure detection. Inherent cues play a relatively large role in decision failures. Inherent cues such as vibration, loud bangs, etc., can be compelling but are often not very conclusive and can even be misleading.

## Introduction and objective

Inappropriate crew response to system failures often plays a role in aircraft accidents. Flight safety could be improved further if inappropriate crew response to system failures would be prevented. The objective of this exploratory study was to identify and analyze factors that are potentially associated with inappropriate crew response to system failures.

## Research approach

The overall approach employed in this study was to

1. identify a sample of events involving aircraft system failures,
2. identify factors relevant for crew response using the accident narratives and literature,
3. analyze the information in the context of the central research question.

## Data sample

*Aircraft system categories*

The scope and size of this study did not allow for an analysis of all accidents and incidents for which information was available. To obtain a set of relevant accidents and incidents, a selection process had to be applied. For the sample to be as representative as possible, the selection was not restricted to a particular flight phase, type of aircraft, or geographical region. Instead, it was decided to focus the analysis on a limited number of aircraft systems.

Aircraft systems are classified by the Air Transport Association of America (ATA), and this classification system is widely used. For the purpose of this study, six systems from this list were selected for further analysis. Only systems that are considered critical to flight safety were selected. The number of different systems was limited to six as this proved to generate a sample size that was large enough to generate robust results yet small enough to allow detailed analysis by the research team. Analyzing accidents and incidents involving failures of particular systems had the additional advantage that it enabled a quicker search of incident databases.

Failures of the following systems were included in the analysis:

- Avionics and instruments
- Electrical systems
- Engine
- Flight controls
- Landing gear
- Hydraulic systems

*Instrument failures*

Instrument failures include failures of instruments (ATA 31) and navigation (ATA 34). Examples are failures and malfunctions of primary or backup flight instruments, such as a failure of the airspeed indicator. The selection may also include failures of the autoflight instruments (ATA Chapter 22, Autoflight), such as the autopilot; however, in case the latter failure results in flight control problems (e.g., control upset), it is classified as a flight control failure.

*Electrical failures*

Electrical failures include failures of electrical power (ATA 24). Examples are failures or malfunctions of the electrical power supply and systems. Failures or malfunctions of the auxiliary power unit are excluded since the APU is regarded as a separate system. Also excluded are incidents in which the only observation is smoke, haze, sparks, or a fire without additional electrical malfunctions.

*Engine-related failures*

Engine failures include failures of propeller (ATA 61), powerplant (ATA 71), engine (ATA 72), engine fuel system (ATA 73), ignition (ATA 74), engine air (ATA 75), engine controls (ATA 76), engine indicating (ATA 77), exhaust (ATA 78), oil (ATA 79), and engine starting (ATA 80). Engine fire protection and extinguishing (ATA 2611 and 2621) are also included. Engine failures include cases of mechanical damage to the engines, compressor stalls, and fuel contamination or fuel starvation. Engine fires are also included.

*Flight control failures*

Flight control failures include failures of flight controls (ATA 27), stabilizers (ATA 55), and wings (ATA 57). Also included are failures of the autoflight system (ATA 22) that directly affect control of the aircraft. Three types of a flight control failure were identified and included in the analysis:

- ***Control automation*** failures include failures and malfunctions of the autoflight systems (e.g., autopilot, autothrottle), flight management system, flight control computers, and navigation systems, for example.
- ***Control upset*** includes failures and malfunctions of any system resulting in a (uncommanded) flight upset and a temporary or permanent loss of control.
- ***Control surface and system*** failures include failures and malfunctions of the flight control surfaces or "general" aircraft handling and control difficulties that are related to the flight control system.

Accidents or incidents that are a result of flight control problems caused by weather conditions (e.g., windshear, icing) or human error are excluded from the "flight control failure" selection.

*Landing gear failures*

Landing gear failures include failure of the landing gear (ATA 32), with the exception of failures of brakes (ATA 3240), tires, and wheels (ATA 3245) and nosewheel steering (ATA 3250). This includes problems with extending, raising, or locking the gear and gear doors, and unsafe gear warnings. Not included in this selection are incidents and accidents in which the gear failed, was torn off, or collapsed during takeoff or landing. However, in some incidents, the gear was damaged during takeoff, while takeoff was continued. In that case, the accident/incident is included since the crew might encounter problems with the gear in the subsequent approach. Incidents where the crew simply forgot to lower the landing gear before touchdown are excluded as well.

*Hydraulic system failures*

Hydraulic failures include failures of the hydraulic system (ATA 29) in the flight phase from takeoff through landing.

## Data sources

Multiple data sources have been used to develop a set of relevant accidents and incidents. The NLR Air Safety Database (Reference 5 and 6) provided a large set of accidents and incidents, which have been reviewed in order to select those accidents or incidents that included a system failure as a significant factor. The NLR Air Safety Database consists of accident data from a large number of sources including official international reporting systems (e.g., ICAO ADREP), accident investigation agencies, and insurance companies (e.g., Airclaims). Full accident reports for selected cases were directly obtained through the accident investigation boards if such reports were available.

## Accident/incident sample and inclusion criteria

The NLR Air Safety Database was searched for accidents and incidents in which a system failure was a significant factor. The search was limited to accidents and incidents that were reported through mandatory incident reporting systems. Voluntary reports such as those collected through the Aviation Safety Reporting System (ASRS) were not used because they can contain unverified and subjective information. The following selection criteria were applied to the database in order to obtain a first set of aircraft accidents and incidents:

1. The accidents or incidents involved aircraft operated by commercial operators, including
   - freight operators,
   - air carriers involved in public transport,
   - business jet flights (e.g., corporate jets),
   - scheduled and non-scheduled flight, and
   - international and domestic flights.

   But excluding
   - military and government flights, and
   - training and experimental/test flights.
2. Aircraft involved in an accident or incident include
   - Western-built aircraft, including manufacturers from North America, Europe, Israel, and Brazil. Eastern-built aircraft were excluded because they were considered not to be representative of FAR 25 certified aircraft.
   - Fixed-wing aircraft, excluding accidents with helicopters.
   - Turbojet and turboprop aircraft, excluding piston-engine aircraft (piston engine aircraft are considered to be not representative of current and future designs).
   - Aircraft in the takeoff weight category of 5,700 kg (12,500 lbs) or higher.
3. The aircraft accidents and incidents occurred in the time span 1990 through 2000.
4. Accidents involving sabotage, terrorism, and military action were excluded.
5. Accidents and incidents in the flight phases from takeoff through landing, including the takeoff roll and landing rollout, but excluding the taxi phase. The taxi phase and standing at the gate were purposely excluded. Although system failures occur relatively frequently during those phases (especially immediately after "powering up" the aircraft and after engine start), the response of the flight crew to system failures is considered to be not representative of the response to inflight failures.

Application of these criteria to the database resulted in a data set containing more than 5,000 records of accidents and incidents. This dataset was further reduced by selecting failures of any one of the six selected systems only (i.e., avionics/instruments, engine, electrical systems, hydraulic systems, landing gear, flight controls). Selection was initially done by searching on key words, followed by individual reading of the accident synopsis by the research team to determine whether the case was actually relevant for the purpose of this study.

For example, an accident where the landing gear fails to extend and the crew has to cope with an "unsafe landing gear" situation is more relevant for this study than a failure of the landing gear upon touchdown due to a hard landing.

Note: The selected systems are not standalone but are in many cases interrelated or even integrated. The hydraulics system is used to power the landing gear and possibly flight control surfaces, instruments are driven by electrical power, and the engines generate electrical power and hydraulics power. The purpose of this study is not, however, to define system boundaries. In cases of doubt, it was left to the interpretation of the researchers to determine whether the case was relevant and which system was involved.

Because of the accident/incident inclusion criteria described above, the final sample cannot be considered a representative random sample of all (reported) incidents that include aircraft system malfunctions.

The final data sample that was used in the analysis consists of 476 accidents and incidents. For each of those cases, additional information was collected as described in the following section.

## Further data collection and analysis

*Aircraft generation*

Since the development of certification regulations around 1970, much research has been conducted in the field of human factors, resulting in a better understanding of human behavior. This is reflected in the design of current generation flight decks. To investigate whether this has also resulted in better crew response to system failures, the effect of aircraft generation was included in the analysis. Four generations of aircraft are distinguished.

*First generation*

These aircraft are typically designed in the 1950s, when there was limited knowledge on, for instance, fatigue of metal structures. Certification was typically before 1965, based on, for example, old British Civil Airworthiness Requirements (BCAR). The engines are first production turbine engines. The aircraft have very limited cockpit automation, simple navigational aids, and no or limited approach equipment. Examples of this generation are Fokker F-27, deHavilland Comet, and Boeing 707.

*Second generation*

Designed in the 1960s and 1970s, these aircraft have better and more reliable engines. Certification was between 1965 and 1980, not yet based on common JAR25/FAR25 rules. The cockpit is better equipped, for instance, with better autopilots, autothrottles, flight directors, and better navigational aids. Examples of second-generation aircraft are Fokker F-28, Boeing 737-200, and Airbus A300.

*Third generation*

The aircraft design of the 1980s and 1990s typically shows consideration for human factors in the cockpit. The flight deck contains electronic flight instruments systems (EFIS) and improved autopilots. Furthermore, jet aircraft of this generation are equipped with engines of a high-by-pass ratio. Aircraft are equipped with performance-monitoring systems. Examples are the Fokker 100, Boeing 737-400, and Airbus A310.

*Fourth generation*

Aircraft are highly automated and equipped with fly-by-wire systems and flight envelope protection. Examples are Airbus A330 and Boeing 777.

## Type of failure manifestation

For the purpose of this analysis, in each of the cases the way in which the failure manifested itself to the flight crew was classified according to the following list:

- Annunciator. This includes warnings or cautions (lights or aural), stickshaker action, warning flags, and system status lights that indicate a malfunction.
- Flight deck instrumentation. This includes abnormal status indications on instruments. An example is slowly rising EGT shown on the EGT gauge.
- Inherent cues. This includes unusual sound, vibrations, abnormal control forces, visible smoke or fire, etc.
- Information from third parties. This includes cases where third parties, such as cabin crew or ATC, report malfunctions to the flight crew.
- No observation.
- Unknown.

## Crew response

For each of the cases, it was determined whether the response of the flight crew was appropriate or inappropriate.

Flight crew is defined as the combination of captain and copilot, or captain, copilot ,and flight engineer in earlier-generation aircraft. For the purpose of this study, the "appropriate" response is regarded from the perspective of the aircraft manufacturer. Appropriate response is defined as a correct execution of the correct procedure, where the correct procedure is the procedure as defined by the aircraft manufacturer. In some cases, the flight crew correctly followed procedures published by the airline, but the airline's procedures were not in accordance with those recommended by the manufacturer. These cases were classified as "inappropriate response."

Flight crew response to a system failure can be divided into three distinct components

- Detection
- Decision or diagnosis
- Action

In the "detection" step, the crew perceives the "raw" information. This can be due to a fire warning going off in the cockpit, but also an unexpected motion of the aircraft, a strange noise, etc. In the decision step, the flight crew diagnoses the problem. Based on the result of this diagnosis, the flight crew decides on the corrective action to be taken, e.g., which procedure to follow.

For each of the sample cases, it was determined whether each of these three steps had been accomplished correctly or incorrectly. Similar to the determination of appropriate and inappropriate response, a case where an airline provided the flight crew with incorrect procedures was classified as "wrong action," regardless of whether the flight crew followed that procedure "according to the book."

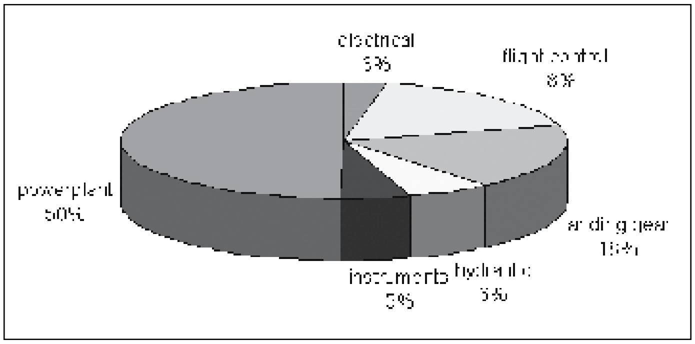

*Figure 1. Distribution of system failures among total sample.*

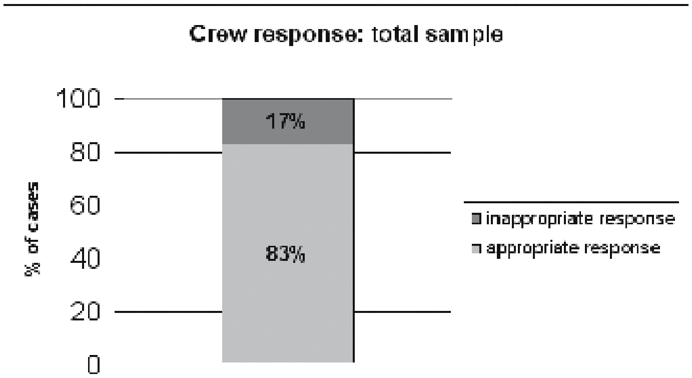


*Figure 2. Crew response: total sample.*

## Findings

Figure 1 shows the relative proportions of failed systems in the total study sample of 476 occurrences. Almost half of the cases are powerplant-related malfunctions. The landing gear and flight control system each account for slightly less than 20% of the total sample. Failures of the hydraulic system, electrical system, and flight instrumentation are relatively less frequent. Note that these figures do not represent the relative frequency of occurrence of failures of the different systems in day-to-day operations; it only represents the relative frequency *in the data sample*.

Percentages of appropriate and inappropriate crew response cases in the total sample of 476 are presented in Figure 2. Crew response was inappropriate in approximately one fifth of all cases.

A comparison of crew response for different aircraft generations (Figure 3) shows that the percentage of inappropriate response decreases for newer generations of aircraft.

Figure 4 presents a comparison of crew response to system failures for turboprop- and jet-powered aircraft. Perhaps surprisingly, there is no statistical significant difference between these two classes of aircraft.

When a comparison is made of flight crew response to system failures for the different aircraft systems that were included in the study, as shown in Figure 5, large differences can be observed.

In particular, the percentage of inappropriate responses to failures of instruments seems very high. It must be noted that this observation is based on a rather small sample of 23 cases.

Figure 6 shows a comparison between turboprop and jet aircraft of the percentage of "inappropriate response" cases, for each of the types of aircraft systems.

Instrument failures show the largest difference between jets and turboprops; however, the total sample of instrument failures

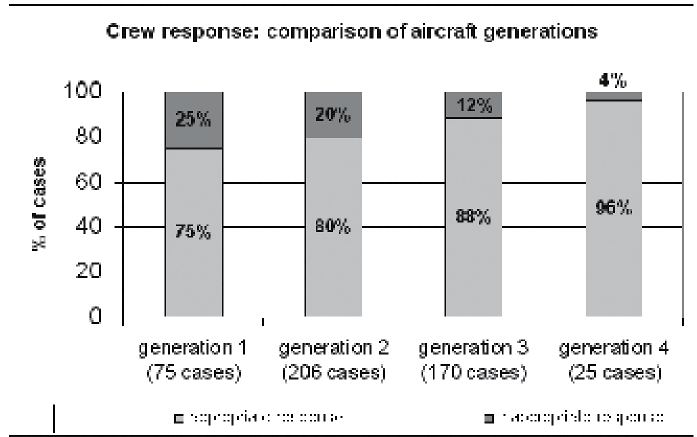


*Figure 3. Crew response: comparison of aircraft generations.*

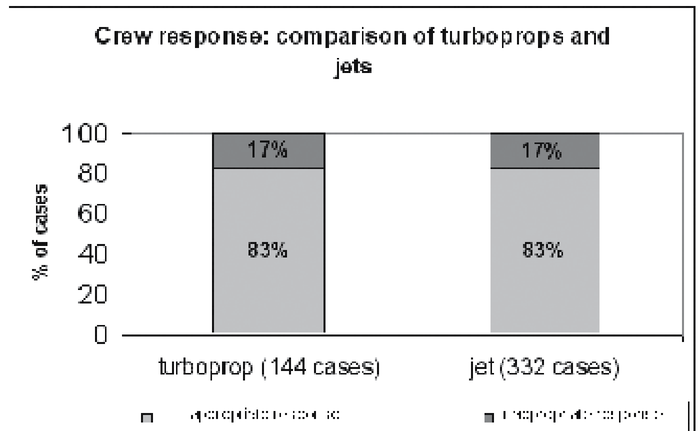


*Figure 4. Crew response: comparison of turboprop- and jet-powered aircraft.*

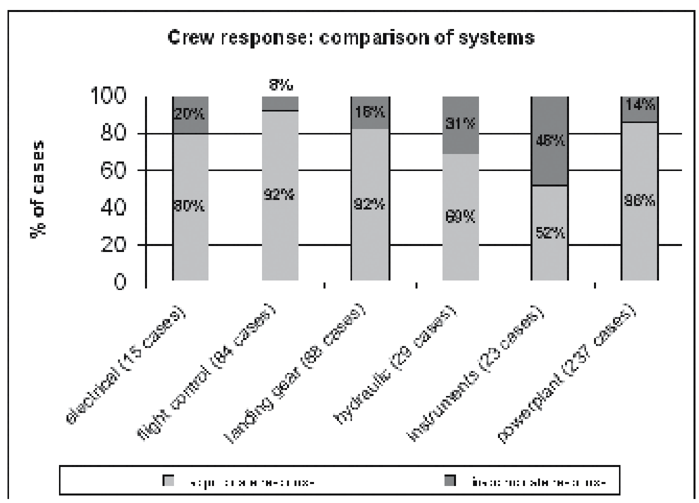


*Figure 5. Crew response: comparison of systems.*

in turboprop aircraft consists of only three cases. The statistical reliability of this information is low. Similarly, the total sample of hydraulic failures in turboprop aircraft consists of only five cases. Again, the observed difference between jet and turboprop aircraft with respect to response to failures of the hydraulic system is statistically not very robust.

The sample sizes for the flight control system, the landing gear, and the powerplant are large enough to provide statistically ro-

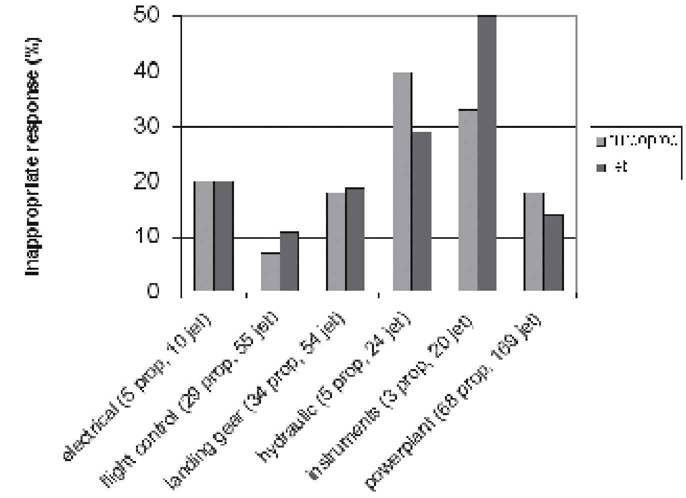


***Figure 6. Comparison of inappropriate crew response for turboprop and jet aircraft for different systems. Numbers in brackets behind categories refer to total number of cases (appropriate and inappropriate response) of the study sample.***

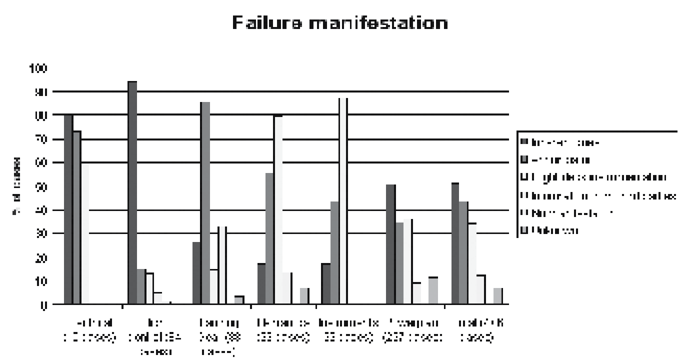


***Figure 7. Failure manifestation.***

bust data. The percentage of inappropriate responses to flight control system malfunctions is lower for turboprop aircraft than for jet aircraft. This may be due to the fact that the flight control system of turboprop aircraft is in general much simpler than that of jet-powered aircraft, reducing the possibility of, for example, autoflight mode confusion. The percentage of inappropriate responses to malfunctions of the landing gear system is similar for turboprop- and jet-powered aircraft. Because there are no basic differences between the landing gear system of a jet-powered aircraft and that of a turboprop aircraft, this result is no surprise. When comparing the percentage of inappropriate responses to powerplant malfunctions, it is again not surprising that this percentage is higher for turboprop-powered aircraft. A failure of a turboprop engine results in a more complex situation because of the necessity to feather the associated propeller and the implications for the flight characteristics of the aircraft.

The way in which the system failures manifested themselves is shown in Figure 7 for each of the six different systems that were analyzed and also for the total sample. Note that these categories are not mutually exclusive: a failure can manifest itself simultaneously in a number of ways. Therefore, the percentages for each of the categories add up to more than 100%. For example, an engine fire can trigger an engine fire warning light (annunciator), while simultaneously the pilots see flames coming from the engine (inherent cues) and they are advised by ATC of an engine fire (information from third parties).

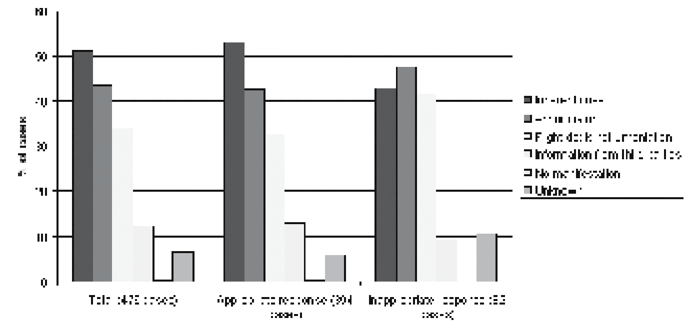

***Figure 8. Comparison of failure manifestation for appropriate and inappropriate flight crew response.***

Large differences can be observed among the different aircraft systems. For instruments and the hydraulic system, the primary source of information is the flight deck instrumentation. Failure manifestation to the flight crew from inherent cues, such as unfamiliar sounds, smoke, etc., are relatively infrequent for those types of failures. For the landing gear, the most important manifestation is an annunciator system, in this case the gear indicator lights. A significant portion of information is also provided by "information from third parties." In this case that would primarily be ATC providing the flight crew with information on the status of the landing gear. It must be noted that in those cases the flight crew is already aware of problems with the landing gear and a fly-by is made for visual confirmation of the problems.

Electrical failures are perceived through annunciators (e.g., generator fail light), flight deck instrumentation (this can also be the popping of a circuit breaker), but also by inherent cues. This is in many cases the occurrence of smoke or a burning odor.

The vast majority of flight control failures are detected by the flight crew through uncommanded aircraft movements or unexpected control forces (inherent cues).

Propulsion failures are detected in the majority of cases by inherent cues. In this case, the crew would observe loud bangs (in the case of compressor stalls or uncontained failures), vibration, or aircraft yaw. Annunciator systems (engine fire warning) and flight deck instrumentation (EGT, N1, etc.) are also important.

In conclusion, the importance of the "inherent cues" group, i.e., unfamiliar noises, uncommanded aircraft movements, observation of smoke, unexpected control forces, etc., must not be underestimated.

To investigate whether the type of failure manifestation would have an effect on the appropriateness of flight crew response, the failure manifestation of the "appropriate" and "inappropriate" flight crew response cases have been compared in Figure 8. The results show that in the case of inappropriate response, the detection by "inherent cues" is relatively less frequent. The annunciators and flight deck instruments are relatively more prevalent for the inappropriate flight crew response cases. However, the differences are relatively small and may not be statistically significant.

As was explained in the previous section, flight crew response comprises three steps: detection, decision, and action. The inappropriate flight crew response cases were analyzed to determine

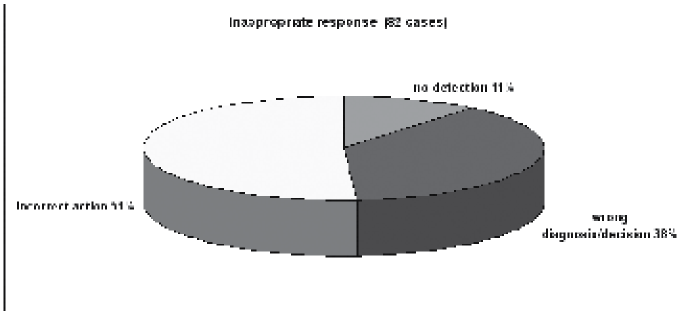


*Figure 9. Failed response steps in cases of inappropriate response.*

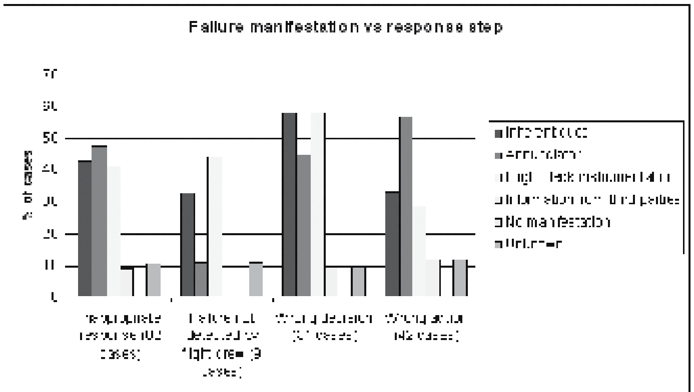


*Figure 10. Failure manifestation for failed response steps.*

which of these steps failed. The result is shown in Figure 9.

The majority of inappropriate responses (51%) involve cases where detection and diagnosis of the failure was correct, but the subsequent action was wrong. In 38% of the cases, the crew failed to correctly diagnose the problem. In 11% of the cases, the failure was not detected by the flight crew.

Combining failed response steps with the type of failure manifestation results in Figure 10.

Notice the pronounced effect of annunciator systems on the probability of failure detection. Also, it can be seen that inherent cues play a relatively large role in diagnosis/decision failures. Inherent cues such as vibration, loud bangs, etc., can be compelling, but are often not very conclusive or even misleading.

## Discussion

The study analyzed 476 aircraft incidents and accidents that involved system malfunctions, using world-wide accident and incident data for 1990 to 2000. The aircraft involved were operated by commercial air carriers or charter operators.

The results show that in 17% of the cases the response by the flight crew to the system malfunction was inappropriate.

The frequency of inappropriate flight crew response to a system malfunction reduces for newer aircraft generations. To some extent this may be attributable to improvements in cockpit design. However, newer aircraft are generally operated by first-tier airlines and are in many cases flown by first-tier pilots. To what extent the lower frequency of inappropriate responses can be attributed to improvements in flight deck design or to other factors such as crew training cannot be determined from this data.

According to the data sample, the frequency of inappropriate flight crew response is similar for turboprop- and jet-powered aircraft. Comparison of the results between turboprop- and jet-powered aircraft for each of the systems that where included in the analysis does show differences. Flight control malfunctions lead to relatively more inappropriate responses in jet aircraft, and powerplant malfunctions lead to relatively more inappropriate responses in turboprop aircraft, while landing gear malfunctions do not show a difference between jet and propeller aircraft.

The difference for the flight control system may be explained by the fact that the flight control system of turboprop aircraft is in general much simpler than that of jet-powered aircraft, reducing the possibility of, e.g., mode confusion. Because there are no basic differences between the landing gear system of a jet-powered aircraft and that of a turboprop aircraft, it is no surprise that no differences are observed with respect to the percentage of inappropriate responses. When comparing the percentage of inappropriate responses to powerplant malfunctions, it is again not surprising that this percentage is higher for turboprop-powered aircraft. A failure of a turboprop engine results in a more complex situation because of the necessity to feather the associated propeller and the implications for the flight characteristics of the aircraft.

The results of this study also show that the frequency of inappropriate responses to system malfunctions decreases for newer generations of aircraft, reflecting the improved design of the flight deck crew interface in more modern aircraft. The importance of hardware design is underlined by the fact that the relative frequency of inappropriate crew responses shows large differences when various systems are compared. The lowest frequency of inappropriate responses occurs for flight control system malfunctions (8% inappropriate response), the highest frequency for instrument failures (48% inappropriate response). Because of the large differences that have been observed, it is recommended to include other flight critical systems, such as navigation and communication systems, in future research. It would also be useful to expand the data set for those systems where the current sample size is very low (electrical system and instruments).

Flight crew response to system malfunctions comprises three steps: detection, diagnosis/decision, and action. An analysis of 82 cases of inappropriate response shows that 11% of those cases involved failure of the flight crew to detect a problem, 38% involved wrong decision, and almost 51% involved wrong action.

In many cases, a system failure manifests itself in different ways. The most frequent manifestation is by inherent cues, i.e., visible smoke, unexpected aircraft movements, unfamiliar sounds, etc. The second most frequent manifestation is from flight deck instrumentation or annunciators, such as a warning light. When comparing failure manifestations for cases of appropriate and inappropriate flight crew response the differences are small and may not necessarily be statistically significant. Comparison of failure manifestations across systems does show large differences, however. For flight control system malfunctions, the failure is manifested in more than 90% of the cases by inherent cues. For hydraulics and instrument malfunction, the failure manifestation in 80% of the cases is from the flight deck instrumentation, i.e., needles in the red region, volts going to zero, etc. For landing gear malfunctions, the most frequent (85%) manifestation by annunciators, in this case the unsafe gear light.

Annunciators have a pronounced effect on the probability of failure detection. Inherent cues play a relatively large role in decision failures. Inherent cues such as vibration, loud bangs, etc., can be compelling, but are often not very conclusive or even misleading regarding the nature of the failure.

While these results in themselves provide insufficient information to draw firm conclusions, the large differences that have been observed among systems of the type of failure manifestation as well as the percentage of inappropriate response cases suggest that additional research would be useful.

## Conclusions

For the data sample as described in this report, the following conclusions can be drawn:

- The percentage of inappropriate flight crew response to system failures decreases from 25% for earlier-generation aircraft to 4% for the newest generation.
- The percentage of inappropriate crew responses shows large differences when various systems are compared. The lowest percentage of inappropriate responses occurs for flight control system malfunctions (8%), the highest percentage for instrument failures (48%).
- Inappropriate response to flight control system malfunction occurs relatively more frequent in jet aircraft. Inappropriate response to engine malfunction occurs relatively more frequent in turboprop aircraft.
- Approximately 11% of the investigated cases of inappropriate flight crew response involved wrong detection, 38% involved wrong diagnosis/decision, and almost 51% involved wrong action.
- Annunciators have a pronounced effect on the probability of failure detection. Inherent cues play a relatively large role in decision failures. Inherent cues such as vibration, loud bangs, etc., can be compelling, but are often not very conclusive and can even be misleading. ◆


## Acknowledgements

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# Boeing Runway Track Analysis

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## Abstract

Over the last few years, Boeing has developed a runway track analysis that has been of significant help with visualizing and understanding incident investigations. The analysis converts the FDR recorded data (time based) into position data (distanced based). The position-based data are plotted to create a map of the airplane's track over the runway. This process makes it much easier to visualize what actually happened, and what airplane or runway factors may have contributed. A profile and flightpath of the final approach can also be created to help understand what factors may have contributed to the incident. This paper reviews the Boeing methodology and provides several examples where this analysis was of benefit to the investigation of the events.


## Introduction

The Boeing Aerodynamics, Stability, and Control Group has developed a runway track analysis to help visualize factors that may have contributed to an event. This analysis has proven helpful when investigating runway-based events such as runway excursions (off side of runway) or runway overruns (off end of runway). The analysis can combine multiple sets of investigation data, including time-based FDR recorded data, distance-based ground scar data, or time-based CVR data, when available. These varying sets of data are combined into a single graphic depiction of the airplane's track over the runway, and also allows key FDR parameters to be viewed as the airplane approaches, touches down, and decelerates down the runway. The analysis of the FDR data relative to position on the runway allows for easy understanding of the factors that may have influenced the airplane's flightpath, including wind effects, timing of control inputs, touchdown point, etc.

Boeing recognizes that this type of analysis may not be entirely new, and that others may have developed a similar approach or capability. This paper discusses the general approach used by Boeing in developing the runway track analysis. This analysis capability is available from Boeing to aid the investigation agencies with their investigation of incidents or accidents

## Overview

There are several methods of calculating the airplane's position (ground track), including integration of the FDR acceleration data, integration of FDR ground speed, and ground track angle, using FDR localizer, and ground speed data, using FDR latitude and longitude data. For each method, assumptions must be made, and each has advantages and disadvantages. Typically, ground track analyses are performed for events occurring near a runway. Using the FDR latitude and longitude data is impractical for this due to poor resolution (only accurate within several hundred feet) and slow sample rate. Many times, key parameters are not recorded (as with older airplanes) or are not valid, resulting in the data not being available on the FDR recorded data set. Additionally, the typical FDR sample rate may be too low for a dynamic situation occurring on the runway.

The methods for analyzing events near a runway and calculating the ground track have been refined by Boeing through the many FDR analyses conducted every year. These methods can provide reasonable results in the presence of many FDR data shortcomings. This runway track analysis has proven particularly helpful for incidents involving older airplanes that have relatively few recorded FDR parameters. The process described below is used by Boeing to accomplish this, followed by the various methods used to calculate the runway track.

## Kinematic consistency of FDR data

It must be recognized that the accelerations measured by the accelerometers and recorded by the FDR are never completely "zeroed," resulting in a bias (or offset) from the actual acceleration. These biases are not always evident when plotted as time history data, but will result in errors when integrating acceleration to get velocity and position. Also, peak load factors occurring during dynamic events may not be captured by the FDR because of relatively low sample rates for acceleration. If the uncorrected, low sample rate FDR accelerations are integrated, the resulting ground speed, drift angle, and altitude will not be consistent with those recorded by the FDR. Thus, the biases must be removed before integrating the FDR-recorded accelerations to get velocity and position.

Because of these issues, a kinematic consistency process is used to correct the FDR data and calculate additional parameters. Kinematics is a branch of dynamics that describes the motion of bodies without reference to the forces that either caused the motion or are generated as a result of the motion. Kinematic consistency process is a general practice used at Boeing for processing flight test data and FDR data to ensure consistency of position, speed, and acceleration data. A Boeing-patented program called KINCON (KINematic CONsistency) is used to accomplish this.

The Boeing KINCON process involves an optimization routine to calculate and remove the biases inherent in the FDR ac-

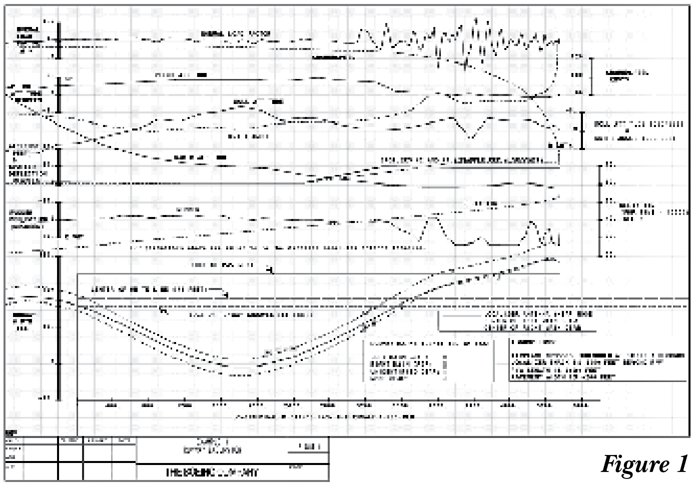


*Figure 1*

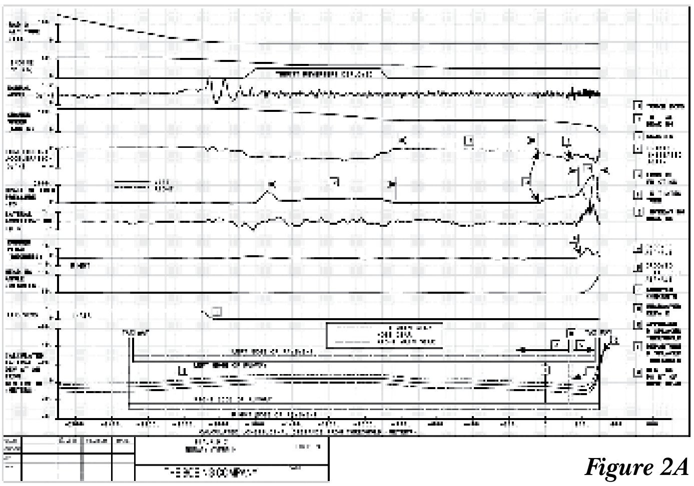


*Figure 2A*

celeration data. This process ensures that integration of the corrected acceleration components result in a ground speed, drift angle, and altitude that are consistent with those recorded on the FDR. The kinematically corrected acceleration components can then be used to derive additional information such as ground track profiles, wind information, or other parameters with higher frequency content than were recorded on the FDR.

KINCON will re-sample the data set to match the sample rate of normal load factor ($N_Z$), which is typically the highest sampled parameter on the FDR. Interpolation is used when re-sampling, which may "clip" the peaks of some dynamic parameters. Therefore, it is important to continue to use the recorded FDR time history data to obtain the peak values of critical parameters in conjunction with the runway track analysis.

Overall, the Boeing KINCON process provides the following:
- Removes erroneous constant biases from FDR accelerations ($N_Z$, $N_Y$, $N_X$), independent of external winds or control surface inputs. This ensures accelerations are kinematically consistent with FDR ground speed, drift angle, and altitude.
- Generates reasonable and smooth angle, angular rate, and angular acceleration data to match FDR recorded Euler angles (pitch attitude, bank angle, and heading).
- Calculates airplane state parameters in place of ones that are invalid or not recorded on the FDR.
- Re-samples all parameters to match the sample rate of normal load factor, resulting in higher sample rates than recorded on the FDR for most parameters.
- Calculates winds at higher sample rates and accuracy than is typically recorded on the FDR.

**Runway distance calculation methods**

The accuracy of the runway track analysis is a function of the number of parameters recorded on the FDR and the quality of those parameters (e.g., resolution, sample rate, availability). Older airplanes typically have less information recorded and, therefore, require more assumptions be used for the analysis. In the past, this runway track analysis has proven particularly helpful for incidents involving older airplanes that have relatively few recorded FDR parameters.

The key to accomplishing the runway track analysis is to calculate the longitudinal ($S_X$) and lateral ($S_Y$) distances, and then be able to accurately "anchor" or attach the calculated airplane track relative to the actual runway. The following three principle calculation methods are used by Boeing to calculate $S_X$ and $S_Y$ distances:

Method A—Distances integrated from kinematically corrected accelerations.
Method B—Distances integrated from FDR ground speed, heading and drift angle.
Method C—Distances calculated using recorded localizer data ($S_Y$ only).

The various methods used to calculate distances usually give similar results, but occasionally there are differences. Differences are resolved via comparison, adjustment of assumptions, engineering judgment, and iteration. Several iterations may be necessary to obtain the best fit alignment between the calculated ground track and the ground scar data. Each method has advantages and disadvantages. Which method is best for a given incident depends on the circumstances of the incident, the data set, and information available from the field. The three methods are discussed in detail below.

*Method A—Distances Integrated From Kinematically Corrected Accelerations*

The position of the airplane is calculated by integrating the kinematically corrected acceleration data ($N_Z$, $N_Y$, $N_X$). This approach is available on most data sets because it requires only a basic parameter set be recorded on the FDR. If the standard set of parameters is not recorded or part of the data is invalid, then assumptions can be made to enable the generation of reasonable results. At Boeing, this method uses groundspeed, heading, and drift angle output from KINCON (based on $N_Z$, $N_Y$, $N_X$, and angles). This method requires ground position information to "attach" the airplane's calculated track to the actual runway.

| *Advantages* | *Disadvantages* |
|---|---|
| • Useful with older airplanes that have a limited FDR data set that does not include groundspeed, heading, or drift angle. | • More assumptions are required due to limited data available from the FDR. which may reduce accuracy.<br>• Requires double integration of the low sample rate acceleration data, which can lead to errors in calculated position. |

*Method B—Distances Integrated From FDR Ground Speed, Heading, and Drift Angle*

The longitudinal and lateral distances are calculated by integrating FDR recorded ground speed, heading, and drift angle. This method requires ground position information to "attach" the airplane's calculated track to the actual runway.

*Advantages*

- This method is quick and simple.
- Can provide reasonable results if drift angle is not recorded and is assumed to be a constant.

*Disadvantages*

- Data are often of low sample rate and resolution, sample rate and resolution, results.

*Method C—Distances Calculated Using Recorded Localizer Data ($S_Y$ only)*

The longitudinal and lateral distances are calculated by using simple geometry and airport information. $S_X$ is calculated from the KINCON process or by the integration of FDR ground speed. $S_Y$ is calculated by using $S_X$ triangulated with the recorded localizer deviation signal, and with the airport information. This method often provides the best accuracy, but is only available if the landing was made on an ILS equipped runway, and if the glideslope and localizer data is recorded on the FDR. Lateral distance calculated with this method is unreliable when the airplane exceeds the localizer antenna's transmission "cone."

*Advantages*

- Airplane can be positioned relative to the runway without ground scar data.

*Disadvantages*

- Infrequent availability of localizer data from FDR (parameter not recorded or non-ILS approach).
- Requires knowledge of localizer antenna location, accuracy, and calibration.

## Runway track plot buildup

Once the distances have been calculated, the data can be plotted, but the calculated distances must be "anchored" or attached to the runway with ground position information reported from the field. If available, items such as ground scars, airplane's final resting position, recorded localizer, glideslope, middle marker, or engineering judgment can be used to affix the track to the runway.

First, the runway dimensions (including taxiways, overruns, etc., if pertinent) are established on the plot, followed by any ground position information received from the field. The airplane track data is then overlaid that represents the track of the CG of the airplane. Additional calculations are necessary using the airplane geometry (CG to gear) to add the track of each gear. Several iterations might be necessary to obtain agreement between the calculated airplane track and the reported ground scar information. Each iteration would make an adjustment to the initial conditions or the assumptions used in the calculations to obtain a better match with the ground position information.

## Examples of previous investigations

Three examples are included to highlight how this runway track analysis has helped in previous investigations. These examples

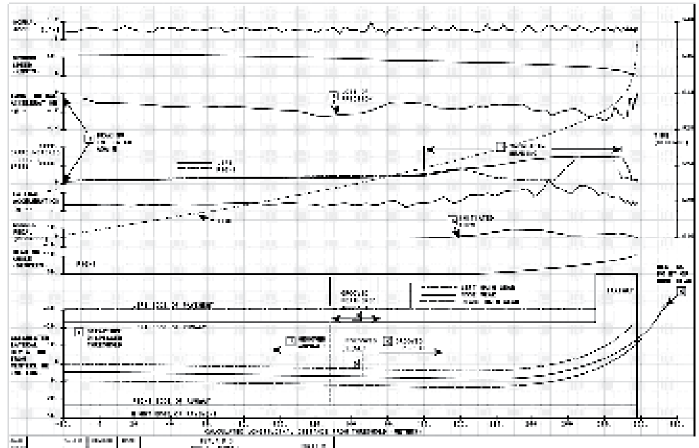


**Figure 2B**

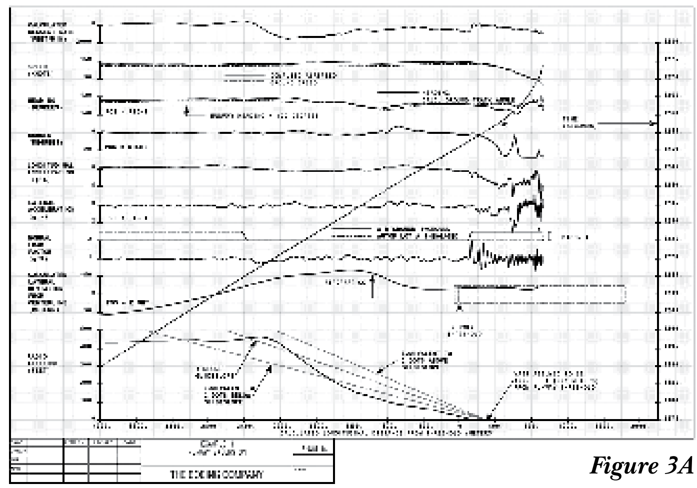


**Figure 3A**

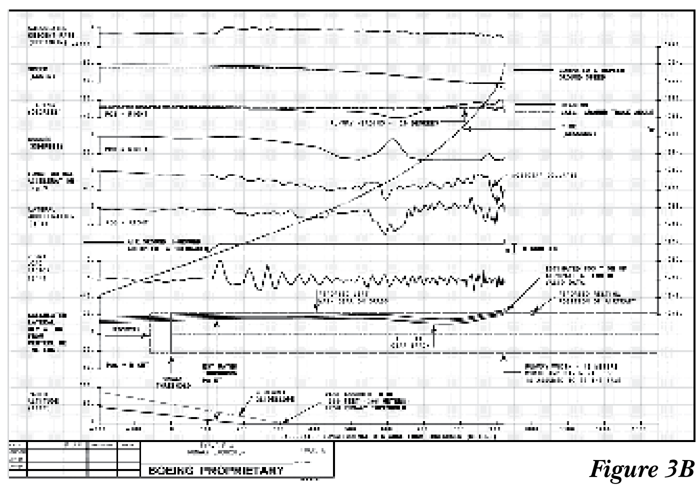


**Figure 3B**

contain actual data from the investigation and are being used with the permission of the investigation agency responsible for the investigation. However, the plots have been de-identified so the operator, airplane, or airport cannot be identified to protect the confidentiality of the parties. The purpose of showing these examples is to highlight how the runway track analysis helped the investigation of the incident. These three examples are not intended to line up with the three methodologies discussed above.

Example 1—Runway Excursion During Landing
Example 2—Runway Overrun During Landing

Example 3—Approach Profile and Runway Excursion

*Example 1—Runway Excursion During Landing*
- **Example shown in**

Figure 1—View of track on runway
- **What the runway track analysis added to the investigation**

—determined 1st set of skid marks were not associated with event airplane
—shows skid developing as a result of rudder input

*Example 2—Runway Overrun During Landing*
- **Example shown in**

Figure 2A—Overview (coarse scale)
Figure 2B—Expanded view of track on runway
- **What the runway track analysis added to the investigation**

—shows normal approach and landing
—shows airplane taxied length of runway to reach exit taxiway
—shows loss of friction when slowing to make the turn
—determined runway features that caused loss of friction

*Example 3—Approach Profile and Runway Excursion*
- **Example shown in**

Figure 3A—Overview showing approach profile (coarse scale)
Figure 3B—Expanded view of track on runway
- **What the runway track analysis added to the investigation**

—shows final approach
—shows airplane touched down left of centerline
—example of incomplete data set (airplane was still moving at end of data)

## Site data needed

First and foremost, it is important that the FDR data be sent to Boeing in raw binary format. Data received in other formats (csv, Excel, etc.) is not time aligned and can limit our ability to provide an accurate analysis of the event. The raw binary FDR data file should include all recorded parameters and the entire event flight at a minimum. It is also beneficial to receive at least one previous flight or all recorded flights from the FDR for use in verification of sign conventions of key parameters.

The distances calculated for the analysis must somehow be referenced or "anchored" to the runway. This is done with ground scar information received from the field. Accurate ground scar and site information is vital to the success of the analysis. The most valuable information from the field is a complete and accurate list of dimensions to all scars. The dimensions should include a measurement to the runway centerline and threshold (painted white stripe).

The following is a list of information that may be helpful from the site:

- **FDR data**

—Provide in *raw binary format*
—Include all recorded parameters
—Include entire event flight (the previous flight may also be beneficial)

- **Ground scar data**

—Sketch of site showing key runways, taxi ways, or airport features
—Point(s) where aircraft exited the paved runway surface
—Point where the aircraft came to rest
—Coordinates and length of all ground scars (skid marks, scrape marks, hydroplaning indications, etc.)
—Each point should be referenced to the runway centerline and threshold

- **Runway data**

—Runway surface—condition (wet, dry, ice), crowned, smooth/grooved
—Width of runway (painted white stripe) relative to centerline
—Width of pavement edge relative to centerline
—Width of grooves relative to centerline
—Runway slope as a function of distance
—Glideslope antenna location relative to threshold
—Localizer antenna location relative to threshold
—Localizer antenna accuracy and calibration data
—Runway surface condition (dry, wet, ice) near time of event.
—Measured runway coefficient of friction near time of event

- **Airplane data**

—Conditions of tires on all gear
—Photos of key features on any tire (wear, scrape marks, reverted rubber from hydroplaning, etc.)
—Photos of any structural damage (scrape marks, etc.)
—Photos of the airplane where it came to rest

## Limitations of the process

This analysis requires engineering judgment and assumptions in preparation of the data. Fewer the recorded parameters require more assumptions to perform the analysis. As such, this analysis may not be precise but instead provides an overview of what occurred. The process of calculating the distances requires the data to be re-sampled and interpolated, which may "clip" the peaks on some dynamic parameters. Therefore, it is important to use the FDR time history data to obtain the peak values of critical parameters in conjunction with the runway track analysis. Often, the scale used for the $S_Y$ axis is not one to one with the scale for the $S_X$ axis in order to clearly see what happened laterally on the runway. This scaling difference causes the lateral movements to be accentuated.

## Who we do this for

The runway track analysis can be used in investigations of in-service events, incidents, or accidents of Boeing products. The analysis is provided at no cost by Boeing as a participant in the investigation.

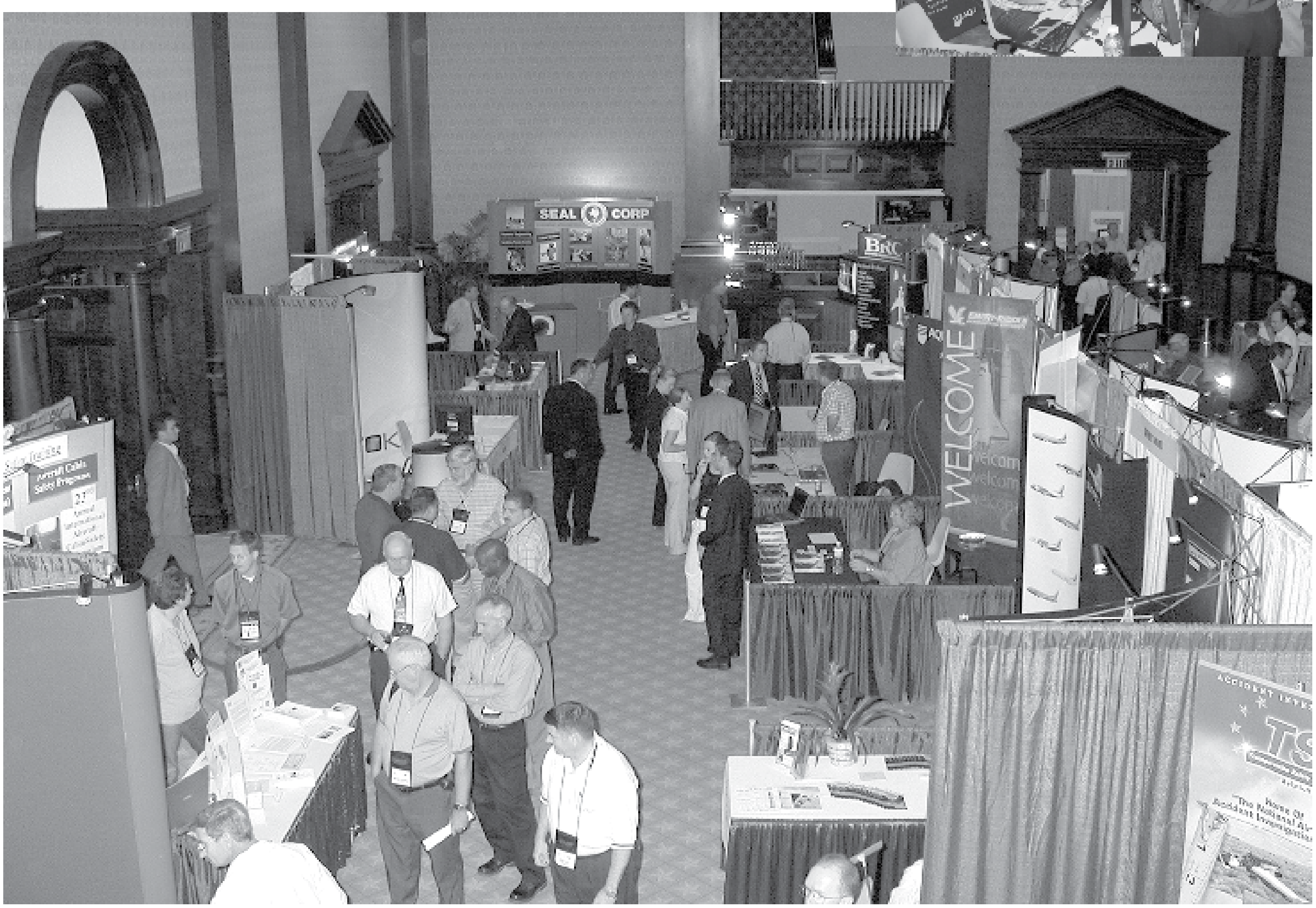
## Summary

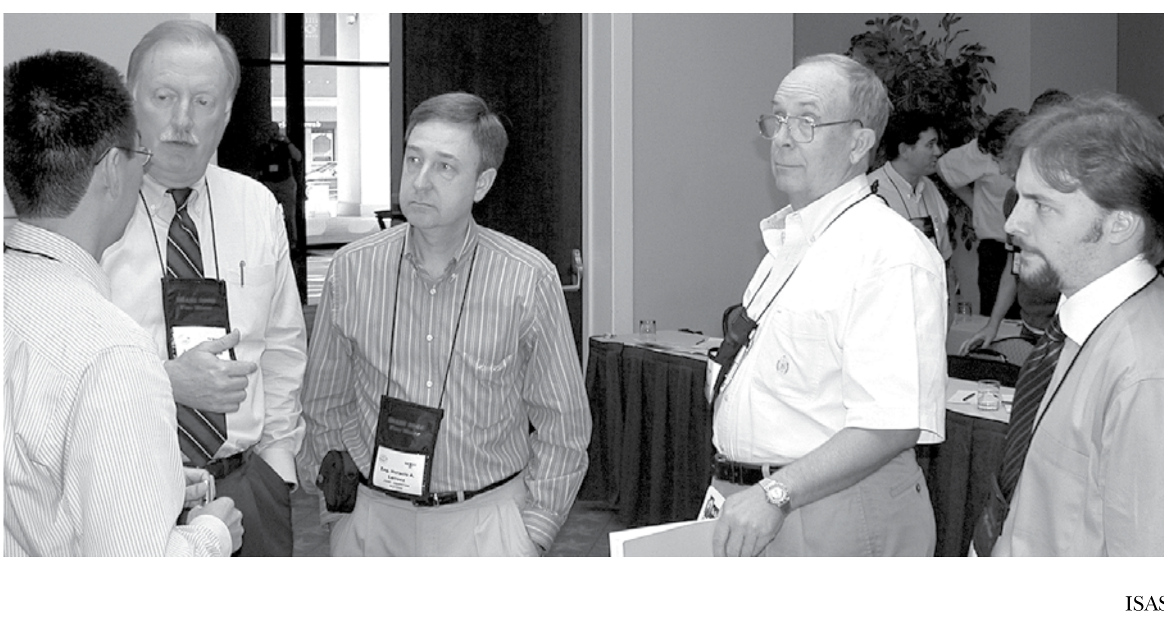
The Boeing runway track analysis has been useful in many incident investigations, from approach upsets and hard landings to runway excursions and runway overruns. The analysis allows investigators to visualize factors that may have contributed to an event. The analysis combines multiple sets of investigation data, including time-based FDR recorded data, distance-based ground scar data, or time-based CVR data, when available. As an investigation participant, Boeing provides this analysis to aid the investigation agencies with their investigation of incidents or accidents. ◆

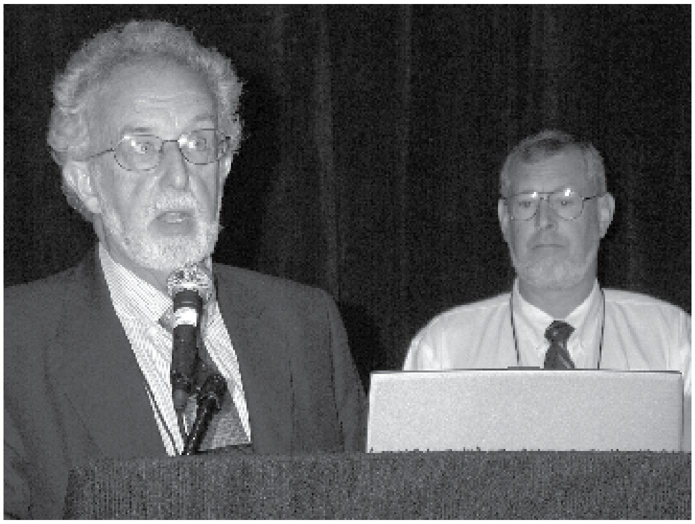
# ISASI 2005 Pictorial Review

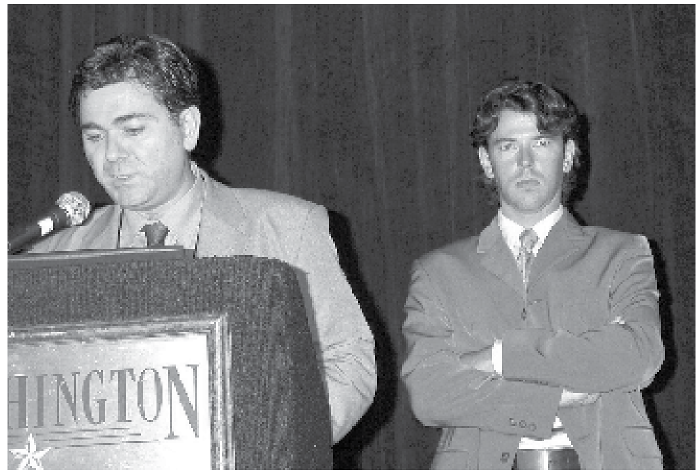
Photos by Esperison Martinez







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Helicopter Emergency Medical Services (HEMS)