VOLCANIC ASH AVOIDANCE

Original idea from Thomas Casadevall & Thomas Murray

A commercial aircraft encounter with volcanic Ash can threaten safety of flight because of resulting conditions that can range from windshield pitting to loss of thrust in all engines. Developments in technology and communication networks have significantly decreased the probability of such an encounter in the last several years. Despite these developments, however, a 737-700 recently flew through a volcanic ash cloud. Updated information about advancements in ensuring safe operations and minimizing damage to the airplane during a volcanic ash encounter is now available to flight crews.

In the past 30 years, more than 90 jet-powered commercial airplanes have encountered clouds of volcanic ash and suffered damage as a result. The increased availability of satellites and the technology to transform satellite data into useful information for operators have reduced the number of volcanic ash encounters. However, further coordination and co-operation, including linking operators and their dispatchers to the network of government volcano observers, is required throughout the industry. Boeing has always advocated that flight crews avoid volcanic ash clouds or exit them immediately if an encounter occurs. The company also recommends specific procedures for flight crews to follow if they cannot avoid an encounter.

Flight crews will be better prepared to avoid volcanic ash clouds and take the appropriate actions during an encounter if they understand the following information:

1 . Results of past events involving volcanic ash.
2. Resources available to help avoid ash encounters.
3. Specific flight crew actions required in response to encounters

RESULTS OF PAST EVENTS INVOLVING VOLCANIC ASH

Significant ash encounters from the past include those involving such well-known volcanoes as Mt. Pinatubo, Mt. Redoubt, and Mt. St. Helens. The airplanes that encountered volcanic ash during these events and in the other events (listed here chronologically) experienced varying degrees of damage.

Mt. St. Helens, United States, 1980.
A B727 and a DC-8 encountered separate ash clouds during this major eruption. Both airplanes experienced damage to their windshields and to several systems, but both landed safely despite the windshield damage.

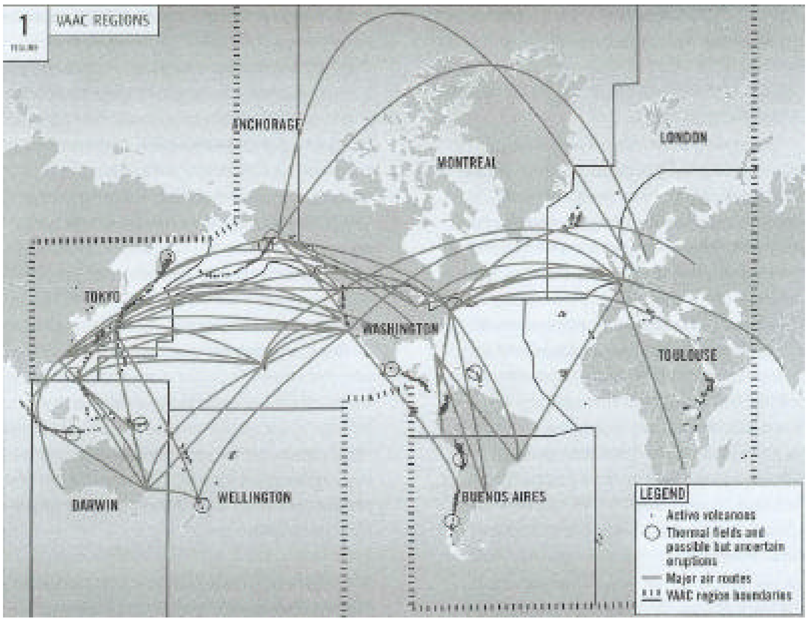
Galunggung volcano, Indonesia, 1982.
Several 747s encountered ash from this eruption. One airplane lost thrust from all four engines and descended from 36,000 feet to 12,500 feet before all four engines were restarted. The airplane, on a flight from Kuala Lumpur, Malaysia, to Perth, Australia, diverted to Jakarta and landed safely despite major engine damage. This airplane subsequently had all four engines replaced before returning to service. A few days after the initial encounters, another 747 flew into the ash cloud and suffered significant engine damage. This airplane also diverted to Jakarta and subsequently performed a successful two-engine landing.

Mt. Redoubt, United States, 1989.
On a flight from Amsterdam to Anchorage, Alaska, a new 747-400 (only three months old, with approximately 900 hours total flying time) encountered an ash cloud from the erupting Mt. Redoubt near Anchorage. All four engines ingested ash and flamed out. The crew successfully restarted the engines and landed safely at Anchorage. All four engines were replaced and many airplane systems also had to be repaired or replaced. For example, the airplane environmental control system was replaced, the fuel tanks were cleaned and the hydraulic systems were repaired. Several other aircraft encountered ash from this eruption, but most damage was minor because operators had been notified of the eruption. Some operators, such as Alaska Airlines, continued scheduled flights once they developed processes to safely identify where ash might he encountered. Although information was available about the Mt. Redoubt eruption, the channels for sharing this information were not well developed at the time (see "Alaska Airlines Procedures for Operating in Volcanic Ash Conditions").

Mt. Pinatubo, Philippines, 1991.
More than 20 volcanic ash encounters occurred after the Mt. Pinatubo eruption, which was the largest volcanic eruption of the past 50 years. The ability to predict where ash was to be found was challenging because of the enormous extent of the ash cloud. Commercial flights and various military operations were affected; one U.S. operator grounded its aircraft in Manila for several days.

Mt. Popocatepeti, Mexico, 1997.
This volcano affected several flights in 1997 and 1998. The damage was minor in most cases one flight crew experienced significantly reduced visibility for landing and had to look through the flight deck side windows in order to taxi after landing. In addition, the airport in Mexico was closed for up to 24 hours on several occasions during subsequent intermittent eruptions.

RESOURCES AVAILABLE TO HELP AVOID ASH ENCOUNTERS



Although some information about volcanic eruptions has been available for many years, the aviation industry and volcanological community began a joint effort to find ways to avoid future encounters after the Mt. Redoubt eruption.
At an international conference in Seattle, Washington, in July 1991, aviation industry members, meteorologists, and volcano scientists gathered to determine what volcano event information the aviation industry needed, how this information could he distributed, and who or which agencies should distribute it. The International Civil Aviation Organisation (ICAO) had laid much of the foundation for the volcanic ash issue through its Volcanic Ash Warnings Study Group; see "ICAO Activities on Volcanic Ash"

One of the outcomes of this initial meeting is the availability of today's Volcanic Ash Advisory Centres (VAAC). The VAACs provide an important link among volcano observatories, meteorological agencies, air traffic control centres, and operators. A total of nine VAACs observe and report on a particular region of the world (figure 1). One product of the VAACs is the Volcanic Ash Advisory Statement (VAAS).

In addition to providing VAASs directly to the airlines, the VAACs also provide information to appropriate meteorological organisations that subsequently issue significant meteorological information (SIGMET) and other reports. The ICAO publication' lnternational Airways Volcano Watch" (ICAO annex 111) contains further information and contact names and numbers. Detailed information on the VAACS, including contacts for each of the nine centres, is available at http://ww.ssd.noaa.gov/ VAAC/.

Operators rely on the VAACs for information, and many operators maintain direct contact with volcano observatories within their flight domains. For instance, the Alaska Volcano Observatory (AVO) in Anchorage, with links to Fairbanks, issues a weekly bulletin by e-mail and fax, detailing the activity of key volcanoes in Alaska. During periods of volcanic unrest and eruption, bulletins are issued frequently as conditions change. Anyone can request to be placed on distribution for the bulletins. The AVO web site (http://www.avo.alaska.edu/) also provides updated information.

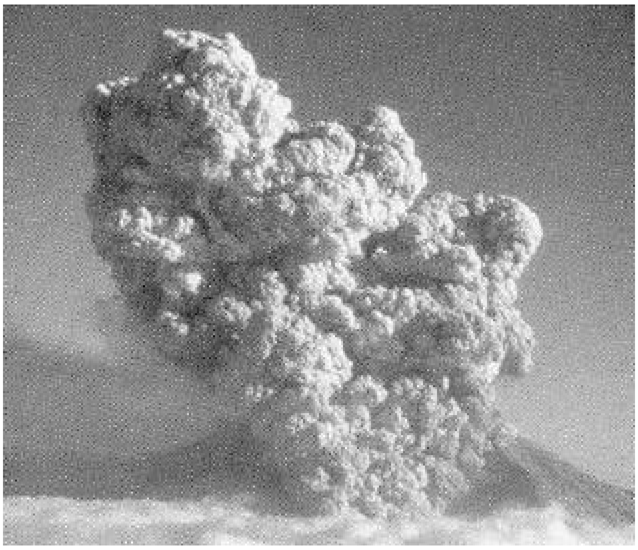
For those without Internet access or unable to access the site if it is overloaded during a crisis, the AVO daily telephone recording at 907-786-7477 provides brief updated information for air carriers. Finally, many operators maintain personal relationships with individuals in the volcano observatories that monitor volcanoes within a particular flight domain.

For instance, Alaska Airlines maintains contact with key individuals at the AVO because a significant portion of Alaska's flight domain could be affected by Alaskan volcanoes.

Many other web sites provide information and links to other sources of volcano information (see Volcanic Ash Resources). A wealth of printed information, such as the "Bulletin of the Global Volcanism Network" through the Smithsonian National Museum of Natural History in Washington, D.C., is also available.
However, the information about current volcanic activity in these printed sources is often two to three months old.

SPECIFIC FLIGHT CREW ACTIONS REQUIRED IN RESPONSE TO ENCOUNTERS

Despite ongoing avoidance efforts, operators can still experience volcanic ash encounters. Guidance on the operational issues surrounding volcanic ash is divided into three aspects: avoidance, recognition, and procedures. The following information is general and flight crews should refer to their respective company's operating manuals for details.



Avoidance.
Preventing flight into potential ash environments requires planning in these areas:

- Dispatch needs to provide flight crews with information about volcanic events, such as potentially eruptive volcanoes and known ash sightings, that could affect a particular route
- Dispatch also needs to identify alternate routes to help flight crews avoid airspace containing volcanic ash.
- Flight crews should stay upwind of volcanic ash and dust.
- Flight crews should note that airborne weather radar is ineffective for distinguishing ash and small dust particles.

Recognition.

Indicators that an aircraft is penetrating volcanic ash are related to odor, haze, changing engine conditions, airspeed, pressurization, and static discharges.

- **Odour.** When encountering a volcanic ash cloud, flight crews usually notice a smoky or acrid odour that can smell like electrical smoke, burned dust or sulphur.
- **Haze.** Most flight crews, as well as cabin crew or passengers, see a haze develop within the aircraft. Dust can settle on surfaces.
- **Changing engine conditions.** Surging, torching from the tailpipe, and flameouts can occur. Engine temperatures can change unexpectedly, and a white glow can appear at the engine inlet.
- **Airspeed.** If volcanic ash fouls the pitot tube, the indicated airspeed can decrease or fluctuate erratically.

- **Pressurization.** Cabin pressure can change, including possible loss of cabin pressurization.
- **Static discharges.** A phenomenon similar to St. Elmo's fire or glow can occur. In these instances, blue coloured sparks can appear to flow up the outside of the windshield or a white glow can appear at the leading edges of the wings or at the front of the engine inlets.

Procedures.

The following nine procedures are general recommendations. Each operator's flight operations manuals will include more specific directions.

1 . **Reduce thrust to idle immediately.** By reducing thrust, engines may suffer less build up of molten debris on turbine blades and hotsection components. Idle thrust allows engines to continue producing electrical power, bleed air for pressurization, and hydraulic power for aircraft control.

2. **Disengage the autothrottles.** This prevents the engines from increasing thrust above idle. Ash debris in the engine can result in reduced surge margins, and limiting the number of thrust adjustments improves the chances of engine recovery.

3. **Exit the ash cloud as quickly as possible.** A 180-deg turn out of the ash cloud using a descending turn is the quickest exit strategy. Many ash clouds extend for hundreds of miles, so an assumption that the encounter will end shortly can he false. Climbing out of the ash could result in increased engine debris build up as the result of increased temperatures. The increased engine build up could cause total thrust loss.

4. **Turn on engine and wing anti-ice devices and all air-conditioning packs.** These actions improve the engine stall margins by increasing the flow of bleed air.

5. **If possible, start the auxiliary power unit (APU).** The APU can power systems in the event of a multiple-engine power loss. It can also be used to restart engines through the use of APU bleed air.

6. **If volcanic dust fills the flight deck, the crew may need to use oxygen.** Use flight deck oxygen at the 1 00% setting. Manual deployment of the passenger oxygen system is not required because it will deploy automatically if the cabin attitude exceeds 14,000 feet.

7. **Turn on the continuous ignition.** Confirm that autostart is on, if available. In the event that the engines flame out or stall, use appropriate procedures to restart the engines. During restart, the engines may take longer than normal to reach idle thrust because of the combined effects of high attitude and volcanic ash ingestion. If an engine fails to start, try restarting it again immediately. Flight crews should remember that the aircraft may be out of the airstart envelope if the encounter occurs during cruise.

8. **Monitor engine exhaust gas temperature (EGT).** Because of potential engine debris build up, the EGT can climb excessively. The flight crew should prevent EGT exceedance. Shut down the engine and restart it if the EGT is approaching limits similar to a hung start.

9. **Fly the aircraft by monitoring airspeed and pitch attitude.** If necessary, follow the procedure for "flight with unreliable airspeed".

SUMMARY

Though the number of commercial aircraft encounters with volcanic ash clouds has decreased significantly over the past several years, the potential for this type of event still exists. Efforts to advance knowledge about how to avoid and recover from these encounters have resulted in improved capability in these areas. By working with members of the volcanological community, the aviation industry has developed procedures to share information about events with flight crews, dispatchers, volcano scientists, and others. Volcano observatories that provide daily updates through e-mail messages or phone recordings have been established. In addition, a variety of Internet sources provide information that operators can tailor to their specific flight domains.
Finally, flight operations procedures are documented and available to flight crews to help them respond immediately and appropriately to maintain the highest possible level of safety.

<u>Alaska Airlines procedures for operating in volcanic ash conditions:</u>

Alaska Airlines has many active volcanoes within its flight domain. To prepare for an eruption and resulting encounter with volcanic ash, the airline has developed focused guidelines for flight operations when eruptions interfere with its own route structures:

1. When in doubt, don't fly.
2. Use facts and data
3. Identify the location of both the ash and clear areas
4. Stay focused

1. When in doubt, don't fly
The fundamental principle by which Alaska Airlines operates is knowing where to find the ash after a volcanic eruption. If unsure of the ash location, it will not allow its flight crews to fly through the eruption area. Though this approach is conservative, Alaska Airlines successfully and safely operated after the 1989 Mt. Redoubt and other volcanic eruptions.

2. Use facts and data
Alaska Airlines has selected several information sources, uses Volcanic Ash Advisory Statements from the Volcanic Ash Advisory Centres and is in direct communication with the Alaska Volcano Observatory. During a major eruption, Alaska Airlines will interview its own pilots as well as other operators' pilots about their observations on ash location. It has also established contacts on the ground that it can call for additional intelligence. These individuals include mayors and police officers in villages and towns near the airline's flight paths. If Alaska Airlines receives inconsistent information, it double checks and continually validates what appears to be correct.

3. Identify the location of both the ash and clear areas
Alaska Airlines tracks the ash by asking a number of questions:

- Where is the ash itself?
- Where is the volcanic source of the ash?

- What are the winds doing?
- What information is available from the volcanological community?
- What information do the reports from the pilots, selected contacts, and others contain?

Alaska Airlines then provides its pilots with information on where to fly and the reasons for not flying in certain areas.

4. Stay focused

Ed Haeseker, manager of air traffic control for Alaska Airlines, worked during the Mt. Redoubt event with Tom Cufley, then chief pilot at Alaska Airlines. They found that a small team worked better than a large team, especially if the chief pilot provided information directly to the flight crew in the early days of the event. In addition, a small team can travel more quickly to the site where the greatest assistance is needed and remain focused on the key task - identifying where the ash is.

ICAO ACTIVITIES ON VOLCANIC ASH

The International Civil Aviation Organisation (ICAO) initiated a volcanic ash effort in 1982 after multiple volcanic ash encounters by 747 aircraft near Jakarta, Indonesia. The resulting Organisation, the Volcanic Ash Warnings Study Group, has worked since then to standardize the information provided to flight crews about volcanic eruptions.

In addition, ICAO formed the international Airways Volcano Watch (IAV\At) in 1987. This effort formalizes the international arrangements for monitoring and providing warnings to aircraft about volcanic ash in the atmosphere. ICAO annex III and the World Meteorological Organisation (WMO) Technical Regulation C.3.1 introduced a requirement to disseminate information about volcanic ash to aircraft in the form of significant meteorological information (SIGMET) and notice to airmen (NOTAM). The first WMO/ICAO workshop on volcanic ash hazards was held in Darwin, Australia, in 1995.

Since then, a number of the designated Volcanic Ash Advisory Centres (VAAC) have come into full operation. A second workshop in Toulouse, France, in 1998 focused primarily on VAAC responsibilities and procedures.

More information about ICAO activities related to volcanic ash avoidance and encounters is available in the organisation's document titled "Operational Procedures And List of Operational Contact Points Between Vulcanological Agencies, Meteorological Watch Offices and Area Control Centres" or from the following address:

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Chief - Meteorology
International Civil Aviation Organisation
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Montreal
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VOLCANO ERUPTION WARNING COLOR CODES

Eruption warnings are issued in the form of colorcoded information releases. Over the past 10 years, this method has proved to be effective for alerting the aviation community to potential volcanic ash.

Red
Volcanic eruption in progress. Ash plume or cloud reported above FL250.
Volcano dangerous, eruption likely, with ash plume or cloud expected to rise above FL250.

Orange
Volcano eruption in progress but ash plume or cloud not reaching nor expected to reach FL 250. Volcano dangerous, eruption likely, but ash plume or cloud not expected to reach FL250.

Yellow
Volcano known to be active from time to time and volcano activity has recently increased significantly. Volcano currently not considered dangerous but caution should be exercised.
(After an eruption a change in alert to yellow from red or orange means: volcanic activity has decreased significantly, volcano not currently considered dangerous but caution should be exercised).

Green
Volcanic activity considered to have ceased and volcano reverted back to its normal state.
The responsible volcanological agency in the region where the volcano erupts should provide the area control centre with :

1. the colour code for the level of alert indicating the status of activity of the volcano and
2. any change from a previous state of activity (e.g. "Red alert following yellow" or "Green alert following orange").

VOLCANIC ASH RESOURCES

Volcanic ash resources are available world-wide and in many forms accessible to operators. Volcano observatories are located throughout the world, including the Alaska Volcano Observatory for information about North Pacific volcanoes and the Nordic Volcanalogical Institute for information about volcanic activity that could affect North Atlantic routes. Many of these observatories provide immediate eruption and volcanic ash updates to operators by fax, e-mail, telephone or teletype. Information is also available on the World Wide Web at the following sites:

- The Smithsonian National Museum of Natural History, Global Volcanism Program; http:// www.volcano.si.edu/gvp/
- The U.S. Geological Survey: http:// www.usgs.go/themes/volcano.html
- The Airline Dispatcher Federation (a detailed paper about volcanic ash by Leonard J. Salinas): http://www.dispatcher.org/library/ VolcanicAsh.htm
- The Istitutio Internazionale di Vulcanologia (a summary of volcanoes in Italy): http:// www.iiv.ct.cnr.it/
- The Nordic Volcanological Institute (information about volcanoes in and around Iceland): http:// www.norvol.hi.is/index.html
- The Volcanological Society of Japan (eruption information and live images of Japanese volcanoes): http://hakone.eri.u-tokyo.ac.jp/kazanNSJI E.htmi and http://hakone.eri.u-tokyo.ac.jp/vrc/erup/erup.html

Information is also available from:

- The Boeing Company, *Airliner* magazine ("Vulcans Blast", April-June 1990 and "Vulcan Returns: Volcanic Ash Effects on Airplanes Revisited", October-December 1991) and video ("Volcanic Ash Avoidance: Flight Crew Briefing").
- U.S. Federal Aviation Administration, Aviation *Safety Journal* reprint ("The Volcano Threat to Aviation Safety").
- Casadevall, T. J. Ed. 1994. The First International Symposium on Volcanic Ash and Aviation Safety: Proceedings Volume: U.S. Geological Survey Bulletin 2047.
- Casavedall, T. J., T.B. Thompson and T. Fox. 1999. World map of volcanoes and principal air navigation features. U.S. Geological Survey Map 1-2700.

The Primary source for any volcanic eruption and ash information is a Volcanic Ash Advisory Centre. The other sources listed may offer more detailed information on a particular eruption.

A B747 ENCOUNTER WITH MT. REDOUBT (ALASKA), December 15, 1989

Mt. Redoubt, near Anchorage, Alaska, experienced an eruption on December 14, 1989. One operator reported the plume rose higher than 35,000 feet and extended about 100 miles from the crater. This eruption had a significant impact on air operations in the area. On the following day, a B-747-400 powered by GE CF6-80C2 engines entered the ash cloud at 25,000 feet and experienced flameouts on all four engines. The flight crew restarted engines number one and two at 17,200 feet and restarted the remaining engines at 13,300 feet. The airplane made an uneventful landing at Anchorage.

A short while before top of descent (at 2025 UTC), air traffic control informed all aircraft about a special Notice To Airmen in stating that the Mt. Redoubt volcano had erupted exactly one hour earlier.

The crew had been cleared for descent from FL390 to FL350 and then to FL250 at the pilot's discretion. While maintaining FL350 for a short while, air traffic control informed the crew that a westbound B-727 had encountered volcanic ash during flight and that the aircraft was returning to Anchorage. Furthermore, the crew was informed that a DC-10 had left Anchorage to the north on a more easterly track and that this aircraft did not encounter any volcanic ash.

During descent, the flight entered a thin layer of altostratus clouds. Shortly after the airplane descended into the cloud layer it became very dark outside, while the crew saw lighted particles (St. Elmo's fire) pass over the cockpit windshields. At the same time, brownish dust with a sulphurous smell entered the cockpit. The captain commanded the copilot to start climbing in an attempt to exit the volcanic ash. The copilot disconnected the autopilot, advanced the thrust levers to 105% N 1 and rotated the airplane to approximately eight degrees nose up. One minute into the climb, all four engines spooled down.

Due to the volcanic ash and dust in the cockpit, the crew donned oxygen masks. The pilot flying noticed the airspeed decaying, initially at a normal rate given the airplane's attitude, but suddenly very fast. All airspeed indications were then lost due to volcanic dust contamination of the pitot system. At the same time there was a stall warning and the stick shaker was activated with no signs of buffeting. As there was no airspeed indication, the crew established a rate of descent of approximately 1500 to 2000 feet per minute (the rate of descent on the B-747-400 is derived from the IRU's). The pilot flying rather firmly put the nose of the aircraft down to avoid a stall and initiated a turn to the left in a further attempt to get out of the volcanic ash. The crew noticed an EICAS warning "Cargo Fire Forward" and deduced that the warning was caused by the volcanic ash so no further action was taken. As the engines spooled down, the generators tripped off and all instruments were lost except for both CRT's on the left side and the upper EICAS CRT which are powered by batteries.
During the time the engines were inoperative, the cabin pressure remained within limits and no passenger oxygen masks deployed. The crew elected not to deploy the masks because the passenger oxygen mask system would have been diluted with volcanic dust in the cabin air.

An emergency was declared when the airplane passed through approximately 17,000 feet.

The crew stated that a total of seven or eight restart attempts were made before engines number one and two finally restarted at approximately 17,200 feet. During the unsuccessful start attempts, EGT and N2 indications were observed to increase, however there was no response from the thrust levers within 30 seconds after selecting the fuel switches to "ON." The fuel switches were put in "CUTOFF."

Initially, the crew maintained 13,000 feet with engines one and two restarted and after several more attempts, three and four were restarted. Due to the fact that volcanic ash had entered the pitot/static system, all air data systems had become unreliable; however, the left hand altimeter indicated correct values. Additionally, the rudder ratio light was on, indicating contamination of this system also. Rudder ratio being incorrect made the aircraft difficult to handle, especially during the period when only engines one and two were operating. The autopilot was initially re-engaged in the "Heading Hold" and "Altitude Hold" mode. However, when "Heading Select" was engaged the auto-pilot disengaged. The remainder of the flight was flown manually. The IRU groundspeed was used for speed reference after having checked with ATC that the indicated values of IRU groundspeed were correct.

After passing abeam and east of Anchorage at 11,000 feet the airplane was given radar vectors for a wide right-hand pattern to runway 06 and further descent to 2,000 feet.

At the moment of glide path capture, the flight director bars on the left hand PFD were biased out of view; however, the captain had the runway continuously in sight during the approach. The vision through the windshields was impaired by the "sandblasting" from the volcanic ash in such a way that the captain and first officer were only able to look forward with their heads positioned well to the side. During the last part of the approach, the EICAS announced the "Equipment Cooling" message, but the captain elected to disregard this message as landing was imminent.

After a normal landing with flaps 30 and autobrakes at position 4, normal reverse was selected during the landing roll. The captain cleared the landing runway and taxied the aircraft to the assigned gate. When turning towards the gate the captain transferred control to the first officer as his vision through the left windshield was impaired during the last part of the docking procedure.

Inspection of the airplane revealed the following :

- All four engines suffered extensive damage and had to be replaced. Inspection of the number one engine found, in part, that in the first stage of the high-pressure turbine, ash had melted and resolidified, or 11 "ceramatized" on the leading edges of the nozzle vanes. The solid ash deposits extended along 75 percent or more of each leading edge length at an average thickness of about 1.5 millimeters. A preliminary hypothesis suggests that the extent of the melted and resolidified volcanic ash deposit on the high pressure turbine nozzle vanes increased the operating line pressure ratio of the compressors, resulting in engine surge. The repeated restart attempts resulted in partial break up of the deposit through "thermal shock." This, in combination with the improved engine surge margin at lower altitudes, resulted in a successful restart of all four engines.

- The entire pneumatic system, the air conditioning system, and the equipment cooling system were heavily contaminated by volcanic ash. To prevent contamination of the four replacement engines, a major portion of the pneumatic system was removed, cleaned and reinstalled.

- Both the captain's and the copilot's windshields and the windshield wipers were 11 sandblasted" and had to be replaced. The leading edges of the wings, the winglets, the vertical fin, and the horizontal stabilizer were "sandblasted" and had to be replaced. Other protruding parts of the aircraft, such as VHF antennas, TAT probes, ice detectors and angle-of-attack vanes were damaged.

- The pitot/static system was damaged and heavily contaminated. The pitot and static ports had to be removed and replaced and the system purged of all ash.

- The entire fuselage, except for the area behind the aft pressure bulkhead, had to be cleaned very carefully. This included all cockpit instrument panels, all circuit breaker panels, passenger cabin areas, baggage compartments and the areas above the cabin ceiling panels, including all systems present in these areas and the entire environmental control system.

- The entire electrical and avionic systems were contaminated and had been exposed to possible overheating due to loss of cooling air. All electrical and avionic units had to be replaced.

- The smoke detection system was contaminated throughout the entire unit, including the associated plumbing and ejectors, which had to be replaced.

- The fuel system, the hydraulic system, and the portable water systems had to be cleaned and checked for proper operation.

- The cabin windows, aft to body station 590 were eroded and pitted.

Initial airplane repair was accomplished by a Boeing repair crew at Anchorage. Work started on January 2, 1990 after all required materials had been positioned. On January 26th, the airplane was ready for a checkout flight to Everett, Washington. The airplane was then flown to the operator's home base for further repairs. The airplane went back into service on March 21, 1990.

Approximately $80 million was required to restore the airplane.

In summary:

- The encounter was not anticipated.
- The signs of encounter (visibility reduction, static discharge) had a rapid onset with little effective time for avoidance decisions.
- The effects on the engines occurred rapidly over a two to four minute period.
- For all engines, post flight inspection showed that a melted deposit had accumulated on the high temperature surfaces reducing the effective nozzle guide vane flow area.