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The 1989–1990 eruption of Redoubt Volcano, Alaska: impacts on aircraft operations

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Abstract

The December 1989–June 1990 eruption of Redoubt Volcano affected commercial and military air operations in the vicinity of Anchorage, Alaska. These effects were due to the direct impact of volcanic ash on jet aircraft, as well as to the rerouting and cancellations of flight operations owing to eruptive activity. Between December and February, five commercial jetliners were damaged from ash encounters. The most serious incident took place on December 15, 1989 when a Boeing 747-400 aircraft temporarily lost power of all four engines after encountering an ash cloud as the airplane descended for a landing in Anchorage. While there were no injuries to passengers, the damage to engines, avionics, and aircraft structure from this encounter is estimated at $80 million. Four additional encounters between jet aircraft and Redoubt ash clouds occurred in the Anchorage area on December 15 and 16, 1989 and February 21, 1990; none resulted in engine failure. Two additional encounters took place on December 17, 1989 when jet airliners encountered the Redoubt cloud over west Texas. At the time of these encounters, the cloud was up to 55 hours old and had traveled in excess of 2,900 nautical miles (5,300 km).

Following the December 15 encounters, Anchorage International Airport remained open, however, most airline companies canceled operations for up to several days. As communications between Federal agencies and airlines improved, and as a better understanding of the nature and behavior of ash-rich eruption clouds was achieved, most airlines resumed normal service by early January 1990. The resulting loss of revenue at Anchorage International Airport during several months following the eruption is estimated to total $2.6 million. The impact on general aviation and military operations consisted mostly of cancellation and rerouting of flights.

1. Introduction and purpose

This report examines the impact of the 1989–1990 eruption of Redoubt Volcano on aircraft and air traffic operations in Alaska and particularly to Anchorage which is the major hub for refueling and provisioning of aircraft using the great-circle routes between North America and Europe with Asia. The report documents how a series of relatively small eruptions at a remote volcano disrupted the Alaska economy. The report also identifies some of the strengths and weaknesses of the current system to warn of an impending eruption or to notify of an eruption in progress. The damage to the airplanes involved in encounters with Redoubt ash clouds has been described in papers presented at the recent symposium on Volcanic Ash and Aviation Safety (Campbell, 1991a; Casadevall et al., 1991; Przedpelski and Casadevall, 1991).

This report is based on more than 80 interviews held in Alaska in 1990 with representa-

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tives from a variety of government agencies and private organizations regarding impacts of the 1989–1990 eruption of Redoubt Volcano on aviation activities. Interviews included a questionnaire survey of the operators at Anchorage International Airport (AIA) to determine the extent of impacts owing to the eruption and to identify how information about volcanic activity was obtained and used by the airline companies during the eruption. It is significant that none of those interviewed could recall having faced the problem of volcanic hazards from ash clouds in the past, despite the fact that the 1976 and 1986 eruptions of St. Augustine Volcano also disrupted air operations in the Anchorage area (Kienle and Shaw, 1979; Kienle et al., 1986; Yount et al., 1987). Also, neither the airlines nor Federal agencies involved with air traffic control were aware of the special procedures developed by the International Civil Aviation Organization (ICAO) and endorsed by the Air Line Pilots Association (ALPA) for pilots to report volcanic activity (Fox, 1988; Miller, 1991).*

2. Redoubt eruption 1989–1990

Previous eruptions of Redoubt Volcano in this century occurred in 1902, 1933, and 1965–1968 (Till et al., 1990, 1994-this volume). The full range of impacts of the 1989–1990 eruption of Redoubt Volcano is discussed in U.S. Geological Survey Circular 1061 (Brantley, 1990). This eruption included 23 individual explosive eruptions between December 14, 1989 and April 21, 1990. From December 14 to 19, 1989, five explosive eruptions destroyed the 1966 lava dome and cleared the vent. Each explosion produced an ash-rich eruption cloud, the largest of which was erupted at 10:15 AST [Except where otherwise noted, all times used in this report are Alaska Standard Time (AST). Greenwich Mean Time (GMT) = AST +9] on December 15 and grew to an altitude that exceeded 39,000 feet (12 km) above sea level. This eruption cloud also contained about 175,000 metric tons of sulfur dioxide gas (Schnetzler et al., 1994-this volume). Within 48 hours, this cloud had moved eastward into Canadian airspace, then southward over the western United States and northern Mexico, and finally eastward over Texas and out into the Gulf of Mexico (Heffter et al., 1990).

For several days after this eruption, there was nearly continuous emission of ash from the crater up to 22,000 feet (7 km) altitude. From late December 1989 through mid-June 1990, activity included almost continuous extrusion of a viscous lava dome (Miller, 1994-this volume) that was disrupted periodically during 18 separate explosive eruptions related to partial or complete collapse of the lava dome. These eruptions were less powerful and produced less ash than those of the vent-clearing phase in December, but each explosive eruption generated ash-rich eruption columns which reached to altitudes of from 22,000 feet (7 km) to greater than 39,000 feet (12 km) (Alaska Volcano Observatory, 1990; Brantley, 1990). Quiescent emission of a whitish steam cloud that contained primarily water vapor, carbon dioxide, and sulfur dioxide gas was a persistent feature of Redoubt's activity both during and following the end of dome growth through 1991 (Casadevall et al., 1994-this volume).

2.1. Ash deposits

Each of the 23 eruptions of Redoubt Volcano in 1989–1990 produced deposits of fine-grained volcanic ash with a total volume of between 0.03 and 0.05 km^3 of ash (Scott and McGimsey, 1994-this volume). The December 15 vent-clearing eruptions produced the largest volume and most widespread ash fall of the 1989–1990 eruption sequence (Fig. 1). Within about 30 km (18 miles) of the vent, pumice fragments up to 5 cm

*Units of measure: When measurements (distance, velocity, and altitude) are discussed in the context of aviation, the units are given in nautical miles, knots, and feet, respectively. Where appropriate, metric conversions are indicated in parentheses. In cases where original data and observations are reported in metric values, these values are used directly.
1 nautical mile = 1.15 statute mile = 1.85 kilometer; meters = feet × (3.24)
Time: Times are reported as Alaska Standard Time (AST). Greenwich Mean Time (GMT) = AST + 9h.

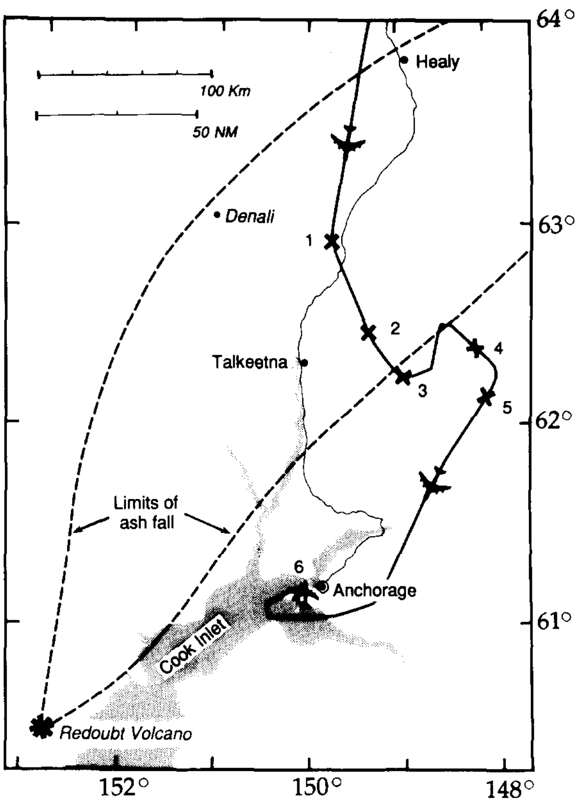

Fig. 1. Map showing position of KLM flight path (heavy solid line) and limits of detectable ash fall (heavy dashed lines) from December 15, 1989 eruption of Redoubt Volcano. Times (AST) of principal events for KLM Flight 867 include: *1* = 11:40, airplane begins descent from 35,000 feet; alters course to avoid ash cloud. *2* = 11:46, airplane encounters ash cloud at 25,000 feet. *3* = 11:47, airplane loses power on all 4 engines after climbing to 27,900 feet. *4* = 11:52, airplane engines 1 and 2 restart at 17,200 feet. *5* = 11:55, airplane engines 3 and 4 restart at 13,300 feet; resumes flight to Anchorage. *6* = 12:25, airplane lands at Anchorage International Airport. Map modified from flight route data provided by National Transportation Safety Board (1990) and FAA Flight Standard Division, Anchorage. Ash-fall data modified from Scott and McGimsey (1994-this volume).

diameter were found with total deposit thickness of up to 5 cm. Ash fall from the December 15 eruptions was reported at distances up to 500 km (300 miles) from the volcano (Scott and McGimsey, 1994-this volume). At these greater distances, the ash deposit decreased in average particle size and in total deposit thickness. The 10:15 eruption of December 15, 1989 was surpassed in vigor and duration only by the January 2, 1990 eruption at 19:27. However, the total mass of ash produced from the January 2 event was less than that of December 15.

3. Effects on aircraft

Despite the numerous ash clouds produced during the 1989–1990 Redoubt eruptions, only 5 jet aircraft encounters with ash clouds were recorded in the Anchorage area, four following eruptions on December 15 and 16, 1989 and one following the eruption on February 21, 1990. Two additional encounters occurred over west Texas on December 17, 1989.

3.1. Eruptions of December 15, 1989

On December 15, 1989, major eruptions at 01:40, 03:48 and 10:15, each generated powerful eruption columns and ash clouds. The eruptions at 01:40 and 03:48 each lasted about 1 hour. At about 03:50, a Boeing 737 was the first aircraft to encounter a Redoubt ash cloud as the aircraft approached Anchorage in darkness on a flight from Kotzebue, Alaska. The encounter occurred as the plane descended through 17,000 feet altitude with engines set at 'flight idle'. The encounter lasted for 17 seconds and consisted of sulfur gas smell and the appearance of St. Elmo's Fire due to charging of the cockpit windshields by ash particles. The ash abraded and dulled the windshields, but did not significantly reduce visibility. The leading edges of the wings were also slightly abraded. The aircraft continued its descent to make a normal landing at Anchorage where the aircraft was inspected for damage. The engines were examined by borescope, but showed no damage and were not replaced. The cockpit windshields were replaced.

The most vigorous eruption on December 15 lasted from 10:15 to approximately 11:00, sending an ash column above 40,000 feet (> 12 km). Upper-level winds of up to 100 knots transported this ash cloud to the northeast (Fig. 1). About 11:00, the cloud moved over communities along the Parks Highway north of Anchorage and particles of volcanic rock up to sand-size fell at Talkeetna, 225 km (140 miles) north-northeast of Redoubt Volcano. At about this time, several jet aircraft were in this vicinity and observed the ash cloud at close range. A Boeing 727 passenger liner had taken off from Anchorage International Airport bound for Bethel, Alaska and at 11:25 this airplane encountered the cloud from the 10:15 eruption while climbing from 15,000 to 18,000 feet altitude. At 18,000 feet, the pilot reported that he had encountered an ash cloud and returned to Anchorage. There is no report of damage for this encounter. At about this same time, the nearly new 747-400 passenger aircraft of KLM Flight 867 was entering the Anchorage airspace from the north.

3.2. KLM Flight 867

KLM Flight 867 originated in Amsterdam as a scheduled service to Tokyo. During the pre-flight briefing in Amsterdam, the crew was advised of the 01:40 eruption of Redoubt Volcano. Because of this eruption, an additional 5,000 gallons of fuel were loaded aboard the airplane in case diversion to another airport became necessary. Flight 867 departed Amsterdam at 03:20 (AST) and was scheduled to land in Anchorage at 12:10. Aboard were 231 passengers and a crew of 14.

At 11:32, Flight 867 had just passed over Fairbanks at 39,000 feet on air route J-436 (J=jetway) cruising at a speed of approximately 490 knots, when the aircraft began its descent into Anchorage (Fig. 1). Transcripts of voice communications between the Federal Aviation Administration (FAA) Anchorage Air Route Traffic Control Center (ARTCC) and several other airplanes in the airspace including Flight 867 indicate a heightened awareness of Redoubt Volcano and its recent activity (NTSB, 1991). In the vicinity of KLM 867 were a northbound DC-10 and a southbound DC-8. The DC-10 was located approximately 30 nautical miles (55 km) south of the location where Flight 867 would soon encounter the ash cloud. The DC-8 was located approximately 12 nautical miles (22 km) to the north of the encounter location.

The DC-10 was northbound from Anchorage on air route V-438 (V=low-altitude airway) climbing through 17,300 feet when its crew reported at 11:39 the ash cloud above the aircraft. The DC-10 continued north, reaching 24,000 feet at 11:45 when it reported it was under the northern edge of the ash cloud and about to pass into clear sky.

At 11:41, the crew of the DC-8, flying southbound on air route J-438, radioed that they could see a cloud to the southeast at 37,000 feet. The DC-8 was approved to climb above the cloud and at 11:43 had reached an altitude of 39,000 feet.

Communications between Anchorage air traffic control and the crew of Flight 867 during and following the reports from the DC-10 and the DC-8, resulted in Flight 867 turning southeast from the normal flight route in order to avoid the ash cloud, which they still could not identify visually. At 11:41, the KLM aircraft was approved to begin its transition to the southeast. About 40 nautical miles (75 km) later, at 11:46, Flight 867 entered the ash cloud at an altitude of approximately 25,000 feet.

On entering the plume, the flight crew immediately acted to climb out of the cloud by increasing engine power. In the minute and a half after the encounter, they climbed 2,900 additional feet, to approximately 27,900 feet, before the 4 engines stalled. After loosing engine power, the pilot turned from a 140 degree magnetic heading to a 120 degree heading. Between 11:47 and 11:51, the aircraft glided without power to an altitude of approximately 17,200 feet before engines 1 and 2 were successfully restarted. Operating with engines 1 and 2, the airplane continued to descend to 13,300 feet before engines 3 and 4 were restarted at 11:55. Terrain elevation in the area ranged from 7,000 to 11,000 feet. After restarting the engines, Flight 867 resumed powered flight to Anchorage and made a successful landing at 12:25, 15 minutes after the scheduled arrival.

The KLM aircraft almost certainly encountered the leading edge of the ash cloud produced by the eruption which began at 10:15 on December 15, 1989. At the time of the encounter at 11:46, KLM 867 was 150 nautical miles (280 km) north-northeast of Redoubt Volcano. The encounter with the ash cloud occurred 91 minutes after the start of the eruption. Winds aloft for the morning of December 15 were forecast at 60 knots at 24,000 feet at 210 degrees; 98 knots at 30,000 feet at 230 degrees; 97 knots at 34,000 feet at 230 degrees; and 75 knots at 39,000 feet at 230 degrees. The position of the leading edge of the ash cloud was in agreement with the forecast wind speeds.

Nature of the encounter — flight crew reaction

The flight deck was staffed by a captain and two other pilots. As the airplane began its descent at approximately 11:32, the crew reported thin layers of white clouds to the south. Their air route (V-436; heading 164 degrees magnetic) carried them south-southwestward towards the newly-risen sun. Sunrise at Anchorage on December 15, was at 10:14. Thus, the ash cloud as well as any weather clouds would have been lit from behind by the rising sun. Upon entry into the cloud, the crew reported greatly reduced visibility and the temporary loss of about half of the cockpit instrumentation when the engines failed (AWST, 1990; NTSB, 1991).

Immediately prior to the encounter, the crew reported entering a cloud that was "a little browner than a normal cloud". Just after entry into the cloud they reported that it became smoky in the cockpit and the "outside environment turned dark black and lighted particles could be seen that looked like fireflies in the dark". The First Officer reported that during the descent of the aircraft from 35,000 to 25,000 feet: "Below us there were thin layers of white clouds and at approximately 26,000 feet we descended into one of those. The environment changed from white to black in a few seconds. Smoke entered the cockpit and we put on our oxygen masks." The other First Officer noted: "At approximately 26,000 feet, descending, the aircraft entered what appeared to be a normal layer of clouds. However immediately after entry, smoke entered the flight deck. Oxygen masks were put on, and as pilot flying I initiated a full thrust climb in order to vacate the ash cloud."

Nature of the encounter—cabin reaction

Newspaper and television accounts of the encounter included interviews with the passengers and cabin crew. These accounts reported that the cabin filled up with smoke and that there was a strong odor of sulfur. In the few minutes following power loss, the attitude of the airplane changed from a climb at a rate of approximately 1,500 feet per minute to a descent as it began a powerless glide at a rate of approximately 1,620 feet per minute. Initially, this caused objects in the cabin to float slightly in a state of near-weightlessness as the pilot maneuvered the airplane to maintain airspeed. The interior of the cabin became dark and a general sense of calm fear appeared to affect the passengers and cabin crew. Several passengers experienced nausea that they attributed to a combination of sulfur gas smell, anxiety, and the discomfort associated with the rapid descent. Bumpiness or other signs of turbulence were not reported. These reactions were similar to those reported during the encounter of a British Airways 747 with an ash cloud from Galunggung Volcano, Indonesia in 1982 (Tootell, 1985).

Damage to the aircraft

Flight 867 glided in the ash cloud for approximately 5 minutes at a speed of approximately 490 knots. During this time, fine volcanic ash was able to penetrate the cabin as well as the engines. The ash deposits in the engines, baggage compartment, and cabin of the aircraft were composed of particles ranging in size from less than 1 up to 100 microns in diameter. Filters in the environmental air handling system screened out particles larger than 5 microns from entering the cabin. Particles collected from the exterior of the aircraft showed a wide range of sizes with a substantial population at 100 microns. Particles obtained from the fuel sump, which contained minor ash, were generally less than 20 microns; the hydraulic system contained moderate ash generally less than 30 microns; and engine oil contained heavy ash contamination with particles generally less than 60 microns (T.M. Murray, Boeing Co., pers. commun., 1990).

Samples of ash from the December 15 eruptions collected from the ground below the airspace of the encounter had a mass per unit area of up to approximately 500 grams per m^3 (W. McGimsey, pers. commun., 1990). The majority of particles at this location were less than 200 microns in diameter with approximately 75% of the particles having a mean diameter of less than 20 microns. The ash was composed dominantly of mineral fragments including plagioclase feldspar, two pyroxenes (hypersthene and augite), hornblende, and Fe-Ti oxides, as well as glass shards and fragments of fresh glassy rock and older rock from the pre-existing lava dome and throat of the volcano. The rock and mineral fragments were sharply angular, blocky to equant and typically coated with a thin film of vesiculated volcanic glass.

Owing to the abrasive nature of the ash, the exterior of the aircraft and its four engines were badly damaged. The principal damage to the engines included abrasion of the compressor blades, accumulation of ash in the combustor, and accumulation of remelted ash at the inlet to the turbine section (Casadevall et al., 1991; Przedpelski and Casadevall, 1991) which eventually caused all engines to stall. Following the successful landing in Anchorage, the aircraft was grounded for two months while repairs were carried out. All engines were replaced before the airplane was flown again.

In addition to the engines, the avionics and electrical systems of the airplane were damaged and numerous components were also replaced (Campbell, 1991a). Abrasion by ash also damaged the cockpit windshields and forward cabin windows, the leading edges of wings, tail rudder, engine cowlings, the fiberglass coverings for the flap screws under the wings, and the radar nosecone. The covers for the navigation and landing lights were badly abraded. The pitot-static system, used to measure the aircraft speed while inflight, was plugged by ash. Engine oil, hydraulic fluid, the potable water supply, the environmental control system and ventilation ductworks were contaminated with ash and were replaced. Cabin fixtures, carpeting, and seat covers and cushions were also contaminated and had to be cleaned. The total cost of damage to this nearly new 747-400 airplane was initially estimated to be between $50 and $80 million dollars (AWST, 1990; Steenblik, 1990).

NTSB finding of probable cause

Because KLM Flight 867 lost engine power while in flight, the pilot was required to file a report of the incident with the FAA and the National Transportation Safety Board was required to investigate to determine the probable cause of the incident. The NTSB finding of probable cause was released in July 1992 and is quoted here *verbatim*.

The National Transportation Safety Board determines that the probable cause(s) of this accident/incident was: inadvertent encounter with volcanic ash cloud, which resulted in damage from foreign material (foreign object) and subsequent compressor stalling of all engines. A factor related to the accident was: the lack of available information about the ash cloud to all personnel involved.

3.3. Other encounters: December 16 and 17, 1989 and February 21, 1990

For several days after the large eruptions of December 14–15, Redoubt Volcano emitted an almost continuous column of ash up to 22,000 feet (7 km) altitude (see figs. 10 and 11 in Brantley, 1990). On December 16, a fourth airplane, a Boeing 737, entered an ash cloud following takeoff in darkness at 08:20 from Anchorage enroute to Nome, Alaska. The aircraft returned immediately to Anchorage. The cockpit windshield had been damaged and was replaced and the two engines were inspected and cleaned.

Two encounters took place on December 17, 1989 over western Texas. The most serious event took place on December 17 at 20:00 (Central Standard Time) and involved a 727 aircraft which was westbound for landing at El Paso, Texas when it encountered ash near Salt Flat, Texas while descending from 36,000 to 29,000. The pilot report at 20:00 (CST) from the pilot of the 727 reported that power to one engine was lost. The 727 which reportedly lost an engine was not identified in the pilot report and inspection of the FAA data base on accidents and incidents listed no 727 or other aircraft which lost an engine on December 17 near El Paso, Texas (D. Fox, FAA, written commun., 1994).

Thirty minutes later, at 20:30 (CST), the pilot of a US Navy DC-9 reported that his airplane had encountered ash over the Salt Flat area after leaving El Paso east-bound while climbing through 26,000. The DC-9 continued to its destination and was inspected after landing. The only sign of the encounter was slight abrasion to leading edges. The engines were inspected and no significant damage was noted. The pilot of a commercial MD-80 reported the cloud near Austin, Texas. The report from the MD-80 only mentions seeing the cloud and apparently the aircraft did not enter the ash cloud. At the locations of these two encounters and the siting over west Texas, the ash cloud had traveled approximately 2,900 nautical miles (approximately 5,400 km) from the volcano and was from 35 to 55 hours old.

On February 21, 1990, more than 2 months and 8 eruptions after the encounters of December 15, 16, and 17, Redoubt Volcano experienced its 12th explosive eruption at 00:32. At approximately 01:50, a Boeing 727 passenger jetliner en-route from Anchorage to Seattle encountered the volcanic ash cloud from this eruption. The 727 had departed Anchorage in darkness at 01:38 on a normal takeoff over Cook Inlet. After takeoff the airplane was directed south and then southeast for its flight to Seattle. The encounter between the aircraft and the ash cloud took place approximately 12 minutes after takeoff as the aircraft climbed to between 18,000 and 20,000 feet altitude, approximately 60 nautical miles (110 km) east of Anchorage. Winds aloft on February 21 at the time of the encounter were from the southwest (220 degrees) at speeds which increased with altitude from 41 knots at 15,000 feet, to 85 knots at 25,000 feet, to 95 knots at 31,000 feet. These wind speed and direction data correctly indicated where the ash cloud was headed. The encounter caused damage to the cockpit windshields and some abrasion to the outer skin of the aircraft. The engines were inspected in Seattle and found to be within standard operating tolerances and the pitot system was undamaged.

In addition to the damage to the five jet airplanes in the Anchorage area, interviews with airport managers at Merrill Field and Kenai airport indicated that several small private and commuter airplanes and one helicopter suffered minor damage to the windshields and aircraft exteriors following encounters with Redoubt ash clouds. Generally, the slower air speeds and different engine types (piston engines on smaller airplanes versus jet turbine engines on larger airplanes) on these airplanes prevented the type of abrasion and deposition that occurred to the larger jet aircraft.

4. Effects on airport operations in the Anchorage–Kenai area

Ash clouds from Redoubt Volcano interrupted operations at the three major airports which serve the Anchorage area. Because of the different types of aircraft and services offered at each airport, the severity of impacts on airport operations from the Redoubt activity varied from airport to airport. It is important to remember that no significant thickness of ash fell in Anchorage during the 1989–1990 Redoubt eruptions, in contrast to the 1953 eruption of Mt. Spurr Volcano which deposited from 3 to 6 mm of ash at Anchorage and caused Anchorage Airport and Elmendorf to close for several days (Juhle and Coulter, 1955). Light ash did fall in Anchorage on December 15 and 16, 1989 and on February 28, 1990; and ash fell over an area just south of Anchorage on February 21, 1990. Thus, it was not fallen ash at airports which had the major impact on flight operations, but rather, the ash clouds which drifted within and contaminated the airspace of the Anchorage Flight Information Region. Kenai airport, located on the Kenai Peninsula, 43 nautical miles (80 km) east of Redoubt Volcano, was shut down by ash fall from the eruption of January 8 and remained closed for several days.

4.1. Merrill Field, Anchorage

Merrill Field in Anchorage is operated by the Municipality of Anchorage and handles the majority of land-based general aviation and charter air traffic in the Anchorage area. A smaller volume of private and charter traffic is handled at Lake Hood, a facility for pontoon and ski operations supervised by the Anchorage International Airport. Approximately 950 aircraft are based at Merrill Field and there were 230,000 airport operations at the field during 1989 (B. Myers, Municipality of Anchorage, personal communication, 1990). These include both fixed wing and helicopter aircraft which use piston or turboprop engines. Other than temporary suspension of some services during mid-December including air charter service to Beluga, 35 nautical miles (65 km) west of Anchorage, there was negligible impact on Merrill Field operations from the Redoubt eruptions. The ash which fell at Merrill Field and at Lake Hood was mostly a nuisance for small plane operators requiring that they brush ash from aircraft surfaces. Many owners avoided the problem by simply covering their airplanes with tarpaulins before the ash fell.

4.2. Elmendorf Air Force Base, Anchorage

Elmendorf Air Force Base in Anchorage handles a variety of military aircraft ranging from jet fighters, to jet powered cargo and troop transport aircraft, to turboprop aircraft. Newspaper reports (Anchorage Times 12/24/89) indicate that during December the air base used turboprop aircraft (C-12) to monitor volcanic activity and plume movement, adding approximately 12 sorties to normal daily operations. These aircraft flew only during daytime hours with Visual Flight Rule (VFR) conditions and provided weather and pilot reports for military operations. Jet fighter operations were limited on December 15–16 and 12 sorties were canceled. During December, about 90 military cargo flights were diverted to either Fairbanks or the Air National Guard base at Anchorage International Airport (AIA). Approximately 45 flights by military turboprop aircraft were canceled in December 1989 due to volcanic activity.

4.3. Anchorage International Airport

Anchorage International Airport is the principal airport facility in Alaska. Since the advent of jet powered passenger aircraft more than 30 years ago, Anchorage has become an important stop for refueling and changing of crews on transpolar great-circle air routes between North America and Europe with the Orient. In addition, there is growing use of Anchorage as an air cargo depot and as a destination for international tourist traffic, especially in the summer months. AIA is operated by the Department of Transportation and Public Facilities of the State of Alaska and it handles the majority of the State's domestic and international air traffic, including passenger and cargo operations. In 1989, Anchorage airport was serving 26 airlines, including 14 international carriers and 12 domestic carriers.

In December 1989 and January 1990, both passenger carriers and air cargo operators significantly curtailed their operations owing to the eruptions of Redoubt Volcano. These affects included cancellation of flights, rerouting of flights, loss of aircraft-related revenue for landing fees, docking fees, fuel flowage fees, and fees for use of the U.S. Customs area, and loss of concession fee revenue for the duty free shops and restaurant services. Total international and domestic landings at AIA in December 1989 were down about 10% compared with December 1988. The resulting loss of revenue from curtailed operations at Anchorage International Airport during several months following the eruption was estimated to total about $2.6 million (K. Burdette, Anchorage International Airport, personal communication, 1990).

5. Information from the Alaska Volcano Observatory

Monitoring the activity of Alaskan volcanoes is the responsibility of the Alaska Volcano Observatory (AVO), established in 1988 as a cooperative program of the U.S. Geological Survey (USGS), the Geophysical Institute at the University of Alaska-Fairbanks, and the Alaska Division of Geophysical and Geological Surveys in Fairbanks. AVO's Anchorage office is the principal component of AVO which interacts with aviation agencies. This facilitates communications with the FAA Regional Air Traffic Control Center (ARTCC), the National Weather Service (NWS), the National Transportation Safety Board, as well as with the twenty six carriers using AIA. At the Alaska region level, the NWS and FAA-ARTCC provide timely weather reports and communications with pilots regarding eruptive activity. During the eruption, representatives from more than half of the carriers, as well as staff members from the Federal agencies and Congressional delegations, frequently visited the AVO office in Anchorage for briefings about the eruption and to learn what information they might reliably expect to receive from AVO. This direct contact between aviation interests and AVO scientists was important in helping to tailor the communication of information to the needs of the aviation community, in terms of the message content, the language used, and the frequency of updates. Discussions with airline dispatchers and the questionnaire survey of airline companies indicated that the timely communication of factual information about the status of Redoubt Volcano was considered to be the single most important element in determining aviator response to eruptions.

To inform government agencies, the public, and the aviation community, four types of information about the status of Redoubt Volcano were developed by the Alaska Volcano Observatory during the activity in 1989–1990. This information was passed directly to the FAA, the NWS, and to officials at Anchorage International Airport and Elmendorf AFB. Immediately after the start of activity in December 1989, the AVO began to issue a printed statement, the *Volcano Update*, which was released one or more times each day and described the status of the volcano, its eruptions, earthquake activity, and volcano-related events such as mudflows and floods. In January 1990, a *Projected Plume Path Map* showing where an ash cloud would go during the next 24 hours, was included with the Volcano Update (Murray et al., 1991). These maps were produced at AVO using forecast wind data provided by the National Weather Service. In February 1990, AVO supplemented the Update with a *Color Code* to indicate the level of concern based primarily on seismic activity and field observations. The Color Code system was introduced to more succinctly describe the status of the volcano when an eruption was in progress or was expected (AVO, 1990; Brantley, 1990). The code used one of 4 colors that ranged from green (volcano dormant=low level of concern), through yellow, to orange, and up to red (eruption in progress=highest level of concern) to represent the concern about the volcano's behavior.

The Volcano Update, the Projected Plume Path Map, and the Color Code were issued regularly each morning during the eruption. Changes to this information could be issued at anytime, 24 hours a day, as events at the volcano demanded. Once an eruption was identified, the new information was issued in the form of an *Event Alert Notification* and was communicated immediately by telephone to the FAA, the NWS, the Alaska Department of Emergency Services, and the US Air Force. To expedite the transmission of the Event Alert Notification, AVO, the FAA, and the carriers agreed to the following brief statement.

'This is an eruption notification from the Alaska Volcano Observatory. Seismic data indicate that a (Small, Moderate, Large) eruption of Redoubt Volcano began at — AST (—Z) on —- (date). The level of concern code is red.'

Anchorage International Airport and the airlines usually received information from AVO through the FAA-ARTCC. Simultaneously, a revised Update was sent by telephone facsimile to a wider user community. To handle the large influx of telephone calls to the AVO-Anchorage office, telephone hot lines with recorded messages were established. These included separate telephone numbers for the news media and for the aviation community. Recorded messages on the hot lines were updated whenever the status of the volcano changed. Callers could request additional information by leaving a recorded message which would be answered by AVO staff members as time and other duties permitted.

The Event Alert Notification was usually all that was required by the airlines in order to initiate their response to an eruption. Each carrier treated information about the volcano in a different way. Some carriers rerouted flights already in the air; others used their own on-board wind speed data to calculate plume trajectories and altered their course accordingly; other carriers with Alaska-bound flights loaded extra fuel to anticipate possible diversion; others relied on FAA controllers to advise them of appropriate actions.

6. Procedures adopted by the airlines

During the 1989–1990 eruptions of Redoubt Volcano, each of the 26 carriers at Anchorage International Airport adopted procedures to deal with the changing situation presented by the volcano. These procedures ranged from cancellation of all flight operations for periods of days to several weeks, to rerouting of great-circle air traffic for stopovers at Fairbanks and Vancouver, Canada, to changing air routes to fly over Russian airspace and thereby avoid the area. Alaska-based domestic carriers such as Alaska Airlines, Reeve Aleutian, and Markair continued to operate their normal schedules, with only minor changes. Carriers based outside of Alaska, with less frequent service, were more conservative. They usually avoided Anchorage airspace until they were reasonably sure that the volcano would present no more problems.

As the Redoubt activity continued into 1990, airline operating procedures evolved in response to improved understanding about the volcano, improved monitoring of the volcano, and improved communications of information about eruptions. Procedural changes were usually initiated through open meetings between representatives of the airlines, air operations agencies (AIA, FAA, NWS, USAF), and scientists of the AVO.

From the start of activity in mid-December 1989, through February 1990, the flow of information to air carriers about the volcano followed a standard routing. Typically, the Alaska Volcano Observatory office in Anchorage would provide eruption notification to the FAA (ARTCC) and the National Weather Service (NWS) in Anchorage. This information was relayed by these agencies to the carriers through the NOTAM (Notice to Airmen) and SIGMET (Significant Meteorological Event) processes (see Aviation Weather Services, 1985). However, because NOTAMs required approval before issuance, they could be delayed from reaching the user by up to 90 minutes. Carriers were generally dissatisfied with the timeliness of this information and the broad area of the regions mentioned in these advisories, and as early as December, they began to develop their own approaches to dealing with the volcanic ash problem (Haeseker, 1991). Individual carriers such as Alaska Airlines and Markair established tracking schemes which relied on the AVO updates and telephone notification of an event from AVO through the FAA. Following event notification, several airlines developed methods to track the movement of ash clouds using pilot reports (PIREPs) from their own pilots as well as from pilots of other carriers. These procedures gained popularity with the carriers and on March 2, 1990 the air carriers and AIA formalized this system as a backup to normal FAA-NWS procedures. Two carriers, Markair representing domestic carriers, and Japan Airlines representing international carriers, were elected by the AIA airport operators council to take responsibility for informing the other carriers about the activity of Redoubt Volcano.

6.1. Alaska Airlines

In December 1989, Alaska Airlines, the carrier with most frequent operations at Anchorage International Airport, operated approximately 48 passenger flights daily, or about 20% of the total domestic operations. Following eruptions on

December 15–16, Alaska Airlines, as well as all other carriers at AIA, temporarily canceled all service. By December 17, the carrier had assessed its cancellation situation and determined that many flights could be resumed with little or no risk. By December 19, Alaska Airlines had resumed its normal schedule (Haeseker, 1991).

Officials of Alaska Airlines indicated that their dissatisfaction with available air operation information led them to establish their own common sense system for dealing with volcanic ash. First, they found that forecast wind data were occasionally incorrect with respect to direction and speed. Thus, for their purposes, projecting movement of the ash cloud based on forecast wind data was not sufficiently reliable. Second, they were skeptical of the NOTAMs and SIGMETs about volcanic activity since these materials are not dated and often remained 'in the system' for up to 36 hours, long after a volcanic event had ended. Third, they became hesitant to accept pilot reports received through the normal FAA channels since these were not usually made in a uniform fashion. As the eruption proceeded from mid-December into early January, it had become clear that one pilot's "major eruption" would be another pilot's "steam cloud".

To improve this situation, Alaska Airlines developed its own system that was based on the concept of an 'On Site Go Team' (Haeseker, 1991). Key elements in making the Alaska Airlines system successful were: 1) clear and direct verbal communications among flight operations personnel in Anchorage; 2) direct reports from Alaska Airlines' pilots in the air; 3) careful debriefings of arriving air crews and pre-flight briefings of departing air crews. This procedure usually began with receipt of the AVO daily Volcano Update describing Redoubt's current activity. Before March 2, this update usually arrived from AVO via the FAA, and after March 2, also from AVO via AIA. Questions about the activity were usually resolved by a phone call from Alaska Airlines to the AVO offices in Anchorage. Visual materials in the Alaska Airlines' operations center in Anchorage included an aeronautical chart of the region with the air routes and ash cloud position and its projected movement prominently displayed. Wind speed data from company aircraft were displayed and reports by company pilots were discussed by flight operations personnel including aircrews and dispatchers.

6.2. Carrier Marshaling System

In response to the need for more rapid dissemination of information among the carriers at Anchorage International Airport, the Carrier Marshaling System came into existence on March 2, 1990. The purpose of this system was to ensure the rapid dissemination of volcano-related information to all carriers operating at Anchorage International Airport. Initiation of the Carrier Marshaling System began with an initial event notification by Alaska Volcano Observatory, the FAA, or the National Weather Service to AIA, which in turn notified two carrier representatives at AIA, which in turn notified each of the carriers at Anchorage airport. The Carrier Marshaling System was similar in many respects to the 'On Site Go Team' system developed by Alaska Airlines and it relied heavily on visual tracking of the volcanic ash cloud through pilot reports. However, in contrast to the Alaska Airlines system, information gathered by the marshaling system was compiled by Markair and Japan Airlines into concise reports which were sent out immediately by teletype to the other carriers and other aviation interests using the SITA (Societe International Telecommunication Aeronautique) communication system. The report also went to selected addressees on the Aeronautical Fixed Telecommunication Network (AFTN), a worldwide communication system managed by the International Civil Aviation Organization for communication between air traffic control facilities, including the US Military. The marshaling system continued in operation until the ash cloud moved beyond the area of air traffic operations or when the ash content of the cloud diminished to the point where visual tracking was no longer possible. In practice, this meant a watchful period of about 4 to 6 hours during which up to 10 messages about the activity might be issued.

7. Discussion and Recommendations

Due to a unique combination of busy air routes, proximity to a major international airport, and an extended period of eruptive activity, aviation agencies in Anchorage developed a range of response schemes during the 1989–1990 eruptions of Redoubt Volcano. These pointed out serious shortcomings in the ways that volcanoes are monitored; ways that ash clouds are detected and tracked; ways that this crucial information is communicated; and ultimately, to ways that pilots deal with this information when they find their aircraft in an ash cloud. Many of the shortcomings, technical issues, and lessons learned at Redoubt Volcano were discussed at an international symposium on Volcanic Ash and Aviation Safety, held in Seattle, Washington in July 1991 (Casadevall, 1991).

7.1. Technical problems

Once a volcano has erupted, three technical challenges face agencies interested in accurate notification of eruptions for the purposes of aviation safety. These are: (1) verification that eruption clouds are ash-bearing; (2) determination of the altitudes of the tops of ash clouds; and (3) forecasting trajectories of drifting ash clouds and the rate of ash removal.

Ironically, the verification that eruption clouds are ash-bearing and the determination of the tops of ash clouds are problems that were largely solved during eruptions over the past 25 years, yet these methods were not available for application at Redoubt Volcano in 1989. For example, during the 1965–1968 eruptions of Redoubt Volcano, accurate cloud heights were obtained using a U.S. Air Force weather radar system located in Kenai (Wilson et al., 1966; Wilson and Forbes, 1969). Currently in Alaska, there is no facility providing weather radar of the type and quality formerly provided by the Kenai facility. Similarly, at Mount St. Helens in 1980 and 1982, FAA weather radar at Portland airport was successfully adapted for defining eruption plumes (Harris et al., 1981; Harris and Rose, 1983).

Ash cloud tops

During the 1989–1990 Redoubt activity, pilot reports were the principal source of information about the maximum altitude of ash cloud tops. Pilot reports of maximum cloud tops ranged from 40,000 to 45,000 feet. For several Redoubt eruptions, infrared imagery from a polar-orbiting military satellite recorded the minimum temperature of the cloud tops. Provided that the temperature-altitude profile of the local atmosphere was known, these data could be used to determine the altitude of the cloud top. However, such infrared satellite data were available for only a few eruptions, and the temperature-altitude profile for the wintertime Alaskan atmosphere typically includes a temperature reversal at approximately 37,000 feet, an altitude where most jet traffic operated. The temperature reversal led to some ambiguity in determining cloud tops. For example, on January 8, the temperature of the top of the eruption column was −56 degrees centigrade, which was equivalent to an altitude of either 37,000 feet or 30,000 feet depending on whether the eruption cloud was above or below the reversal in the temperature-altitude profile. Independently, a research airplane flew below the January 8 cloud shortly after the eruption and detected the edges of the cloud at about 37,500 feet using on-board lidar. However, the ash cloud was too dense for the lidar signal to penetrate to detect the maximum cloud top (Hobbs et al., 1991).

Ash in volcanic clouds

During the 1989–1990 eruptions of Redoubt Volcano, bad weather and darkness often prevented direct observation of eruptions. At these times, the seismic signals from seismometers located on the volcano were used to indicate when an eruption was taking place. However, the seismogram recordings did not allow scientists to determine whether the seismic event had produced an ash cloud.

Observers of ash clouds produced during the mid-December eruptions, and on January 2, 8, and 16, reported the occurrence of lightning in these clouds. Electrical charge accumulation in ash clouds is a common feature of many volcanic eruptions, but little research into the phenomena has been conducted (Gilbert et al., 1991). Charge buildup apparently occurs as particles strike against one another in turbulent eruption clouds. Combining seismic monitoring with lightning detection offers the possibility of detecting ash-rich clouds and distinguishing them from simple steam emissions which are normally free of ash. In 1990, a lightning detection system operated in Alaska by the Bureau of Land Management for monitoring of forest fires was successfully adapted for ash cloud monitoring at Redoubt Volcano (Hoblitt, 1994-this volume).

Ash cloud trajectories

Of broad importance to both aircraft as well as to ground-based municipal services, including surface transportation, hospitals, and military facilities, is the need to provide early warning of ash fall. For projecting the ash cloud trajectory, a simple procedure using forecast wind data was developed for Mount St. Helens eruptions in 1980 (Smith, 1980; Miller et al., 1981) and was adapted for use at Redoubt Volcano in 1990 (Murray et al., 1991). The trajectory forecast plots have the advantage that they are available in advance of an eruption, however, they provide no information about the ash content of a cloud or the rate of removal of ash from the cloud. Models of ash trajectories prepared by NOAA-Air Resources Laboratory for Redoubt Volcano using forecast wind data at the time of the December eruptions accurately indicated the position and time of the cloud as it passed over the conterminous western United States and into west Texas (Heffter et al., 1990).

Satellite imagery, especially from geostationary platforms, has been used to track ash clouds and to measure their rate of horizontal movement (Hanstrum and Watson, 1983; Malingreau and Kaswanda, 1986; Sawada, 1987, 1989). However, it remains difficult to distinguish between ash-bearing clouds and water vapor clouds using conventional satellite imagery (Sawada, 1989). An added problem for the Alaskan region is that only polar-orbiting satellites are available for surveillance.

7.2. Communications

Because volcanic ash clouds can drift far from their source, often over international boundaries, speedy communications about volcanic hazards between Flight Information Regions are essential. The December 15, 1989 eruption cloud from Redoubt Volcano drifted over eastern Alaska, western Canada, and finally dissipated over the western and south-central United States and northern Mexico (Heffter et al, 1990; Schnetzler et al., 1994-this volume), traveling through airspace of three different countries and in at least 5 different Flight Information Regions.

Three essential sources of information about volcanic activity and ash clouds include observations from ground-based observers to alert and verify of an eruption; from pilots through pilot reports about eruptive activity and ash clouds; and from satellite observations to detect and track ash clouds. No single source of information is completely reliable and feedback among these three sources is essential for the most complete and accurate communication. For aircraft still on the ground or en-route towards a potentially hazardous ash cloud, communications between air traffic controllers, flight dispatchers, and the pilots usually leads to a successful avoidance strategy that will typically mean carrying additional fuel or planning alternate routes to avoid the contaminated airspace.

Pilot reports

Air traffic has a tradition of relying on pilot reports (PIREPs) to indicate the nature of conditions encountered by pilots while in flight. These are usually reliable for commonly occurring weather phenomena, but have proved to be less reliable for infrequently observed activity such as volcanic eruptions. A standard reporting form for use when a volcanic eruption is detected or suspected, was developed (Fox, 1988) to ensure that air crews make uniform reports of volcanic events which are accurate and complete with regards to location, time, and nature of the event. Frequently, a pilot leaving a cloud-covered Anchorage area would pass up through the clouds into bright clear skies, view the quiescent, ash-free steam plume at Redoubt Volcano, and report to Anchorage ARTCC that he was seeing an ash-bearing eruption cloud. These reports were widely monitored by other pilots and airlines and often resulted in an avalanche of phone calls to AVO-Anchorage requesting verification of the pilot reports. Typically, these reports were of the persistent steam plume.

NOTAMs and SIGMETs

NOTAMs (Notice to Airmen) and SIGMETs (Significant Meteorological Information) are the two common forms of rapid reports issued by the FAA and National Weather Service to pilots. Numerous rules and traditions govern the preparation and issuance of these reports (Aviation Weather Services, 1985). Like pilot reports, these reports are generally reliable in providing information about commonly occurring weather phenomena. However, they have several shortcomings when applied to volcanic events which are often short-lived and where time is critical. First, the issuance of SIGMETs usually requires approval in Washington DC, followed by formal release by the National Weather Center in Kansas City. Usually this approval and issuance occurs within half an hour of initial preparation of the report by the local Flight Center. Secondly, reports often omit the time of the observed event and the time of the pilot report about an event. Since volcanic eruptions are often transient events lasting from a few minutes to several hours, and since ash clouds usually disperse rapidly from their origin, it is important for the users of these reports to know the time history of such information. At Redoubt Volcano, NOTAMs were issued and remained active for up to 36 hours after an eruption had occurred. Since NOTAMs carried an alarming statement about potential hazards from ash, carriers who knew that reports were dated gradually lost confidence in such reports (Haeseker, 1991).

Each NOTAM and SIGMET should clearly state the time at which the event occurred or was reported, as recommended for standard reporting procedures (Aviation Weather Services, 1985). This information will allow pilots and other users of this information to evaluate conditions and make independent decisions about flight conditions, which is the intent of such notifications (Aviation Weather Services, 1985).

Education and Awareness

There is no completely safe way to fly through an ash cloud without damaging an aircraft. Avoidance of an ash cloud is the only way to guarantee aircraft safety. Since ash clouds cannot be detected using the present generation of airborne radar, immediate communications to a pilot about a potential volcanic threat are essential to successful avoidance. Avoiding an ash cloud may be difficult or even impossible for an airplane in-flight, especially at night. While such an encounter will almost surely result in some damage to the airplane, depending on the ash content of the cloud and the duration of the encounter, there are steps which the aircrew can take to minimize the damage from such an encounter (Campbell, 1991b). These steps include reducing engine power and turning the aircraft 180 degrees to escape the ash cloud. Such actions require that the pilots be well informed about the nature of ash clouds and trained beforehand about the procedures recommended to minimize damage. For aircraft still on the ground or enroute towards a potentially hazardous ash cloud, communications between controllers, dispatchers, and the pilots can usually lead to a successful avoidance strategy.

Far-traveled ash clouds

The west Texas encounters on December 17, 1989 indicate that even far-traveled ash clouds can threaten the safety of an aircraft. The following guidelines should be followed if a pilot, dispatcher, or air traffic controller believes that volcanic ash might be encountered.

- If an ash cloud is visible to a pilot, entry into the cloud must be avoided.
- Since visibility requires daylight, an extension of this rule should be that if pilot reports, NOTAMs and SIGMETs, and analysis of satellite imagery and/or ash cloud trajectory forecasts indicate that ash might be present in an airspace, that airspace must be avoided until it can be determined to be safe for entry.

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