INTRODUCTION

By Thomas J. Casadevall

Volcanic ash from the 1989–90 eruptions of Redoubt Volcano disrupted aviation operations in south-central Alaska and damaged five jet passenger aircraft, including a new Boeing 747-400, which cost in excess of $80 million to repair (Steenblik, 1990). The Redoubt eruptions served to increase interest by the aviation community in volcanic hazards and made it clear that mitigating the hazards of volcanic ash to aviation safety would require the cooperation and efforts of volcanologists, meteorologists, air traffic managers, engine and airframe manufacturers, and pilots.

Soon after the December 1989 eruptions of Redoubt, Senator Ted Stevens of Alaska requested that Federal agencies form an interdepartmental task force to develop and coordinate both an immediate and a long-term response to the Redoubt eruptions. In March 1990, in response to this request, the U.S. Geological Survey, the Federal Aviation Administration (FAA), and the National Oceanic and Atmospheric Administration (NOAA) formed an interagency task group and began planning for an international technical symposium to review the available information about volcanic ash clouds and to assess what was being done to address the ash hazard, both domestically and internationally. This interagency group received strong support from the aviation community, and the Federal agencies were soon joined by the Air Line Pilots Association (ALPA), the Aerospace Industries Association (AIA), the Air Transport Association (ATA), the Flight Safety Foundation (FSF), and the American Institute of Aeronautics and Astronautics (AIAA). An important early result from this cooperation was the "First International Symposium on Volcanic Ash and Aviation Safety," to address the effects of volcanic activity on aviation safety in a multidisciplinary way and at a global scale. The aims of the symposium were: to bring together individuals who were interested in the volcanic ash problem but who may have been unaware of other scientists, engineers, pilots, and aviation authorities with similar interests; to encourage and define needed improvements in the detection, tracking, and warning of volcanic ash hazard so that aircraft may avoid ash clouds; and to review the effects of volcanic ash on aircraft so that pilots who encounter ash can respond appropriately. The symposium was held in Seattle, Wash., from July 8–12, 1991.

The symposium was attended by more than 200 participants from 28 countries, representing the major air carriers, airplane and engine manufacturers, pilots and aviation safety organizations, air traffic managers, meteorologists, and volcanologists. More than 100 technical presentations were made during the symposium, including a special session on the effects on aviation operations of the June 15, 1991, eruption of Mt. Pinatubo in the Philippines (Casadevall, 1991). Field trips to the Federal Aviation Administration air traffic control facility in Auburn, Wash., to the Boeing 737 assembly plant in Renton, Wash., and to the Mount St. Helens National Volcanic Monument gave participants the opportunity to view the volcanic hazard–aviation problem from several perspectives. Such broad participation demonstrated a clear need and wide support for a meeting of this type.

In the past 15 years, more than 80 jet airplanes have been damaged owing to unplanned encounters with drifting clouds of volcanic ash in air routes and at airports. Seven of these encounters caused in-flight loss of jet engine power, which nearly resulted in the crash of the airplane. The repair and replacement costs associated with airplane–ash cloud encounters are high and, to date (May 1994), have exceeded $200 million. In addition to the high economic costs of these encounters, more than 1,500 passengers aboard the seven airliners that temporarily lost engine power were put at severe risk.

The hazard is compounded by the fact that volcanic ash clouds are not detectable by the present generation of radar instrumentation carried aboard aircraft and are not likely to be detectable in the foreseeable future. Complete avoidance of volcanic ash clouds is the only procedure that guarantees flight safety, and this avoidance requires communication between the pilot and observers outside the aircraft.

Since the Seattle meeting, eruptions at Pinatubo, Sakurajima Volcano (Japan), Pacaya Volcano (Guatemala), Galeras Volcano (Colombia), Hudson and Lascar Volcanoes (Chile), Mt. Spurr (Alaska), Nyamuragira Volcano (Zaire), Sheveluch Volcano (Russia), and Manam Volcano (Papua New Guinea) have further disrupted air traffic, damaged aircraft in flight, and delayed flights and curtailed operations at a number of airports. The issue of volcanic hazards and aviation safety continues to be timely and in need of more effort if we are to improve the margin of flight safety in the presence of volcanic ash.

ISSUES AND NEEDS

During the symposium, discussions focused on the following technical areas: the 1989–90 Redoubt eruptions and their impacts on aviation operations, the nature of volcanoes and their ash clouds, the effects of volcanic ash on aircraft, methods and procedures of communicating the ash-cloud hazard to pilots, the role of meteorology and the use of atmospheric models to forecast cloud movement, and detection and tracking of ash clouds. This volume contains reports for 60 of the 108 technical presentations made during the symposium. The papers presented about the Redoubt eruptions have been published elsewhere (Miller and Chouet, 1994).

In addition to the technical presentations, symposium discussions identified a number of key issues and needs that participants felt must be addressed in order to mitigate the volcanic threat to aviation safety. These included:

1. Improved communications among volcano observers, meteorologists, air traffic controllers, flight dispatchers, and pilots about drifting ash clouds, including immediate notification of volcanic eruptions to pilots.
2. Improved education of pilots, flight managers, and manufacturers about the ash-cloud hazard, including specific recommendations for avoiding ash clouds.
3. Improved detection and tracking of ash-cloud movement using remote-sensing techniques and atmospheric-transport models.
4. Improved monitoring of the Earth's active volcanoes, especially in the remote Aleutian-Kamchatka-Kurile volcanic region.
5. New methods for eruption identification and ash-cloud detection.
6. Development of instruments that will enable pilots to detect ash clouds while in flight, especially useful when flying over remote, unmonitored regions of the Earth.
7. Development of better methods to remove and clean ash from airplanes and airports.
8. Determination of minimum levels of ash concentration that are capable of damaging aircraft and engines.
9. Development of a worldwide notification system and clearinghouse for information about active volcanoes, including planning charts to show the location of volcanoes relative to air routes.

DEVELOPMENTS SINCE THE SYMPOSIUM

A number of ad hoc working groups were formed following the symposium to examine these topics and have produced significant progress on many of these technical issues. Accomplishments include:

1. A training video for pilots entitled "Volcanic Ash Avoidance," produced by the Boeing Company in cooperation with the Air Line Pilots Association and the U.S. Geological Survey (Boeing Company, 1992).
2. An international workshop on communications among volcanologists, meteorologists, air traffic managers, and pilots was held in Washington, D.C., in September 1992.
3. An FAA review on aviation safety as affected by volcanic ash (FAA, 1993a).
4. A workshop on the dynamics and characteristics of the ash clouds from the 1992 eruptions of Mt. Spurr was held in Washington, D.C., in April 1993 (FAA, 1993b).
5. An international workshop on volcanic ash and airports was held in Seattle, Wash. (Casadevall, 1993).
6. New communications links with Russians for warnings and information about Kamchatkan volcanoes, which underlie the increasingly busy air routes of the north Pacific region, were established in 1993 (Miller and Kirianov, 1993).
7. An interagency plan for volcanic ash episodes in Alaska was put into effect by the FAA, NWS, USGS, Department of Defense, and the State of Alaska in 1993 (Alaska Interagency Operating Plan, 1993).
8. A global planning chart showing the position of active volcanoes relative to air routes and air navigation aids was published (Casadevall and Thompson, 1994).

INTERNATIONAL EFFORTS

Since 1982, the International Civil Aviation Organization (ICAO) has worked to address the volcanic threat to aviation safety worldwide (Fox, 1988, this volume). This threat came to wide public attention in 1982 when two 747 passenger jets encountered ash at night from separate eruptions of Galunggung Volcano in Indonesia. In these incidents, volcanic ash extensively damaged exterior surfaces, instruments, and engines, resulting in the loss of thrust and powerless descents of nearly 25,000 feet before the pilots of both aircraft restarted their engines and landed safely at Jakarta (Smith, 1983). The Galunggung encounters occurred for two main reasons. First, the pilots were unable to see the ash or to otherwise detect it using on-board instruments, and second, no warnings about the activity of the volcano were contained in the aeronautical information generally available to pilots, such as notices of significant meteorological events—SIGMET's--or in notices to airmen—NOTAM's. These incidents led in 1982 to the formation of a volcanic ash warning group under leadership of the ICAO.

Eruptions and aircraft encounters with ash clouds during the past 15 years have prompted several other important international efforts to mitigate the volcanic hazard to aviation safety. Because volcanic ash clouds are carried by upper-level winds and often cross national boundaries as well as boundaries separating flight-information regions, efficient and prompt communications between regions are essential to avoiding encounters. The May 1985 encounter between a jumbo jet and an ash cloud from an eruption of Soputan Volcano in Indonesia prompted the Indonesian and Australian governments to form a bilateral volcanologicall airspace liaison committee to improve communications about volcanic eruptions in the Indonesian region (Johnson and Casadevall, this volume). In North America, drifting ash clouds from the 1989–90 eruptions of Redoubt Volcano, and the 1992 eruptions of Mt. Spurr, sent ash clouds over Canada and disrupted operations in Canadian airspace. These incidents prompted establishment of closer bilateral communications between Canadian and U.S. agencies including volcanologists, meteorologists, and air traffic controllers (Hickson, this volume).

In 1988, ICAO member states adopted regulations to provide alerts to pilots about eruptive activity worldwide. These efforts included a special volcanic activity report form (VAR), which requires that pilots make a number of critical observations about the location, timing, and nature of an ash cloud. This information is communicated directly to the nearest area control center and is introduced into the communication network so that other aircraft may avoid airspace contaminated by volcanic ash (Fox, 1988, this volume).

Also in 1988, the World Organization of Volcano Observatories (WOVO), in cooperation with ICAO and with the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), requested WOVO member institutions to establish contacts with civil aviation authorities to improve communications between ground-based observatories and air traffic in order to minimize the volcanic hazards to aircraft. Currently, WOVO is examining ways to improve the exchange of information between observatories and agencies concerned with aviation operations, including the use of electronic mail (Riehle and Fink, 1993).

Following the 1991 Seattle symposium, ICAO addressed the volcanic threat to aviation safety at regional meetings in Bangkok (September 1992) and Mexico City (October 1992). In November 1992, changes to the international standards and recommended practices for meteorological services (ICAO, 1992) went into effect. The changes relate to the types of information about volcanic clouds that are entered into aeronautical communications networks using the SIGMET mechanism. The new regulations require that a volcanic advisory forecast be issued every 4 hours regarding the status of a volcanic cloud, with a 12-hour forecast of ash-cloud behavior.

Information for these advisories could come from many sources, but would most likely come from analysis of satellite images and from analysis of ash-cloud movement using atmospheric-transport models (Stunder and Heffter, this volume; Tanaka, this volume). For example, an important source of information for these volcanic advisories for the Southwest Asia region is the Darwin Regional/Specialized Meteorological Centre, established in 1993 by the Australian Bureau of Meteorology. The Darwin center utilizes satellite imagery to provide outlook advisory information about the occurrence and movement of ash clouds from eruptions in the Indonesian region. The center also serves as a venue for training meteorologists from the Asian region about detection and tracking of volcanic ash clouds so other countries in the region might carry out similar analysis at the local level.

To further assist ICAO member states in meeting the requirements for more detailed advisories, ICAO established a special implementation project to member states with active volcanoes as well as to those states responsible for flight information in regions adjacent to areas with active volcanoes. Through this project, an ICAO team consisting of a volcanologist and an aeronautical meteorologist visited countries in the Asia-Pacific region in 1992–93 (Casadevall and Oliveira, 1993) and the South American region in 1993–94 to advise on methods for meeting the new ICAO regulations. The new regulations should result in more rapid and clearer communications about volcanic ash clouds to the aviation community.

In addition to these bilateral efforts to improve the speed and quality of information, several countries have addressed specific volcanic threats to aviation operations by applying existing technology and by seeking to develop new methods and equipment for ash detection. For example, in 1991, scientists and aviation authorities in Japan installed specialized seismic and infrasonic detectors at Sakurajima Volcano to detect ash-producing eruptions. Results from these sensors are continuously transmitted to nearby Kagoshima Airport to provide real-time notification of explosive eruptions that threaten airport operations (Kamo and others, this volume; Onodera and Kamo, this volume). In another example, scientists in Australia are seeking ways to supplement information that is available to the pilot by developing an ash-detection sensor that can be carried onboard the aircraft to detect the presence of ash in the flight path (Barton and Prata, this volume; Prata and Barton, this volume). Such a sensor would be especially valuable for international flights over regions where volcanoes are poorly monitored and where ground-based communications are poorly established.

EFFORTS IN THE UNITED STATES

The United States has approximately 56 volcanoes with historical eruptive activity; 44 are located in Alaska. The U.S. Geological Survey (USGS) is the principal Federal agency with responsibility for assessing volcanic hazards and monitoring active volcanoes in the United States (Wright and Pierson, 1992). This work is carried out primarily from volcano observatories in Hawaii, Alaska, California, and Washington. For example, the Alaska Volcano Observatory monitors the activity of volcanoes in the Cook Inlet area, including Redoubt and Spurr. Continuous seismic and other monitoring of these volcanoes, day and night, in all seasons and weather conditions, enables volcanologists to detect eruption precursors as well as eruptions themselves. Early detection of eruptions and prompt communication of this information to the FAA and to the National Weather Service offices in Anchorage are an essential part of the role played by USGS scientists in mitigating the ash hazard to aircraft.

The National Oceanic and Atmospheric Administration (NOAA) and the Federal Aviation Administration (FAA) also have responsibilities for dealing with the hazard of volcanic ash clouds that affect aviation operations in the United States. Cooperation between these two agencies was formalized shortly before the December 1989 eruption of Redoubt, when a memorandum of understanding between the agencies created a volcanic hazard alert team and established procedures to respond to volcanic eruptions affecting air operations in the United States. Since 1989, these procedures have been activated for eight volcanoes in the United States (J. Lynch, NOAA-SAB, written commun., March 1993). In 1993, a letter of agreement between the USGS and NOAA attempted to speed the exchange of information that notifies the aviation community of ash-cloud hazards and formalized the de facto collaboration between these agencies that has existed since the Redoubt eruptions.

The principal tools used by NOAA for assessing volcanic activity are analysis of data from satellites (Krueger and others, this volume; Matson and others, this volume) and wind-field data, which enables the forecast of drifting ash clouds (Murray and others, this volume; Stunder and Heffter, this volume). Since 1990, the National Weather Service office in Anchorage has implemented several new techniques for detecting and tracking volcanic ash clouds from volcanoes in the Cook Inlet and Aleutian regions (Hufford, this volume). These efforts are integrated with the monitoring efforts of the Alaska Volcano Observatory and with the air-traffic-control efforts of the FAA. The FAA, through its area control centers, has the primary responsibility for communicating with pilots and for providing NOTAM's.

Following the 1989–90 eruptions of Redoubt, the 1992 eruptions of Mt. Spurr also had an important impact on aviation, affecting operations in Alaska, Canada, and the conterminous United States (Alaska Volcano Observatory, 1993). Ashfall from the August 18, 1992, eruption of Mt. Spurr deposited from 1 to 3 mm of ash in Anchorage and caused Anchorage airports to curtail operations for several days (Casadevall, 1993). The cost of airport cleanup alone in Anchorage from the August 18 ashfall was more than $650,000. The ash cloud from the September 17 eruption disrupted air traffic routing around the volcano--2 days later it disrupted air routes over western Canada and in the congested air corridors of the northeastern United States. Fortunately, there were no encounters between aircraft and the drifting Spurr ash clouds. The lack of damaging encounters following the Spurr eruptions reflects increased awareness about the hazards of ash clouds and improvements made since 1990 in the warning, detection, and tracking of volcanic clouds. These improvements are largely a direct result of the previously mentioned initiatives by Federal and international agencies to reduce the hazards from volcanic ash.

From an operational perspective, experience in the Australia-Indonesia region and in Alaska has indicated that the threat of volcanic ash can be effectively addressed at the regional or local level. For example, the 1989–90 Redoubt eruptions and the 1992 Spurr eruptions prompted Federal and State agencies in Alaska to establish a regional plan for aviation-related volcanic hazards (Alaska Interagency Operating Plan, 1993). The plan outlines the responsibilities of the agencies involved in eruption responses to meet the public's need for information to protect against volcanic ash hazards. The Redoubt and Spurr eruptions also prompted U.S. and Canadian agencies to refine bilateral operational plans for communicating about volcanic hazards (Hickson, this volume).

In addition to the efforts by international and Federal agencies, the major airplane and jet engine manufacturers have also studied the damage to aircraft from ash encounters in efforts to develop mitigation strategies, including practical steps for pilots to minimize damage should an ash cloud be entered accidentally. The manufacturer's principal trade association, the. Aerospace Industries Association (AIA), formed a volcanic ash study committee in 1991 to evaluate the volcanic threat to aviation safety (AIA Propulsion Committee, this volume). The findings of this committee are reflected in a number of the reports presented in Seattle (Campbell, this volume; Dunn and Wade, this volume; Przedpelski and Casadevall, this volume).

The Air Line Pilots Association (ALPA), the Air Transport Association (ATA), and the Flight Safety Foundation (FSF), as well as the American Institute of Aeronautics and

Astronautics (AIAA) and the Aerospace Industries Association (AIA) have all taken active roles to communicate about the ash problem with their members and constituents, both nationally and internationally. ALPA and ATA were sponsors of the Seattle Symposium, along with the FAA, NOAA, and the USGS. AIA, AIAA, FSF, IAVCEI, and the National Transportation Safety Board were co-sponsors of the symposium.

FUTURE DIRECTIONS

As we gain understanding about the nature of ash clouds and the hazard of volcanic ash to aviation operations, we constantly improve our abilities to deal with the threat (Casadevall, 1992). Multidisciplinary cooperation and communications were major factors in the success of the Seattle meeting. This cooperation created an excitement among the participants that has been kept alive at later workshops and in cooperative efforts such as the production of the Boeing training video (Boeing Company, 1992). Even though the ash–aviation safety problem is global in scope, the solutions that have worked best have often been on a local or regional scale. The optimal solutions require understanding the location and character of the nearby active volcanoes, the structure of the air routes that cross or pass by these volcanoes, and an understanding and use of all available resources to detect, track, and forecast the movement of ash clouds. At the same time, as new pilots are introduced to new routes, efforts to educate pilots must continue.

The Seattle symposium and the efforts following the symposium indicate that we have much to do to satisfactorily address concerns about the threat of volcanic ash to aviation safety. This requires application of existing technologies, such as methods that enable scientists to detect eruptions from remote, unmonitored volcanoes; early detection of ash clouds; tracking of ash clouds in real time; and development of better and faster ways to get information into the cockpit. Also, despite the recent advances in testing jet engines for their tolerances to volcanic ash (Dunn and Wade, this volume) and advances in using remote-sensing technologies to detect and track ash clouds (Schneider and Rose, this volume; Wen and Rose, 1994), it is essential that ash clouds be sampled directly as they drift from their source volcanoes (Riehle and others, 1994). Only direct sampling will allow us to obtain information with which to corroborate and validate laboratory tests and computational models. The results of the Seattle symposium should be viewed as a start of efforts to address the threat that ash clouds present to aviation safety. Volcanoes will certainly continue to erupt, and air traffic and aircraft sophistication will continue to grow. To successfully coexist with the threat of volcanic ash, we must continue to address the volcanic hazard in a responsible fashion. Open communications about these efforts are essential to successfully dealing with the volcanic hazard to aviation safety.

ACKNOWLEDGMENTS

The success of the Seattle symposium required the energy and efforts of a large number of colleagues. The symposium was organized under the leadership of Chris Newhall of the USGS and came about through the efforts of an interagency task group that was first suggested by Senator Ted Stevens of Alaska. Principal representatives on this task group included Robert Machol of the FAA, Mike Matson of NOAA, Doug Wade of the Department of Defense, Ed Miller of the Air Line Pilots Association, and Don Trombley of the Air Transport Association. Their assistance and support in the production of this report is gratefully acknowledged. The editor of this report served on this task group as program coordinator for the symposium.

Several colleagues provided long-term encouragement for this project, including Grant Heiken (Los Alamos National Laboratory), Tom Fox (ICAO), Mike Dunn (CALSPAN), Tom Simkin (Smithsonian Institution), and Bill Rose (Michigan Technological University). A special thanks goes to Robert Wesson of the USGS, who had the earliest and clearest vision of what the Seattle symposium should be.

The cooperation of those who acted as reviewers is especially appreciated. They include: Robert Anders, Steve Brantley, Marcus Bursik, Dan Dzurisin, David Hams, Grant Heiken, Wally Johnson, Steve Lane, Steve McNutt, C. Dan Miller, Tom Murray, Tina Neal, Chris Newhall, John Power, Jim Riehle, Bill Rose, Dave Schneider, Steve Self, George Stephens, Barbara Stunder, and Bob Tilling.

Deloris Klausner of the Branch of Volcanic and Geothermal Processes (USGS, Denver) was responsible for collating all the manuscripts. Rick Scott, geologist and technical publications editor (USGS, Denver), provided editorial guidance and supervised preparation of illustrations and the final layout of the volume.

REFERENCES CITED

Alaska Interagency Operating Plan, 1993, Alaska Interagency Operating Plan for Volcanic Ash Episodes: Anchorage, Alaska, Alaska Division of Emergency Services, Alaska Volcano Observatory, Department of Defense, Federal Aviation Administration, and National Weather Service, June 16, 1993, 18 p.

Alaska Volcano Observatory, 1993, Mt. Spurr's 1992 eruptions: Eos, Transactions, American Geophysical Union, v. 74, p. 217 and 221–222.

Boeing Company, 1992, Volcanic ash awareness: Seattle, Wash., Boeing Customer Training and Flight Operations Support, video 911202, 33 minutes.

Casadevall, T.J., ed., 1991, The First International Symposium on Volcanic Ash and Aviation Safety, Program and Abstracts: U.S. Geological Survey Circular 1065, 58 p.

Casadevall, T.J., 1992, Volcanic hazards and aviation safety—Lessons of the past decade: FAA Aviation Safety Journal, v. 2, no. 3, p. 9–17.

———1993, Volcanic ash and airports: U.S. Geological Survey Open-File Report 93-518, 53 p.

Casadevall, T.J., and Oliveira, F.A.L., 1993, Special project in the Asia/Pacific region boosts awareness of danger posed by volcanic ash: ICAO Journal, v. 48, no. 8, p. 1618.

Casadevall, T.J., and Thompson, T.B., 1994, Volcanoes and air navigation aides—A global planning chart: U.S. Geological Survey Geophysical Investigations Map GP–1011.

Federal Aviation Administration, 1993a, Assuring aviation safety after volcanic eruptions: Washington, D.C., Office of the Associate Administrator for Aviation Safety, Special Review, 35 p.

———1993b, FAA Workshop on old volcanic ash clouds: April 22–23, 1993: Washington D.C., Office of the Chief Scientist, abstract volume, 37 p.

Fox, T., 1988, Global airways volcano watch is steadily expanding: ICAO Bulletin, April, p. 21–23.

International Civil Aviation Organization [ICAO], 1992, Meteorological service for international air navigation—International standards and recommended practices: Montreal, International Civil Aviation Organization, Annex III to the Convention for International Civil Aviation, 11th edition, 82 p.

Miller, T.P., and Chouet, B.A., eds., 1994, The 1989–1990 eruption of Redoubt Volcano, Alaska: Journal of Volcanology and Geothermal Research, v. 62.

Miller, T.P., and Kirianov, V.Y., 1993, Notification procedures for Kamchatkan volcanic eruptions: A case history of Sheveluch Volcano, April, 1993: U.S. Geological Survey Open-File Report 93-569, 9 p.

Riehle, J.R., and Fink, J.H., 1993, Some advantages of global electronic communications among volcanologists [abs.]: World Organization of Volcano Observatories workshop (Volcano observatories, surveillance of volcanoes, and prediction of eruptions), Guadeloupe, 13–17 December, 2 p.

Riehle, J.R., Rose, W.I., Schneider, D.J., Casadevall, T.J., and Langsford, J.S., 1994, Unmanned aerial sampling of a volcanic ash cloud: Eos, Transactions, American Geophysical Union, v. 75, p. 137–138.

Smith, W.S., 1983, High-altitude conk out: Natural History, v. 92, no. 11, p. 26–34.

Steenblik, J.W., 1990, Volcanic ash: A rain of terra: Air Line Pilot, June/July 1990, p. 9–15, 56.

Wen, Shiming, and Rose, W.I., 1994, Retrieval of sizes and total masses of particles in volcanic clouds using AVHRR bands 4 and 5: Journal of Geophysical Research, v. 99, p. 5421–5431.

Wright, T.L., and Pierson, T.C., 1992, Living with volcanoes: U.S. Geological Survey Circular 1073, 57 p.