FIRST INTERNATIONAL
SYMPOSIUM ON

VOLCANIC ASH AND AVIATION SAFETY

PROGRAM AND ABSTRACTS

SEATTLE, WASHINGTON
JULY 8–12, 1991

Sponsored by
Air Line Pilots Association
Air Transport Association of America
Federal Aviation Administration
National Oceanic and Atmospheric Administration
U.S. Geological Survey

Co-sponsored by
Aerospace Industries Association of America
American Institute of Aeronautics and Astronautics
Flight Safety Foundation
International Association of Volcanology and Chemistry of the Earth's Interior
National Transportation Safety Board

U.S. GEOLOGICAL SURVEY CIRCULAR 1065

Cover—Ash billows from the vent of Mount St. Helens Volcano, Washington, during the catastrophic eruption which began at 8:32 a.m. on May 18, 1980. View looks to the northeast. USGS photograph taken about noon by Robert M. Krimmel.

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U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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FIRST INTERNATIONAL SYMPOSIUM ON VOLCANIC ASH AND AVIATION SAFETY

Thomas J. Casadevall, *Editor*

INTRODUCTION

Volcanic ash produced by the 1989-90 eruptions of Redoubt Volcano in Alaska widely affected commercial and military air operations in the vicinity of Anchorage (Brantley, 1990). These effects included damage to some jet aircraft, as well as indirect impacts to the Anchorage economy resulting from rerouting and cancellations of flight operations.

Between December 1989 and February 1990, five commercial jetliners suffered damage from encounters with volcanic ash from Redoubt Volcano. The most serious incident occurred on December 15, 1989, when a new Boeing 747-400 aircraft encountered an ash cloud at a distance of 150 nautical miles northeast of the volcano as the jet was descending for a landing in Anchorage. While there were no injuries to passengers, the damage to engines, avionics, and aircraft structure from this encounter cost in excess of $80 million (Steenblik, 1990). Additional encounters between jet aircraft and volcanic ash clouds occurred on December 15 and 16, 1989 and February 21, 1990, but did not result in engine failure.

During the days following the December 15-16 incidents, Anchorage airport remained open; however, most airline companies cancelled operations for up to several days. Several international carriers cancelled or curtailed operations through January 1990 and normal service did not resume until mid-February. Impacts to military flight operations consisted mostly of cancellation of flights and rerouting of aircraft. The resulting loss of revenue from curtailed operations at Anchorage International Airport during several months following the eruption is estimated to total $2.6 million (Brantley, 1990).

One outcome of the Redoubt incidents has been to increase interest in the issue of volcanic hazards and aviation safety among a broad group which includes commercial and military air operators, aircraft manufacturers, the Federal Aviation Administration, the National Weather Service, and the U.S. Geological Survey. To focus this interest, the First International Symposium on Volcanic Ash and Aviation Safety is being held in Seattle, Washington in July 1991. The AIMS of the symposium are: 1. to encourage improvements in the detection, tracking, and warning of volcanic ash hazard so that aircraft may avoid ash clouds; and 2. to review the effects of volcanic ash on aircraft so that pilots who encounter ash can respond appropriately.

Technical sessions The response to the initial call for papers for the symposium was enthusiastic. Eighty-eight abstracts have been submitted for presentations in Seattle. The symposium includes six principal topics: the Redoubt eruptions and their impacts; Volcanoes and Ash Clouds; Damage and Impacts; Communications and Procedures; Meteorology and Ash Cloud Modeling; and Detection and Tracking. About 30 papers will be presented orally in plenary session; the remainder will be presented in poster displays during technical session on July 9-11, 1991.

We will prepare a SYMPOSIUM PROCEEDINGS VOLUME to permanently record the papers and discussions held during the symposium. The volume will follow the same major headings as in the symposium and all presenters are requested to submit papers describing their presentations.

Field trips The symposium will include two day-long field trips. On Monday, July 8, participants will visit the FAA Air Route Traffic Control Center in Auburn, Washington, and the Boeing Airplane Co. factory in Renton, Washington, where 737 and 757 aircraft are manufactured. On Friday, July 12, participants will visit the Mount St. Helens Volcanic Monument. The May 18, 1980, eruption of Mount St. Helens was the most costly volcanic eruption in U.S. History. This tour provides an opportunity to view the devastation caused by the eruption and to see the lava dome, which has grown within the 1980 crater.

INTEREST IN THE ASH CLOUD HAZARD

Volcanic ash clouds are very difficult to detect by aircraft during flight using onboard sensors and current technology. Development of new sensor technology is currently underway, especially in Australia. The greatest success to date in mitigating the ash cloud hazard has come through the combined efforts of ground-based observers, pilots, meteorologists, and air-traffic-management agencies working together to provide early warning to aircraft.

The problem of volcanic hazards to aviation safety came to wide public attention when several jet aircraft suffered damage after flying through volcanic ash clouds from the 1980 eruptions of Mount St. Helens volcano, Washington. Interest in the problem grew rapidly in the early 1980's following several near-fatal encounters of jumbo-jet aircraft with ash-rich eruption clouds that had traveled considerable distances from their sources. In 1982, two incidents occurred within 3 weeks of each other when Boeing 747-200 passenger jets encountered ash from two separate eruptions of Galunggung Volcano in Java, Indonesia (Smith, 1983). In both cases, volcanic ash entered the jet engines and caused thrust loss of all four engines. After powerless descents of nearly 25,000 feet, the pilots of both aircraft restarted their engines and landed safely at Jakarta Airport although both aircraft suffered extensive damage to engines and exterior surfaces. Other eruptions during the decade in Indonesia, Japan, Italy, and the United States also led to damaging encounters.

These encounters triggered international efforts to evaluate and address the problem of volcanic hazards to aviation safety. In 1982, a *Volcanic Ash Warnings Group* (VAW) group was organized under leadership of the *International Civil Aviation Organization* (ICAO) in Montreal, and the *Airways Volcano Watch* was created by the Australian Department of Aviation. A May 1985 encounter between a 747-200 and an ash cloud from Soputan Volcano in Sulawesi, Indonesia, prompted the Indonesian and Australian governments to form a Volcanological/Airspace Liaison Committee (VULCAN) to improve communications about volcanic eruptions in the Indonesian region. In 1988, ICAO member states adopted a set of amendments to ICAO regulations for an International Airways Volcano Watch to provide alerts from eruptive activity worldwide. ICAO efforts included development of a special form of pilot report (PIREP) for reporting volcanic events (Fox, 1988).

Redoubt Volcano emits a vigorous plume of water vapor, sulfur dioxide, and carbon dioxide during a period of quiescent degassing between explosive eruptions. The plume is drifting to the west. View is to the north. Plumes such as this are described in the paper by P. V. Hobbs, L. F. Radke, and D. J. Coffman. Photograph by Steven R. Brantley on January 22, 1990.

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.

USA efforts In the United States, there are approximately 56 volcanoes with historical eruptive activity. Forty-four of these are located in Alaska. The United States Geological Survey (USGS) is the principal agency of the United States Government with responsibility for assessing volcanic hazards and monitoring restless volcanoes. The work of the USGS Volcano Hazards Program is carried out through volcano observatories located in Hawaii, Alaska, and Washington. While USGS efforts focus on ground-based studies, two other agencies, the National Oceanic and Atmospheric Administration (NOAA) and the Federal Aviation Administration (FAA), recently joined efforts to monitor and track volcanic ash clouds in the United States.

In 1989 a Memorandum of Understanding on volcanic hazard alerts between NOAA and FAA created a *Volcanic Hazard Alert Technical Team* to respond to volcanic eruptions affecting air operations in the United States. This cooperation requires that a volcanic advisory forecast (SIGMET) be issued every 4 hours regarding the status of the volcanic cloud, with a 12-hour forecast of ash cloud behavior. The NOAA-FAA memorandum is currently being revised in light of experiences gained during the 1989-90 Redoubt eruptions and will more formally link the USGS with NOAA-FAA efforts.

In addition to the efforts by Federal agencies, most airplane and jet engine manufacturers have studied the problem in efforts to develop mitigation strategies. The manufacturer's principal trade association, the Aerospace Industries Association of America (AIA), formed a Volcanic Ash Study Committee (PC334-1) in 1991. The recommendations of this committee will be presented during the Seattle Symposium.

One of the keys to addressing the problems aircraft have with volcanic ash is to effectively communicate experiences and practical solutions to the air crews and airline carriers. In connection with the symposium, the Air Line Pilots Association (ALPA), the Air Transport Association (ATA), and the Flight Safety Foundation (FSF) have all taken active roles to communicate about the ash problem with their members and constituents, both nationally and internationally. Members of these organizations were involved in both the planning of the Seattle Symposium and earlier efforts under the direction of ICAO.

We hope that all participants in the First International Symposium on Volcanic Ash and Aviation Safety will leave Seattle with a clearer understanding about the threat which volcanic hazards pose to aviation safety.

REFERENCES CITED

Brantley, S. R., (ed.), 1990, The eruption of Redoubt Volcano, Alaska, December 14, 1989-August 31, 1990: U.S. Geological Survey Circular 1061, 33 pp.

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

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.

ACKNOWLEDGMENTS

Working to bring together experts from many diverse fields has been a unique experience in multicultural relations. In addition to participants from more than a dozen foreign countries, we had to learn to view the problem of aircraft encountering ash through the eyes of passengers and aircrews, geologists and meteorologists, engineers and manufacturers, airline carriers and air-traffic managers, and even attorneys. We hope that this multi-disciplinary dimension is apparent in the program for the symposium. We especially appreciate the cooperation of those from outside the scientific community for their willingness to work within the more traditional meeting format of scientific exchange.

We gratefully acknowledge the skill and efforts of Marsha Simpkins and Deloris Klausner of the Branch of Igneous and Geothermal Processes (USGS/Denver) who assisted in preparation of this volume, and the editorial guidance provided by the Branch of Technical Reports (USGS/Denver).

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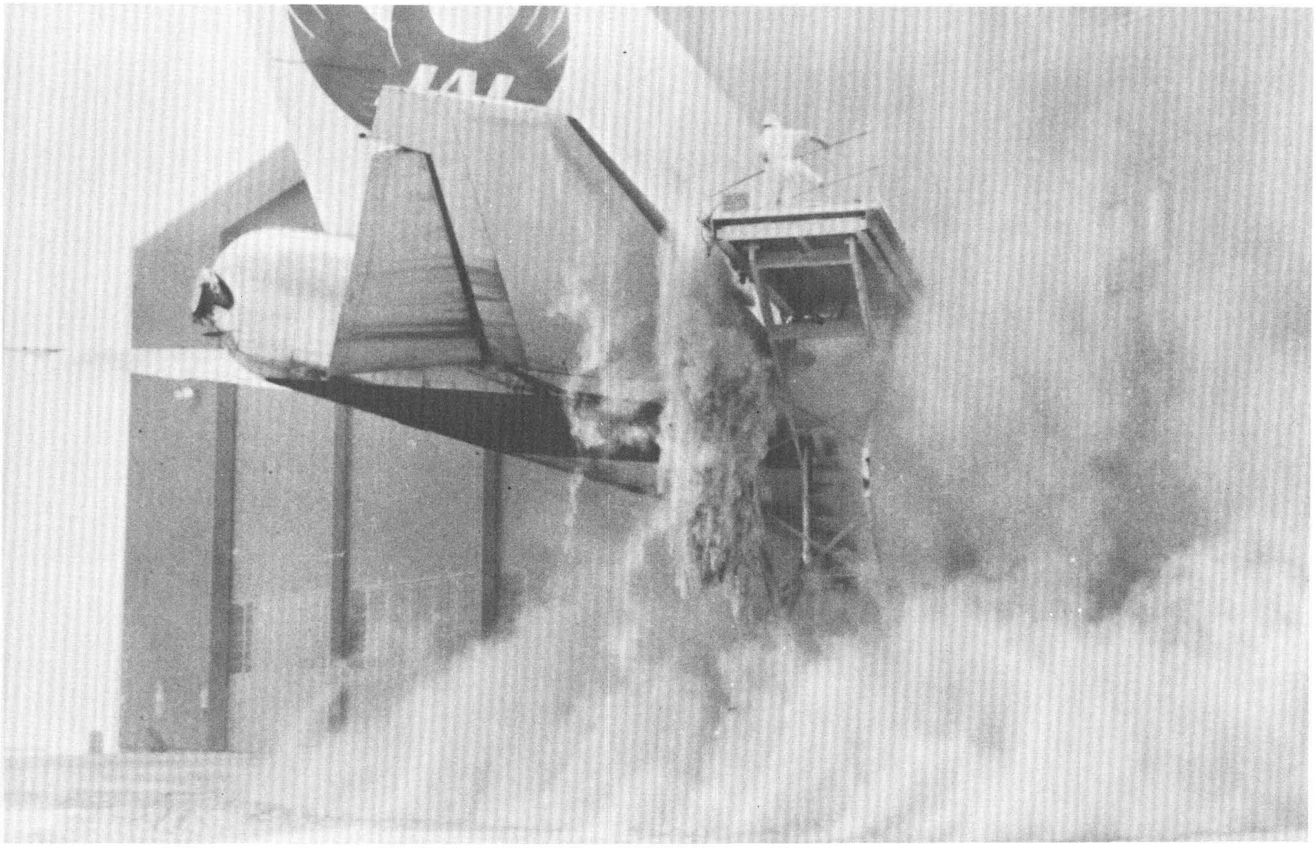
CLEANUP OF GRANT COUNTY AIRPORT AFTER MAY 18, 1980, ERUPTION OF MOUNT SAINT HELENS

David M. Bailey, *Port of Moses Lake, Moses Lake, WA*

On May 18th of 1980, Mount Saint Helens, located in the southwest portion of the State of Washington, erupted. This eruption spewed a considerable amount of volcanic material throughout the State which eventually progressed over the northern tier states. The amount of volcanic material that eventually was deposited at the Grant County Airport ranged from 3-4 inches of fine powder ash.

As a brief background, the Grant County Airport, located in central Washington, is approximately 120 miles from Mount Saint Helens. The airport, formerly known as Larson Air Force Base, contains over 4,500 acres. Our main runway is 13,500′ x 300′ and our cross-wind runway is 10,000′ x 100′. The airport is extensively used as a research and development, heavy jet training facility by a number of air frame manufacturers and air carriers. We provide services to the Boeing Company, Japan Airlines, McDonnell Douglas, McChord Air Force Base, Alaska Airlines, Big Bend Community College and approximately 300 other foreign and domestic air carriers.

During the Symposium, I would like to discuss the effect the ash had on the Airport and a detailed description as to the process that we used to remove the ash from both the Airport operating areas and the Industrial Park. I would also like to further discuss some of the problems we had with disposing of the material and the effect on aircraft and equipment. Basically, we had the airport back in operation within thirty days.



An airport maintenance worker removes ash from the tail assembly of a Boeing 747 airplane at Moses Lake, Washington following the May 18, 1980 eruption of Mount Saint Helens Volcano. This eruption had a major impact on air operations in the Pacific Northwest and caused the temporary closing of several important airfields. Photograph courtesy of the Port of Moses Lake.

VOLCANOES AND AVIATION SAFETY IN COSTA RICA

Jorge Barquero H., *Observatorio Volcanologico y Sismologico de Costa Rica, Universidad Nacional, Heredia, Costa Rica*

The active volcanoes in Costa Rica are located in the Guanacaste Volcanic and Central Volcanic Ranges. Poas and Irazu volcanoes had several strombolian eruptions in historical times that issued large quantities of ash. Fine ash moved to the west and southwest of the volcanoes reaching different distances and altitudes due to the predominant trade wind directions. Therefore, precautions should be taken for the air traffic during future eruptions.

Juan Santamaria International Airport (main Costa Rican airport) is located 23.2 km south from Poas volcano and 41.6 km southwest from Irazu volcano. Commercial airline routes fly over or very close to the volcanoes. For example, Poas volcano (8,884 feet high) is in the route of commercial airlines to Miami with a minimum flying altitude of 12,000 feet. Irazu volcano (11,457 feet high) is in the airline routes to Panama and Puerto Limon with a minimum flying altitude of 14,000 feet. Arenal volcano (5,380 feet high) is located 73.6 km from the Santamaria airport. Arenal is the most active volcano in Costa Rica and it is in the course of commercial flights to Managua, Nicaragua, with a minimum flying altitude of 11,000 feet. Between 1963-1965, during the last active period of Irazu volcano, large quantities of ash were deposited on the Santamaria airport, however, we do not have official records to explain what happened with the air traffic during times of heaviest ashfall.

The cooperation between pilots, air controller and volcanologists is very important. From the air it is possible to see anomalous activity in volcanoes. For example, in 1962 a pilot called a newspaper to inform about the first columns of vapor issued by Irazu volcano during the 1963-65 active period. This was the beginning of cooperation between aviation and volcanology. Three years ago, Poas volcano had very strong gas emissions. At times private and commercial airline pilots reported to air controllers strong odors and the height of the gas columns. We do not have an official linkage with the civil aviation authorities, but concerned air controllers notified our observatory. We hope that by the end of this year (1991) we will have a working group to make this type of cooperation more effective. It is imperative to take into account possible ash and gas eruptions when planning air traffic and future airport sites.

DETECTION AND DISCRIMINATION OF VOLCANIC ASH CLOUDS BY INFRARED RADIOMETRY II: EXPERIMENTAL

I. J. Barton and A.J. Prata, *CSIRO, Aspendale, Australia*

To test the feasibility of using infrared radiation to detect and discriminate volcanic ash clouds, an absolute, self-calibrating, filter radiometer has been built. The radiometer has up to five selectable filters and two temperature controlled precision blackbodies for internal calibration. The input signal is chopped against that from a third reference blackbody. The radiometer has been flight tested up to 25,000 feet and has performed well. During the flight tests, measurements were made in both clear skies and cloudy conditions at varying heights and viewing angles. Results from these tests will be presented and compared to theoretical calculations.

The radiometer has also been used to view the volcanic plume emanating from Mt. Sakurajima on the Japanese island of Kyushu. For these tests the radiometer was ground based and pointed up towards the plume. These results will be presented and compared with measurements of normal water/ice clouds. Measurements were also made at 8.6 μm in an attempt to monitor the SO_2 concentration in the volcanic plume. Corroborative measurements of SO_2 were also made using a COSPEC instrument.

VOLCANIC ASH CHARACTERIZATION

G. Bayhurst, A. Mason, and K. Wohletz, *Los Alamos National Laboratory, Los Alamos, NM*

Detailed studies of ash particles can be used to better understand problems associated with ash transport such as engine damage, visibility, sunlight blockage, and dispersion and deposition of ash. We are using several analytical techniques to characterize ash particles in terms of size, mineralogy, and elemental composition.

We have developed a program to characterize particles using a scanning electron microscope (SEM) with an energy dispersive X-ray detector (EDS). Once we have properly prepared and mounted the ash samples, the SEM and its software can describe the particles' size, area, shape, chemical composition, and density. The data obtained from the SEM are then reduced by a computer program to obtain distribution graphs for size, density, shape, and mineralogy. Finally, we analyze the samples by traditional optical microscopy to verify their mineralogy and to examine their crystallinity.

This method was used on the ash that damaged the engines from the KLM flight of December 15, 1989, which flew through the ash cloud from Redoubt Volcano. The sample studied was collected from the pitot-static system and had not been exposed to any engine parts that may have changed its characteristics. This sample will be used to demonstrate the capabilities and information obtained from our program.

FREQUENCY AND REGIONAL EXTENT OF ASH ERUPTIONS FROM ALASKAN VOLCANOES

James E. Beget, Samuel E. Swanson, and David Stone, *University of Alaska, Fairbanks, AK*

Historic records indicate Alaskan eruptions large enough to disrupt air traffic have had an average recurrence interval of about 5-10 years during the last century. These small eruptions typically each last a few hours, and disperse about 0.1-0.2 km^3 of ash in a plume several hundred kilometers long. Mt. St. Augustine and Mt. Redoubt have erupted most often and so constitute the greatest hazards to air traffic.

The frequency and style of tephra eruptions from Alaska volcanoes has changed through time. Some prehistoric eruptions were hundreds of times larger than the 1989-1990 Mt. Redoubt event. The 1912 Katmai eruption put an estimated 25 km^3 of ash into the atmosphere during a sustained eruption lasting almost 3 days, while prehistoric ashfalls have reconstructed volumes of 50-100 km^3 and produced significant fallout more than 1,500-2,000 km from the source volcanoes over areas of 10^5-10^6 km^2. If a large Alaskan volcanic eruption occurred today it would put huge volumes of ash into the air and might blanket most of Alaska and northwest Canada or large regions of the northern Pacific Ocean for a week or more.

THE INGESTION AND MELTING PROPERTIES OF VOLCANIC ASH IN AIRCRAFT ENGINES

A. Bernard, *Universite Libre, Brussels, Belgium* and F. LeGuern, *CEN-Saclay, Gif sur Yvette, France*

Volcanic eruptions represent a significant hazard for civil air transport. Numerous encounters of aircraft flying through volcanic plumes have been reported in the past 15 years. These incidents were sometimes serious as in December 1989 when a KLM Boeing 747 flying through the eruptive plume of Redoubt volcano in Alaska suffered severe engine damage resulting in an emergency landing in Anchorage.

We present here a SEM study of volcanic ash deposits found in engines of aircraft which flew through volcanic plumes. These ash deposits are characterized by a uniform glassy layer with a flat surface where all the characteristics of the original material have been obliterated. This glassy layer is often covered by a second layer formed by the accumulation of ash fragments slightly adhering together on a party melted matrix. The original crystal morphology is conserved in this second layer. On top of the glassy layer, abundant microspherules (0.1-15μm) with morphologies similar to fly-ash are observed. These microspherules show variable compositions of silicates and oxides. All these observations are consistent with pronounced melting and dehydration of the volcanic material in the high temperature regions of the aircraft engine and subsequent deposition on the cooler surfaces of the turbine vanes. This melting is the most significant process for volcanic hazard considerations because it causes the volcanic ash to adhere to engine surfaces and lead to the build-up of a significant deposit (several mm thick) which was the main cause of the engine shutdown. The volcanic material seems to have unique melting properties (low melting point, small size) since aircraft operations in other geographic areas with a high loading of dust (i.e. desert sand) are not suffering from this problem (W. W. Smith, 1983).

PREDICTING THE TIMES AND INTENSITIES OF EXPLOSIVE VOLCANIC ERUPTIONS

Sutikno Bronto, *Volcanological Survey of Indonesia, Bandung, Indonesia*

Galunggung explosive volcanic eruptions in 1982 caused two international flight accidents which occurred on 24 June and 13 July when the 747 Jumbo Jets passed above the volcano, from Kuala Lumpur, Malaysia to Perth, Australia. The planes were forced to make an emergeny landing on Jakarta. On 15 December 1989, a KLM 747 - 400 aircraft entered a cloud of volcanic ash from Redoubt Volcano, Alaska. Although the aircrafts landed successfully, extensive repairs were required.

In the last century, two of the largest eruptions in historic time occurred in Indonesia, i.e., Tambora (1815) and Krakatau (1883). Their ash cloud reached up to 150 km high. In the last decade (1980 - 1990), there were 100 events of explosive volcanic eruptions in Indonesia, and

11 of them ejected ash reaching 4 - 27 km high. These ash clouds could affect both domestic and international air traffic.

On the basis of past occurrences, a study of volcanic eruptions, particularly to predict the times and intensities of explosive volcanic eruptions, is being carried out in order to avoid air traffic accidents. This study is based on statistical data of precursors through crisis stage to volcanic explosions, and processes in the volcanoes' magma chamber.

It is concluded if the magma is fractionated, the most explosive eruption occurs near the beginning of an eruption period, and the intensity of explosions caused by magma fractionation is lesser than that caused by magma mixing.

747-400 AIRPLANE DAMAGE SURVEY FOLLOWING A VOLCANIC ASH ENCOUNTER

Ernest E. Campbell, *Boeing Commercial Airplane Group, Seattle, WA*

On December 15, 1989, a 747-400 airplane powered by CF6-80C2 engines, encountered volcanic ash at approximately 26,000 feet during descent for a landing at Anchorage, Alaska. All four engines flamed out, however, they were restarted and an uneventful landing was accomplished.

The following survey provides a brief summary of the airplane damage:

All four engines sustained extensive compressor erosion and hot section damage. All four engines, nose cowls and thrust reverses were removed and replaced.

Fuel, oil, hydraulic and potable water system were contaminated. Each system was drained and cleaned.

Pilots' windshields, cabin windows forward to door two, navigation and landing light covers were sand blasted, all removed and replaced.

Wing, stabilizer and vertical-fin leading edges and leading-edge flaps were sand blasted, all were removed and replaced.

All pilot and static probes were plugged, removed and replaced.

Electronic equipment (black boxes) contaminated, all removed and replaced.

Entire interior of airplane contaminated. All seats, equipment, side walls, ducts, etc., were removed and cleaned or replaced.

Cost of airplane repair over 80 million dollars.

RECOMMENDED FLIGHT-CREW PROCEDURES IF VOLCANIC ASH IS ENCOUNTERED

Ernest E. Campbell, *Boeing Commercial Airplane Group, Seattle, WA*

<u>GROUND OPERATION</u>

If airplane operations from or to airports contaminated with volcanic ash can not be avoided, accomplish the following:

--Airplane exposed surfaces should be cleared of any ash which may contaminate lubricated parts, enter engines gas path, air-conditioning system and other orifices.

--Restrict APU use to engine starts.

--Avoid use of air conditioning packs on the ground.

--Do not taxi with any engine shutdown.

--Allow ash and dust to settle prior to takeoff.

--Use rolling take-off technique.

<u>FLIGHT OPERATIONS</u>

<u>Avoidance</u>

Use all possible means to avoid areas of known volcanic activity:

--Review all NOTAMs and ATC directives for current status.

--Plan flight to stay upwind of volcanic ash.

WARNING: Airplane radar will not detect volcanic ash.

<u>Recognition</u>

The following conditions have been observed by flight crews:

--Heavy static discharges.

--Glow in engine inlets.

--Ash appearing in the cockpit and cabin with an acid odor.

--Multiple engine malfunctions and flame-outs.

--Decrease in, or loss of airspeed.

--False cargo fire warnings.

<u>Procedures</u>

If volcanic debris is inadvertently encountered, accomplish the following:

--Immediately reduce thrust to idle.

--Exit ash as quickly as possible.

--Autothrottles off.

--Engine and wing anti-ice on.

--All A/C packs on/high.

--Start APU (if available).

--Oxygen mask on and 100% (if required).

--Ignition on.

--Monitor EGT limits.

--Engine restart (if required).

--Monitor airspeed and pitch attitude.
--Land at nearest suitable airport.

VOLCANIC ASH INGESTED BY JET ENGINES

T. J. Casadevall, G. P. Meeker, *U.S. Geological Survey, Denver, CO,* and Z. J. Przedpelski, *General Electric Aircraft Engines, Evendale, OH*

Ingestion of volcanic ash by jet engines may cause serious deterioration of engine performance due to erosion of moving engine parts, such as compressor blades and turbine blades, and accumulation of partially melted ash in hot zones within the engine. Since 1980, at least 5 encounters between jet-powered aircraft and volcanic ash clouds have resulted in temporary engine failure.

In this study we used petrographic thin section, scanning electron microscope, and electron microprobe techniques to analyze volcanic ash deposits from the December 15, 1989, eruption of Redoubt Volcano as well as deposits found within the engines of a Boeing 747-400 that flew into the ash cloud created by the December 15 eruption.

Ash from the deposits of the December 15 eruption ranges in diameter from less than 1 micron to slightly greater than 100 microns with a mean diameter of about 20 microns. Volcanic ash was reduced to about 7 microns diameter by the time it entered the combustor section of the engine where melting occurred. Melted ash deposits in the hot combustor and turbine sections of the engine display fluidal textures that indicate flowage of material occurred during or after initial deposition. Vesicles are common in the remelted deposits. The glass is enriched in total $Si0_2$ as compared to the deposits from the ash cloud. In addition to the primary minerals of plagioclase, pyroxene, and Fe-Ti oxides found in deposits from the ash cloud, deposits from the engines also include metal particles derived from abrasion of engine parts, principally from the compressor area where titanium metal alloy and stainless steel are used extensively. Oxide particles rich in Fe, Cr, and Ni derived from stainless steel are found coating the surfaces of ash grains and are present as spheres in the melted ash matrix.

The principal components of volcanic ash are volatile-poor glass and minerals, which are unlikely to melt at temperatures below 900-1,000^{o}C. By reducing engine power to the minimal setting, the engine temperature can be reduced below the threshold at which volcanic ash is likely to melt.

GASES AND AEROSOLS IN VOLCANIC ERUPTIONS CLOUDS: IMPACTS ON AIRCRAFT

T. J. Casadevall, *U.S. Geological Survey, Denver, CO,* and T. M. Murray, *Boeing Company, Seattle, WA*

Gases and aerosols of volcanic origin are essential components of ash clouds produced during explosive eruptions. Major species include nonreactive gases H_2O, CO_2, CO, and H_2, and reactive (corrosive) gases SO_2, H_2S, HC_1, and HF. Concentrations of these gases in ash clouds depend largely on the degree of dilution by ambient atmosphere and in distal clouds are in the range of <<1 ppm to 100 ppm. Water vapor also condenses from the atmosphere ingested into the growing eruption cloud. Volcanic gases are removed from the ash cloud during the formation of acidic aerosols and through adsorption onto silicate ash particles. Aerosols vary in diameter from <<1 micron up to 10 microns. In the cold, oxidizing environment of the lower stratosphere, SO_2 is converted to sulfuric acid H_2SO_4 aerosols and eventually to sulfate particles that may remain suspended long after the larger silicate particles have settled from the cloud.

At these low concentrations and for the usually brief exposures of most encounters, volcanic gases and aerosols by themselves do not pose an immediate threat to human life or to aircraft integrity. SO_2 and H_2S may be detected by smell to produce nausea and cause anxiety; however, in the concentrations found in volcanic clouds these gases are not toxic and do not threaten health. The principal problem for airplanes from gases and related sulfate particles is the deterioration of materials prompted by direct chemical attack or enhanced corrosion processes. These processes pose a potentially serious long-term threat to the integrity of the aircraft. The major deterioration processes include corrosion of metal parts and surface coatings in the hot sections of jet engines (sometimes referred to as "hot corrosion"); contamination of plastic insulation and neoprene hosing in air distribution systems; corrosion of electrical contacts in avionics; and pitting, crazing, and embrittlement of windows due to sulfuric acid attack. In addition, the dielectric properties of some conformal coatings covering printed circuit cards may change due to the presence of the volcanic gases.

VOLCANO ERUPTION NOTIFICATION AND AIRCRAFT AVOIDANCE

Charles F. Criswell, *Federal Aviation Administration, Anchorage, AK*

Since the first eruption of Mt. Redoubt, Alaska, in December 1989, the Federal Aviation Administration (FAA) has made every effort to keep the aviation community apprised of volcanic activity. While our initial attempts at eruption notification were not totally satisfactory, we have made substantial progress in that area to date. However, even with the progress, nothing in the notification and alerting process can prevent penetration of the ash cloud.

Eruption notification in Alaska begins with a report from the Alaska Volcano Observatory or a pilot report. Following eruption notification by either source, the Anchorage Air Route Traffic Control Center (ARTCC) notifies all air carriers via the "CEDA" network that an eruption has occurred and begins preparing a Notice to Airman (NOTAM). The Center Weather Unit (CWU) develops a Significant Meteorological Information statement (SIGMET) and a Center Weather Advisory (CWA). A NOTAM, SIGMET, or CWA are aviation advisories that identify a change in the components of the National Airspace System or identifies weather phenomena that could affect the safety of flight. While these advisories are being formatted, the ARTCC notifies all other aviation users via an automated, multi-tasked fax machine that an eruption has occurred. Once the advisories have been formatted, they are then transmitted by air-to-ground radio or teletype, whichever is appropriate, to all users. Aircraft in flight are immediately issued SIGMET and NOTAM information as it becomes available, including all updates.

Immediately after the NOTAM's, SIGMET's, and CWA's are formatted and transmitted, the CWU develops a chart depicting the flow pattern of the ash cloud. This instrument is developed using winds aloft reports and upper winds forecast. Once this chart is designed, it is transmitted via automated fax to all fax recipients. Aircraft in flight do not have access to this chart; therefore, in order to avoid ash, they must depend on controller advisories and their own visual contact with the ash cloud. Controllers must also depend on pilot observations to assist them in helping other aircraft avoid ash clouds. In the case involving ash damage to a B-747, controllers issued at least two advisories to the aircraft about the ash pattern, including other aircraft reports of the ash cloud's position before the aircraft entered the ash.

Not only do air traffic controllers depend on pilot observations to tell them where the ash cloud is, they also relay this vital information to other pilots to assist them in avoiding the cloud. Controllers cannot see ash clouds on radar; therefore, they are unable to provide course guidance to avoid them. Radar vectors are still issued for arrival and departure routings; however, pilot occurrence is solicited. Even with all the multiple notifications and in-flight advisories given to pilots, controllers still depend on the pilot's ability to see ash clouds in order to avoid them.

CURRENT AND FUTURE CAPABILITIES IN FORECASTING THE TRAJECTORIES, TRANSPORT AND DISPERSION OF VOLCANIC ASH CLOUDS AT THE CANADIAN METEOROLOGICAL CENTRE

Real D'Amours, *Canadian Meteorological Centre, Dorval Canada*

A 3-D Trajectory Model has been operational at the Canadian Meteorological Centre for several years. The model is executed on a request basis to estimate future trajectories of air parcels originating from anywhere in North America at any desired level. The model has been used extensively to support the forecasting needs of the Canadian Regional Weather Centres during volcanic eruptions. The model executes very quickly on CMC's Cray-XMP and results are transmitted within a few minutes both in chart and message form. A description of the model will be given along with examples of applications to the eruptions of Mount Redoubt in early 1990.

A large-scale transport/dispersion/deposition model (CANERM) is also operational at CMC. Although it has been primarily designed for tracking the radioactive cloud resulting from a large nuclear accident, CANERM can be used to estimate the evolution of the ash plume from a large volcanic eruption. Given a reasonable description of the source characteristics, concentration estimates of airborne ash particles can be obtained. A brief description of the model will be given, along with its current capabilities and limitations. Example of results will be shown and future prospects will be discussed.

ANALYSIS OF SATELLITE IMAGES OF REDOUBT VOLCANO PLUMES

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The discharge of ash and the resulting danger to air transportation was one of the primary hazards associated with the 1989-1990 eruption of Redoubt Volcano. Satellite images are a valuable source of information for the analysis of the plume, especially if the data is available in a timely manner. Advanced Very High Resolution Radiometry (AVHRR) images were acquired and analyzed, and the results provided to the Alaska Volcano Observatory (AVO). AVO used this information to access the plume and ash trajectory and distribution. During the first few weeks of the eruption, six hours elapsed after a satellite pass before images were provided to the AVO. However, six hours was considered unacceptable due to the dynamics of volcanic processes. Thus, a procedure was developed to provide satellite images within 1.0 to 1.5 hours after a satellite pass.

Since the start of the eruption, approximately 50 AVHRR and Landsat digital data tapes have been collected for retrospective studies. AVHRR images recorded in late December reveal plumes that emanate from Redoubt and trail off to the east across Cook Inlet and over Prince William Sound and the Gulf of Alaska. Images recorded after December show plumes that were circular with a diameter of a few tens of kilometers. The plumes, as recorded by the satellites, were cold (-20 to -60°C) because they cool and expand upon rising, and come to equilibrium with the surrounding atmosphere. By relating the plume temperature recorded on the images to the temperature/altitude structure of the atmosphere as measured by soundings, the altitude of the plumes were accessed. An atlas of the satellite images is being compiled.

MULTIPHASE FLOWS AND THE MODELING OF GAS/PARTICLE FLOWS

Rand Decker, *University of Utah, Salt Lake City, UT*

There are two categories of multiphase flow theories that are commonly specialized for modeling dilute gas/particle flows; the "two-fluid" model and particle tracking schemes. The resulting models have been used to simulate the transport of particulate through straight and curved gas ducting, and turbine rotor cascades. In this paper the elements of multiphase flow mechanics are reviewed and those efforts, to date to apply these theories to gas/particle flows in air breathing propulsion and airfoil environments is presented. These multiphase flow models may have some potential in providing analysis of possible response scenarios to engine and/or airfoil performance degradation or loss during aircraft operations in particle-laden flows.

INFLUENCE OF VOLCANIC CLOUDS ON GAS TURBINE ENGINES

Michael G. Dunn, *CALSPAN Corporation, Buffalo, NY,* and Douglas P. Wade, *Defense Nuclear Agency, Alexandria, VA*

For many years, a technology program has been ongoing at CALSPAN in the area of gas turbine propulsion research that utilizes a unique facility and a unique experimental technique which allows one to subject operating gas turbine engines to an adverse environment like that associated with a volcanic ash cloud without endangering either an airplane or a flight crew. The response of several different engines, among them the Pratt/Whitney JT3D turbofan and the Pratt/Whitney J57 turbojet, to typical volcanic ash clouds has been determined during this technology program.

The behavior of the individual components that make up a volcanic cloud are separately studied using an Allison T56 combustor can, a row of T56 high-pressure turbine inlet nozzle guide vanes, a dust injection system and an external air compression source. Data obtained using this device provide guidance for the full-scale engine measurements.

The damage modes that an engine will experience depends upon the particular engine, the thrust setting at which the engine is operating when it encounters the dust cloud, the constituents of the cloud, and the respective melting temperature of these various constituents. In addition, the rate at which events will occur depends upon the particle density (or concentration) of the cloud.

An important part of the CALSPAN effort has been to identify which engine parameters can be read by the flight crew to provide an early warning of impending engine problems. Having determined that one has a problem, it is then important to learn how to operate the engine after it has sustained considerable damage.

ADPIC CALCULATED VOLCANIC ASH CLOUD TRANSPORT AND FALLOUT FROM THE 20 DECEMBER 1990 MOUNT SAINT HELENS PUFF

James S. Ellis and Thomas J. Sullivan, *Lawrence Livermore National Laboratory, Livermore,* CA

The 20 December 1990 Mount Saint Helens volcanic ash puff is used to demonstrate the regional capability of the ADPIC (Atmospheric Diffusion Particle-in-Cell) code for characterizing the ash cloud, its transport, and the fallout pattern at the ground. The sensitivity of the cloud transport to the uncertainty in the atmospheric winds, particle size distribution, and density are demonstrated. Results are presented as isopleths of atmospheric concentration at various altitudes and as ground deposition amount. A unit source amount of ash material is used in the calculation.

The ADPIC code and associated wind field model, MATHEW, facilitate the calculation and visualization of the three-dimensional structure of dispersing ash clouds, particularly as influenced by surrounding complex topography. Such a calculation capability, operating in real-time, could be of assistance to FAA centers and airport facilities faced with managing air traffic in volcanic-hazard regions.

Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48

DEVELOPMENT OF A REAL TIME ATC VOLCANIC ASH ADVISORY SYSTEM BASED ON THE AVIATION WEATHER INFORMATION SYSTEM

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The overall Air Traffic Control decision-making and communications system for volcanic-ash surveillance should be based on treating volcanic ash as a type of aviation weather hazard from the viewpoint of information dissemination. Maximum advantage should be taken of the aviation weather product generation and dissemination system currently under development by the FAA and the National Weather Service. This system will provide improved access to all NWS and FAA sensors for hazard determination and prediction, and the use of a local (i.e., weather forecast office domain) numerical model to create an aviation gridded forecast which can be manipulated by the FAA Aviation Weather Products Generator (AWPG) to provide real time hazard warning displays for enroute and terminal controllers.

Detection and tracing of the ash clouds can be facilitated by use of the data acquisition systems associated with this initiative. In particular, we consider the use of ash-concentration data, as measured by sensors on air carrier planes and communicated via the ACARS (ARINC Communications Addressing and Reporting System) downlink, and the use of the WSR-88D Doppler weather radar mosaic maps, resident in the AWPG, to validate numerical model predictions. Systems issues associated with the incorporation of data from specialized ash sensors and non FAA/NWS systems are addressed.

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WARNING SYSTEMS AND PILOT ACTIONS

Peter M. Foreman, *International Federation of Air Line Pilots Associations, Canada*

When aircraft and volcanic emissions share the same airspace, safety depends upon arranging the aircraft flight paths so that they do not encounter the volcanic products. Pilots are not always able to observe ash in the air. Therefore, they need the assistance of an external detection and warning system. Pilots will be the last link in the chain of communications and decision making. Pilots have to act, to ensure the safety of the aircraft. There are limitations on the ability of pilots to respond to warnings. These limitations need to be recognized and addressed by the warning systems if pilots are to successfully avoid the volcanic material. Pilots are participating in the design of the warning systems to be sure that the operational result is reliable avoidance. Crews can assist the warning system by timely and precise reporting of any observations of volcanic material or events.

Nothing that comes out of volcanoes does aircraft any good. Should an aircraft blunder into volcanic material, the results can range from early windshield replacement, following encounters with just a few ash particles, to rapid destruction of the aircraft, if it were to fly into an eruptive column. In between those two extremes is a spectrum from escalating early maintenance costs, to complete engine flame out and failure of many aircraft systems, in an environment of blinding, choking dust and toxic fumes. The lowest order of problems are merely an economic concern. Those of a higher order are a threat to air safety. There are certain actions which will minimize damage and regain control of the aircraft flight path. It is important to make all crews aware of the appropriate sequences of actions for the aircraft types which they operate.

VOLCANIC ASH--INTERNATIONAL REGULATORY ASPECTS

Tom Fox, *International Civil Aviation Organization (ICAO), Montreal, Quebec*

Following the incidents in Indonesian airspace in June/July 1982 when two jet transport aircraft suffered engine flame-out on all four engines due to ingestion of volcanic ash from the Mt. Galunggung eruption, ICAO has moved swiftly to amend its regulatory documents to include requirements to provide volcanic ash warnings to aircraft. The warnings are issued using existing aviation message formats such as the NOTAM (Notice to Airmen) and the SIGMET (information on meteorological phenomena hazardous to aviation).

In order to support the warnings system, ICAO sought help from States and international organizations to form an international airways volcano watch. The idea was to base the watch on an observing triad comprising aircraft reports, reports from ground-based observing stations, and monitoring by satellite. In organizing the watch, advantage was taken of existing observing-reporting networks and procedures. In this regard, the success of the watch is largely due to the enthusiastic support of the International Air Transport Association (IATA) and International Federation of Air Line Pilots' Associations (IFALPA) in providing special air reports of volcanic activity; the World Meteorological Organization (WMO) in arranging the provisions of observations of volcanic activity from all the many international ground-based observing networks which it co-ordinates and coordinating the use of meteorological satellites and techniques for forecasting volcanic-ash trajectories; and from the World Organization of Volcano Observatories (WOVO) in arranging for critically important observations from volcano observatories strategically sited near active volcanoes.

Current work is concentrated on consolidating and extending the airways volcano watch and improving the warning system based on operational experience gained during volcanic eruptions near routes in S. E. Asia and in N. America.

LESSONS FROM THE 16 SEPTEMBER 1986 ERUPTION OF LASCAR VOLCANO, NORTH CHILE

P. W. Francis, S. Self, *University of Hawaii, Honolulu, HI* and L. S. Glaze, *Jet Propulsion Laboratory, Pasadena, CA*

Lascar is a 5641 m high volcano on the crest of the Andean chain in northern Chile. Its brief eruption in September 1986 illustrates some aspects of importance to the aviation community. The eruption took place at 10.39 UT (2 min) on September 16, and lasted less than five minutes. A vulcanian eruption column rose to a height of about 15 km, and was rapidly borne downwind. Ground observations and geostationary satellite (GOES) images showed that the eruption plume formed a discrete extended slug about 2 km thick at elevations between about 10 and 14 km, which passed overhead the major city of Salta, Argentina, 285 km distant from Lascar, less than 2 hr after the eruption. Ash fell at Salta, but no aircraft incidents are known, although the city has a major airport. By 14.12 UT the plume had diffused, having travelled 400 km in 3.5 hr and covered an area greater than 100,000 square km. Ash collected in Salta was 200 microns in diameter and consisted mostly of finely fragmented lava particles; in contrast to the glassy pumiceous material involved in recent aircraft incidents.

From an aviation safety stand-point, the Lascar eruption is significant because:

(1) it took place at an obscure volcano, not generally regarded as hazardous. The eruption went unnoticed in Chile, and might not have been recorded at all if ash had not fallen on Salta.

(2) it was extremely brief, but discharged an ash plume which was potentially hazardous over a wide area.

(3) the ash cloud travelled remarkably rapidly from its remote source volcano into populated areas and air corridors.

There are many Lascar-like volcanoes in the world capable of unpredictable ash eruptions that may abruptly place downwind air routes at risk. While satellite monitoring and response techniques are clearly desirable, the short time scales involved emphasize the desirability of developing autonomous aircraft-borne sensor systems. Detectors sensitive to acid aerosols or particles in the engine airflow giving warning that the fringes of a plume have been entered, and enabling immediate response, may be more realistic than modified weather radars.

PARTICLE AGGREGATION CONTROLLED BY ELECTRICAL CHARGE IN VOLCANIC PLUMES

J. S. Gilbert, S. J. Lane, R. S. J. Sparks, *Bristol University, U.K.,*

Observations at Sakurajima volcano in Japan reveal that during nearly continuous daily eruptions, which generate large volumes of ash, particles fall from eruption columns (at distances 2.5 - 5 km from the vent) as loosely bound aggregates <3mm in diameter, particles >200 μm in diameter coated with fine ash, or as accretionary lapilli. Field experiments yield absolute charge to mass (q/m) ratios, for particles 1-250 μm in diameter, which range from +3 to + 6 x 10^{-4} Ckg^{-1} and - 2 to -5 x 10^{-4} Ckg^{-1}. The average q/m ratio ranges from + 2 to +5 x 10^{-5} Ckg^{-1}. Surface charge densities calculated from the field data are similar to those carried by streams of insulating particles in laboratory and industrial situations. Thus, the ash particles generated during explosive volcanic activity at Sakurajima are nearly saturated with charge. These surface charges provide attractive forces sufficiently large to cause aggregation of smaller particles and the adhesion of dust to larger particles. Particle aggregation during fallout may explain the polymodal grain-size distributions commonly found in ash-fall deposits, and the proximal distribution of fine ash, as well as the distal deposition of coarse particles in these deposits. Our data suggest that electrostatic effects greatly influence the dispersal and deposition of ash during explosive volcanic eruptions.

MITIGATION METHODS OF VOLCANIC HAZARDS DURING ERUPTIONS: CASE OF THE 1982-83 CRISIS AT GALUNGGUNG VOLCANO (INDONESIA)

A. Gourgaud, G. Camus, M. C. Gerbe, and
P. M. Vincent, *University Blaise Pascal, Clermont-Fd, France*

The Galunggung volcano is located in West Java. Recorded historic activities (1822, 1894, 1918, 1982) were confined in an avalanche caldera. In 1982, three main eruptive styles occurred, generating (1) ash-and-scoria flows, (2) phreatomagmatic surges and ash falls, and (3) strombolian ashes and scoriae.

During the phreatomagmatic phase, the explosivity increased considerably, while paradoxically the magma composition had evolved from andesite to primitive basalt. A wide maar crater was excavated. On June 24th and July 13th, 1982, two Boeing 747 aircrafts experienced engine power loss due to volcanic ash during flights in the Galunggung area. The evolution in explosivity is explained by an increasing ground water/magma ratio during the eruption, from magmatic phase 1 to hydromagmatic phase 2.

Morphoscopic analyses and frequency of the xenolitic and juvenile grains have been made for the entire sequence of 1982-83 pyroclastic deposits. Preliminary results show clearly that the progressive increase of the xenolith/juvenile magma ratio, before the end of magmatic phase 1, announces the phreatomagmatic activity (and increasing explosivity). In the same way, the decrease of this ratio at the end of phreatomagmatic phase 2, announces the strombolian phase 3 (and decreasing explosivity).

Such a method may be used easily on ash fall deposits during the course of eruption, to anticipate the volcanic hazards.

ALASKA AIRLINES OPERATING PROCEDURES DURING THE 1989-1990 REDOUBT ERUPTIONS

Edward Haeseker, *Alaska Airlines, Seattle, WA*

The eruption of Mt. Redoubt, 1989-90, and the subsequent incident with a B747 encountering the initial ash cloud, sent a shock wave through the aviation community. A B747 ingesting sufficient quantities of ash to cause all four engines to stop operating in flight forced the airlines serving Anchorage to react by suspending operations. Alaska Airlines was among that group.

Anchorage is too important to Alaska Airlines to just wait for an "All Clear" Signal before resuming service, so we needed a plan of action.

Chief Pilot, Tom Cufley, was to fly on the first airplane from Seattle that would try a landing at Anchorage. On December 16 after the eruption, one of the normally scheduled cargo planes landed at Anchorage International Airport. There was a break in the cloud cover that would allow the flight to descend while maintaining visual contact with the ground. This was to be the foundation of our plan to resume full service. The idea is if ash was not visible in these cloud openings, then there is no danger of encountering ash while descending. I followed on the next flight.

By focusing on where the ash had not fallen, Alaska Airlines was able to resume a full schedule. With the aid of wind direction and velocity information from our arriving airplanes, we were able to accurately determine ash trajectories. On-site coordination allowed for a realistic flight-crew briefing and debriefing. These combined factors made the operation a success.

Once our flights started to arrive and depart, the demand for tickets increased due to other carriers cancelling flights. Approximately 1,800 Holiday passengers were stranded in Anchorage wanting to fly south while nearly 600 passengers were in Seattle trying to go north. Alaska Airlines had an obligation to fulfill by making sure everyone made it home for the Christmas Holidays.

In addition to the 18 scheduled flights, 26 passenger and 20 cargo flights were added during this period. This caused a strain on our schedule for assigning crews to cover the extra flights, and it took a Herculean effort to free up airplanes from our regular schedule. The extra trips were scheduled mostly during the night and early morning hours when the schedule is lightest.

The operation was also based on the "On Site Go Team." The team was able to evaluate the situation, make decisions from the scene, and be able to interpret the FAA Notices to Airmen (NOTAMS) as they related to the real conditions. The "On Site" concept allows decisions to be made in "Real Time". Remote operations rely on ash and weather forecasts and FAA NOTAMS. Too often, NOTAMS are broadly scoped and cover too wide an area, and, as we witnessed, can be misleading for an operation such as ours at Alaska Airlines.

SEATTLE AIR ROUTE TRAFFIC CONTROL CENTER (ARTCC) RESPONSE TO ERUPTIONS OF MOUNT SAINT HELENS

R.F. Hamley and D.H. Parkinson, *FAA ARTCC, Auburn, WA*

Following notification of an eruption of Mount Saint Helens, the Center Weather Service and Traffic Management Units begin a mutual effort to determine the extent of volcanic emissions. Ash-cloud reports are gathered from ground and airborne observers and ash-plume movement is determined using available wind data. Short-term advisories and projections of volcanic emissions are produced within format and time constraints usable to air traffic operations.

Existing data sources are extremely limited. Radar and satellite imagery within the ARTCC have provided little data on volcanic emissions during recent eruptions. Visual ash-cloud reports have constituted the primary information on the presence of ash but are not available after dark. Their credibility is a problem.

Considerable upper wind data and wind forecast guidance is available but must be used with caution. Currency of upper wind observations, accuracy of numerical models and the possibility of recent or pending direction changes are vital considerations. Aircraft wind reports provide an essential supplement and verification.

Based on the observed and predicted extent of volcanic emissions, the Traffic Management Unit examines the impact of the event upon air traffic routes. Advisories are sent to air traffic facilities and to system users, identifying affected areas and suggesting alternate routes.

AUTOMATED DETECTION OF VOLCANIC ASH CLOUDS, EVALUATION OF HAZARDS TO AVIATION, AND GLOBAL NOTIFICATION: AN INTEGRATED SYSTEM

David M. Harris, *Salem, OR*

An automated real-time system for detecting ash clouds, forecasting their positions, evaluating their hazards to aviation, and global notification is feasible. The system requirements include (1) ash-cloud sensors; (2) an instrumental method for estimating eruption rates and ash-cloud source parameters; (3) a global communications system; (4) a real-time ash-cloud forecasting system; (5) a hazards evaluation scheme; and (6) an automated system of notification. The system requirements can be satisfied in the following ways: (1) ash eruptions can be detected instrumentally using ground based electric field sensors; (2) eruption rates, amounts erupted, and duration can be estimated from the amplitude and duration of harmonic tremor; ash-cloud source parameters can be calculated from these data by using moist-atmosphere plume rise theory; (3) commercial satellites provide communications; (4) real-time ash-cloud forecasts are feasible using existing software for PCs; (5) forecast conditions can be evaluated using quantitative criteria and reviewed by an expert; (6) automated notification can be provided through an interface to existing civil aviation and hazards information systems. This paper reviews the system performance requirements, technical solutions, a possible system configuration, and estimated cost to develop and implement a demonstration system.

GEO-TOMS: TOTAL OZONE MAPPING SPECTROMETER FOR OZONE AND SULPHUR DIOXIDE MONITORING FROM A GEOSTATIONARY SATELLITE

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GEO-TOMS (Total Ozone Mapping Spectrometer) is a proposed ozone and sulphur-dioxide mapping spectrometer designed to fly on a geostationary platform. It is an adaptation of the Nimbus-7 TOMS, but is capable of imaging the whole earth disk on a CCD detector array. The instrument will provide 12.3 km spatial resolution and will provide a complete 6-wavelength image set every 10 minutes. Based on the performance of the Nimbus TOMS, GEO-TOMS will be capable of detecting volcano eruptions and plumes and monitoring their progress in real time.

A conceptual design study has identified a feasible design approach with modest weight and power requirements. The design images depolarized light from a 20-degree field of view onto a grating. Light from the grating passes through a single exit slit onto a 1024 x 1024 CCD with an optical system that corrects the monochromator aberrations. Wavelength scanning uses a reliable cam mechanism, and a simple shutter provides optical zeroing.

DESCRIPTION OF THE WIND PROFILES INSTALLED IN HOMER, ALASKA

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As a part of the overall system to detect and predict the motion of volcanic ash clouds, plans are being made to establish a small network of Wind Profilers in Alaska. One Wind Profiler operating at 404.37 MHz has been in operation in Homer, Alaska, since December 1990. The remainder of the network will be installed when a new frequency allocation is approved that will prevent potential interference with the 406.05 MHz band used by Search and Rescue Satellites (SARSAT).

The Wind Profiler in Alaska is almost identical to the ones being installed in the NOAA Wind Profiler Demonstration Network in the midwestern United States. It consists of an equipment shelter and an antenna array. The shelter houses all the active components: transmitter, receiver, beam steering unit, and signal and data processors. Adjacent to the shelter is the antenna, which is a coaxial-collinear phased array measuring 13 meters on a side.

The standard NOAA Wind Profiler which was installed in Alaska required modifications in order to provide accurate data on the speed and direction of the upper winds in the presence of spurious reflections from glacial mountains and nearby sea clutter. These changes were accomplished by additional perimeter clutter fences and new computer processing algorithms to remove the effects of wave motion returns from the clear-air atmospheric echoes.

VOLCANIC ASH: WHAT IT IS AND HOW IT FORMS

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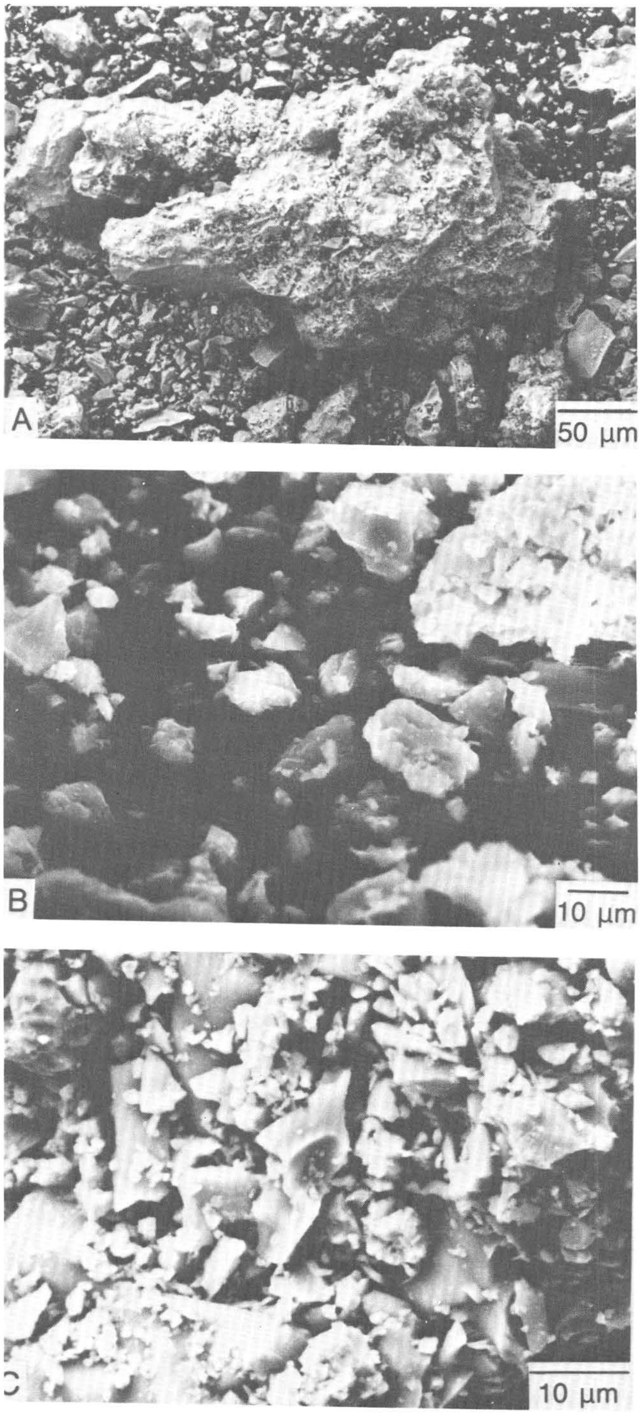
There are four basic eruption processes that produce volcanic ash: (1) decompression of rising magma, gas bubble growth, and fragmentation of the foamy magma in the volcanic vent (*magmatic*), (2) explosive mixing of magma with ground or surface water (*hydrovolcanic*), (3) fragmentation of country rock during rapid expansion of steam and/or hot water (*phreatic*), and (4) abrasion during collision of ash grains. Variations in eruption style and the characteristics of volcanic ashes produced during explosive eruptions depend on many factors, including magmatic temperature, gas content, viscosity and crystal content of the magma before eruption, the ratio of magma to ground or surface water, and physical properties of the rock enclosing the vent.

Volcanic ash is composed of rock and mineral fragments, and glass shards. Glass shard shapes and sizes depend upon size and shape of gas bubbles present within the magma immediately before eruption and the processes responsible for fragmentation of that magma. Shards range from slightly curved, thin glass plates, which were broken from large, thin-walled bubble walls, to hollow needles broken from pumiceous melts containing gas bubbles stretched into thin tubes by magma flow within the volcanic vent. Pumice fragments make up the coarser-grained portions of the glass fraction. Particle sizes range from meters for large blocks expelled near the volcanic vent to nanometers for fine ash and aerosol droplets within well-dispersed eruption plumes.

Most of the ejecta from volcanic eruptions fall out within a few tens of km of the source. Of major concern to aviation are widespread eruption plumes, which are dispersed downwind at elevations of 8 to 20 km and can drift for thousands of km. These plumes, which overlap



Volcanic ash from the March-April 1986 eruption of Saint Augustine Volcano, Alaska. Scanning electron micrographs show ash collected in Anchorage, 180 miles northeast of the volcano. The ash is composed mostly of dacitic glass shards and rare mineral fragments. The large clast in (a) is pumice coated with fine-grained glass shards. Photographs (b) and (c) show details of glass shards coating the pumice fragment in (a). Photograph courtesy of Grant Heiken.

operational levels for air traffic, consist of very fine-grained ash (mostly glass shards of <0.0001 mm) and even smaller acid droplets. Very few plume densities have been determined *in situ*, but *average* densities for a plume from the 1986 eruption of Augustine Volcano, Alaska, observed 90 km downwind, were 63-125 x 10^{-3} g m^3 (with an average grain size of 1 µm, this is equivalent to 4.8-9.6 x 10^{13} particles/m^3)

HOLOCENE VOLCANISM IN THE CANADIAN CORDILLERA

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British Columbia (BC), Canada and the Yukon are geologically dynamic regions, encompassing subduction zones, rifting, and thermal anomalies (hot spots?). Some 100 volcanic vents are arranged in five broad belts and all have had Holocene eruptions. Volcanoes range from monogenetic mafic cinder cones, to peralkaline shield volcanoes and calc-alkaline strato-volcanoes. The most recent documented eruption occurred about 200 years ago in northwestern BC. The most recent large explosive eruption occurred ca. 1.2 ka ago when a vent near the Alaska-Yukon border expelled ca. 30 km^3 of pyroclastic material, covering 300,000 km^2 of Yukon under a blanket of ash. In southwestern BC, a plinian eruption from Mount Meager strato-volcano, occurred ca. 2.4 ka ago. This eruption spread ash across southern BC into Alberta. The tectonic forces that produced these volcanoes are still active today, thus it must be assumed that potential for a volcanic eruption in Canada still exists.

In the short term, perhaps the greatest impact on Canadian aviation may be from eruptions elsewhere in western North America. During the recent eruption of Mount Redoubt, Alaska, tephra drifted into Canada on at least two occasions and within 24 hours of the May 18, 1980, eruption of Mt. St. Helens, enough tephra fell in southern BC, Alberta and Saskatchewan to cause concern among residents and the aviation community. Two previous eruptions of Mount St. Helens left thin ash layers in southern BC and the eruption of Mount Mazama left a blanket of ash several centimetres in thickness over southern BC and much of Alberta. An eruption of Mount Baker, close to one of Canada's busiest air routes into Vancouver International Airport, might have serious repercussions. Response procedures are being coordinated between the United States and Canada to ensure safety and minimize disruption among residents and aviators.

AIRBORNE LIDAR DETECTION AND IN SITU MEASUREMENTS OF ASH EMISSIONS FROM THE 1990 VOLCANIC ERUPTIONS OF MOUNT REDOUBT

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In January and June 1990 we obtained airborne in situ and remote sensing lidar measurements of volcanic emissions from Mt. Redoubt, Alaska. The lidar provided excellent real-time information on the distribution of the volcanic effluents. The in situ measurements provided information on the size distributions, mass concentrations, and nature of the particles, as well as the concentrations of various trace gases, in the volcanic emissions.

In post analysis, the lidar observations were combined with the in situ measurements to derive the fluxes of particles and gases from the volcano. For the intraeruptive emissions, the derived fluxes were: water vapor, ~160-9440 kg s^{-1}; CO_2, ~30-1710 kg s^{-1}; SO_2, ~1-140 kg s^{-1}; particles (<48 m diameter), ~1-6 kg s^{-1}; SO_4, <0.1-2 kg s^{-1}; HC1, <0.01-2 kg s^{-1}; and NO_x, <0.1-2 kg s^{-1}. During a paroxysmal eruption of Mt. Redoubt on January 8, 1990, the particle (<48 μm diameter)-emission flux averaged ~10^4 kg s^{-1}.

The particle-size distributions for both paroxysmal and intraeruptive emissions showed nucleation (<0.1 μm diameter) and accumulation (~0.1-1.0 μm diameter) modes. On January 8, 1990, the number of concentrations of particles were initially mostly in the accumulation and coarse particle (>1.0 μm diameter) modes; there were comparatively few nucleation-mode particles. After seven hours of aging, the concentrations of particles of all sizes had decreased, but nucleation-mode particles were relatively more prominent. Most of the particle mass in the January 8 eruption was in giant-sized particles, predominantly diameters of ~10 μm and ~30 μm. Most of the particle mass in the intraeruptive emissions was in the accumulation mode, with diameters of ~0.8 μm. The particles in the intraeruptive emissions consisted primarily of mineral elements without any sulfuric acid coating. Very little of the SO_2 (~0.1%) was oxidized to sulfate in the cold, dark conditions of the arctic atmosphere.

LIGHTNING DETECTION AND LOCATION AS A REMOTE ASH-CLOUD MONITOR AT REDOUBT VOLCANO, ALASKA

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Few of Redoubt volcano's recent eruptions were observed directly because of bad weather and brief winter days. The unseen ash clouds were a substantial hazard to aircraft. In the absence of direct observation, the presence of ash clouds was deduced, with some uncertainty, from seismicity. Lightning, normally rare around Cook Inlet, accompanied nearly all of Redoubt's ash-producing eruptions. Lightning radiates broadband radio waves that allow remote detection and location of lightning and, therefore, ash clouds. As an experiment, the Alaska Volcano Observatory deployed a commercially available lightning detection system (LDS) around Cook Inlet. This LDS is normally used by the Bureau of Land Management's Alaska Fire Service to detect and locate cloud-to-ground lightning in Alaska's interior during summer months. The Cook Inlet LDS became operational on February 14, 1990. Lightning was detected in 11 and located in 9 of the 12 subsequent eruptions. Most cloud-to-ground lightning strikes occurred at or near the volcano. The number of cloud-to-ground discharges produced by a given eruption was directly related to the quantity of ash produced. Discharges that occurred early in an eruption had a negative polarity, while late discharges tended to be positive; this phenomenon suggests that coarse particles carried a negative charge and fine particles carried a positive charge. Intracloud lightning, as determined from eyewitness accounts but not detected by the LDS, was more abundant than cloud-to-ground lightning and tended to persist in the ash clouds even at substantial distances from the volcano. In the February 15, 1990 eruption, intracloud discharges persisted to a distance of at least 120 km from the volcano. A system capable of locating intracloud lightning could potentially track ash clouds as long as discharges persist. Lightning data dispel the ambiguity inherent in using seismic data alone, for the coincidence of seismic lightning signals provides compelling evidence of an ash cloud. Lightning detection also provides a rapid remote measure of eruption magnitude. Alaska Volcano Observatory has now acquired and deployed a cloud-to-ground LDS dedicated to monitoring Cook Inlet volcanoes.

PASSIVE, TWO SPECTRAL CHANNEL THERMAL INFRARED IMAGING SYSTEMS FOR DISCRIMINATION OF VOLCANIC ASH CLOUDS

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NOAA AVHRR image data recorded and displayed in Perth on the 25th June 1982 by a joint CSIRO and Curtin University team dramatically demonstrated the capability for observation of the position and distribution of volcanic ash from the eruption of Mount Galunggung, Indonesia. Analysis of the data, based on an understanding of the spectral emissivity properties of silica-rich materials, and of water clouds, resulted in discrimination and display of the ash cloud over a period of several days. These analysis procedures using the two thermal infrared channels of the AVHRR sensor are presented and discussed and the advantages of passive two-channel thermal infrared sensors over passive visible sensors, and active (lidar and radar) systems are outlined.

Intense interest in the techniques applied to this discrimination procedure led the author in 1982 to propose a two spectral channel passive thermal-imaging system that could be mounted in the wing of an aircraft. Display of the enhanced data from the imaging system could be multiplexed into existing aircraft avionics and alert the crew to the presence of silica-rich materials in the flight path potentially several tens to hundreds of kilometres in front of the aircraft, assuming clear line of sight. Limitations to the application of such an instrument were outlined at the time. The initial instrument design is discussed, and several improvements on the original concept are outlined.

Polar orbiting satellites such as the NOAA series do not provide adequate or timely coverage of the areas prone to volcanic eruption. The twice-daily coverage of each of the NOAA satellites leaves extensive periods during which an eruption could occur, not be observed, and aircraft travelling through the area could be jeopardized. More frequent coverage is provided by the existing geosynchronous meteorological satellites. Unfortunately, these satellites lack the spectral channels necessary to discriminate the ash clouds from water/ice clouds. The author proposes that serious consideration be given to incorporating two thermal infrared channels on future generations of the GMS and GOES satellites to provide a capability for more frequent observation of eruptions.

NEW TECHNOLOGIES TO SUPPORT FORECASTING VOLCANIC PLUME MOVEMENT

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The Mt. Redoubt eruptions revealed a number of deficiencies in current National Weather Service operations that greatly hamper the forecaster's ability to accurately forecast and issue timely advisories on the movement of the volcanic debris. The forecaster lacks knowledge of (a) the current location of the ash both vertically and horizontally, (b) real-time winds near and downwind of the volcano, and (c) rapid access to volcanic-debris tracking models

To help resolve these deficiencies, an Alaskan volcano-monitoring system has been designed and acquired. The system consists of (a) a wind profiler located at Homer, Alaska that provides hourly vertical profiles of winds near the volcano, (b) a satellite downlink and processing system capable of ingesting, processing, and displaying imagery from a variety of polar orbiting satellites to track ash plumes, (c) a C-band radar located across Cook Inlet from Mr. Redoubt to provide vertical and horizontal extent of the ash plume, (d) and an upgrade to the regional computer and communications network to handle the new volume of data from the monitoring instrumentation described above. A volcanic debris tracking model has been developed by the NOAA Air Resources Laboratory. The volcano monitoring system provides the forecaster with vital information to generate warnings, forecasts, and advisories.

ECONOMIC CONSEQUENCES OF THE 1989-90 MT. REDOUBT ERUPTIONS: ASSESSMENT METHODOLOGY AND ANECDOTAL EMPIRICAL EVIDENCE

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The eruptions of Mt. Redoubt in the late fall and winter of 1989-90 resulted in major disruptions of air transportation, both with respect to people and freight, threatened the physical integrity of the Drift River oil terminal facility, caused the shut-down of Cook Inlet oil production, and in other ways caused the total production of goods and services in Alaska to decrease. The eruptions may also have caused some firms to reconsider south-central Alaska as a site for doing business.

This paper presents a methodology and design for a social accounting framework that structures the classification and regional distribution (or redistribution) of economic impacts attributable to the 1989-90 Mt. Redoubt eruptions. The accounts design attempts to deal with several issues that arise in the assessment of the impacts of natural disasters. These include measurement of increases and decreases in economic activity attributable to the disaster, the distribution of these changes across regions, and the separation of mitigation costs from direct costs of the disaster. The paper illustrates the use of the account structure with some preliminary applications of the methodology to specific episodes associated with the eruptions.

COPING WITH THE AIRCRAFT/ASH-CLOUD PROBLEM IN AUSTRALIA

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Notable encounters between in-flight commercial aircraft and high-rising eruption clouds have taken place in two main regions of the world: in the Pacific Northeast and in the southeast Asia/southwest Pacific region. The belt of active volcanoes extending from Indonesia and the Philippines, through Papua, New Guinea and Vanuatu in New Zealand, represents a zone that international aircraft must traverse before reaching, or after leaving, Australia.

Indonesia, particularly, is a formidable volcanic barrier consisting of almost 80 historically active volcanoes distributed throughout the nearly 6,000-km-long archipelago. About 40 Indonesian volcanoes produced eruptions during the 1980's, the largest of which were from Galunggung (west Java) in 1982. Two Boeing 747 aircraft flying to Australia at night suffered multiple-engine failures as a result of nighttime encounters with high-rising Galunggung ash clouds, and a DC-9 jet on a daytime domestic flight was damaged. These events led to the creation by the Australian Department of Aviation (now the Civil Aviation Authority) of an Airways Volcano Watch.

An eruption from Soputan volcano (Sulawesi) damaged a Qantas 747 aircraft en route to Melbourne in May 1985 (the engines surged but did not fail). This encounter galvanized Australian mitigation efforts that had been underway since 1982, through the establishment of the Volcanological/Airspace Liaison Committee Australia-Indonesia (VULCAN). The Australian part of this committee (VULCAN-AUS) has been active on four main fronts in addressing the aircraft/ash-cloud problem: (1) establishing better communications about volcanic eruptions in the Indonesian region; (2) encouraging the use of satellites (particularly the operational GMS weather satellite) in the identification and tracking of eruption clouds; (3) participating in international efforts to provide better early warnings to pilots; (4) creating a Volcanic Ash Detection and Aviation Study Group (VADAS) whose task was to investigate the most appropriate technologies that could be used to mitigate aircraft/ash-cloud encounters. CSIRO scientists, in association with VADAS, have devised the prototype of a small radiometer that could be mounted on aircraft and would look ahead to discriminate volcanic-eruption clouds from normal weather clouds.

SEISMIC IDENTIFICATION OF GAS-AND-ASH EXPLOSIONS AT MOUNT SAINTT HELENS: CAPABILITIES, LIMITATIONS, AND REGIONAL APPLICATION

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During the past 10 years, analysis of seismic signals recorded by the UW/USGS Mount St. Helens network and correlation of these signals with observations made by field crews, pilots, radar operators, and the general public have led to the development of seismic criteria that enable us to identify most kinds of repetitive events at Mount St. Helens. Such events include volcanic earthquakes, tremors, rockfalls, debris flows, dome-building eruptions, gas-and-ash explosions, and many types of cultural noise. Identification criteria are based on comparisons of signal envelopes, dominant frequencies, and relative amplitudes and timing among stations.

In general, gas-and-ash explosions at Mount St. Helens are characterized by emergent, low-frequency signals of extended duration, often with pulsating amplitude changes. Relative amplitudes are similar among stations on the flanks of the mountain but are much higher at stations within the crater. Several factors may complicate signal identification. These include 1) changes in the volcanic processes generating the explosions, 2) overlap of signals from closely spaced events, and 3) the temporary loss of key stations.

Nevertheless, we have had considerable success identifying explosions within minutes of their occurrence.

The University of Washington also operates seismic stations or mini-networks at or near most other Cascade Volcanoes in Washington and Oregon. When future seismicity increases significantly at one of these volcanoes, the local network will be enhanced to improve monitoring capabilities. The criteria used to identify gas-and-ash explosion signals at Mount St. Helens and the techniques used to develop these criteria will provide a strong foundation for signal identification at other active volcanoes.

PREDICTION AND DETECTION OF EXPLOSIVE ERUPTIONS AT SAKURAJIMA VOLCANO, JAPAN

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The volcanic activity of the explosive summit eruptions has continued since 1955 at Sakurajima volcano, Kyushu, Japan. The frequency of the explosive eruptions amounts to more than 6,000 during the last 35 years. The explosions at the summit crater can be predicted by the tilt and strain data at the summit area and the swarms of the shallow earthquakes generated beneath the active crater. The onset of explosions are detected by the explosion-quakes, the air-shocks accompanied with them, and the visual erupting images. The success rate of the Automated Warning System for the actual eruptions is more than 70 percent. The detecting system for volcanic eruptions by the infrasonic air-waves with microphones array at Kariya, Nagoya, 710 km away from the volcano, has the capability to detect the air-waves generated by volcanic eruption which occurred at the volcanoes a thousand and several hundred km distant. A world-wide network system for detecting the air-waves from volcanic explosions will be useful to acquire the information of location where the eruption occurs and of estimating the magnitude of the eruptions. The system should be very effective to aviation safety similar to Tsunami Warning System which is operating world-wide.

FORECASTING VOLCANIC DEBRIS IN ALASKA

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The Center Weather Service Unit (CWSU) of the National Weather Service has the responsibility to provide forecasts that insure smooth flow of air traffic into and out of Alaska. The Mt. Redoubt eruption presented a number of problems to the region. Numerous explosive episodes caused significant damage to aircraft, severely disrupted air traffic, and resulted in airports closing operations.

The major forecast problem centers around a lack of information concerning plume characteristics: (1) lack of ash particle size and concentration; (2) no current ash location; and (3) lack of real-time winds near and downwind of the volcano. The forecaster is forced, for safety sake, to include a large hazardous zone around the estimated trajectory of the ash for aircraft to avoid. This can cause unnecessary delays to travel around the zone when most of it is ash free.

To assist the aviation community in their need for information on ash distribution, the CWSU generated an ash-trajectory plot with 4 hour movement of the ash plume. This plot was updated as new information became available. The biggest source of information was from pilot reports. This plot was distributed to over 90 users.

VOLCANIC AIR-AIRCRAFT INCIDENTS IN ALASKA IN THE YEARS PRIOR TO THE DECEMBER 15, 1989 747 REDOUBT ENCOUNTER

Juergen Kienle, *University of Alaska Fairbanks, Alaska*

Commercial and military aircraft have encountered volcanic ash in the Cook Inlet basin on three other occasions besides the most recent events near Redoubt Volcano in 1989/90. Over the past 36 years, aircraft have met volcanic ash plumes on four occasions, three times in the past 13 years alone, resulting in a variety of technical problems. No crashes or deaths resulted from these encounters so far.

Mt. Spurr 1953: A short one-day eruption of Mt. Spurr, 120 km west of Anchorage, caused heavy ash falls that lasted for three hours from noon until 3 p.m. Maximum plume heights were about 21 km (70,000 ft.) and extensive lightning was observed by L. Metzner. Twenty-six aircraft of the Air Force's 5039th Air Transport Squadron were evacuated to Laird and

Eielson Air Force Bases near Fairbanks. Three aircraft flew through the ash plume resulting in sandblasted leading edges, windshields, side panels and front portions of the canopies, reducing pilot visibility. Most planes remaining in Elmendorf were hangared in time, except for several large C-124 transport aircraft (Globe Trotters). These required ten days of clean-up for the removal of the fine volcanic ash. The 10th Division had completely lost its capability of meeting an air defense mission between July 9 and 13. It was only on 17 July that the three Elmendorf fighter-interceptor squadrons returned to normal operations

I have found no information whether or not commercial aircraft were affected at Anchorage International Airport or elsewhere in Cook Inlet.

Mt. St. Augustine 1976: Mt. St. Augustine erupted in January 1976, after 12 years of dormancy. Subplinian eruptions occurred from January 22 to 26 and spread ash generally northward and eastward over the Kenai Peninsula with fine ash falling as far away as Sitka, 1,100 km downwind.

On January 22, two F-4E Phantom jets on a flight from Galena to King Salmon intercepted an ash plume at 1430 AST. The pilot reported instant, complete darkness in the cloud. No engine failure occurred. Upon landing at King Salmon, the canopy of the aircrafts were scoured, and the paint at the wind tips was sandblasted off. Very fine jewelers rouge-colored material was ingested into the cockpit through the engine air intake. The material was sticky and was found in every "nook and cranny" of the planes.

On January 25, cargo flight JL672, a DC-8, entered an Augustine ash cloud near Whitefish Lake, 25 km southeast of Sparrevohn. Upon landing in Tokyo, the scoured center windshield had to be replaced; much ash had adhered to the plane. Slight abrasion damage was found on external radio parts, landing gears and the air-conditioning system, but none of these parts needed to be replaced.

Two other passenger planes, a Boeing 747 and a DC-8, also bound for Tokyo and departing within one hour after flight JL672, reported ash suddenly adhering to the planes near Sparrevohn which caused minor damage, but not as extensive as that to the DC-8 of flight JL672.

Mt. St. Augustine 1986: Airborne ash disrupted aircraft operation throughout the Cook Inlet basin during the 1986 eruption. Early in the morning of March 27, with the eruption just beginning, the Air Force evacuated most of their planes from Anchorage and kept them away until March 30. Air carrier service at Anchorage was nearly at a standstill March 27-29. Alaska Airlines canceled 40 Anchorage arrivals and departures out of 68 scheduled operations on March 28. Western Airlines canceled its entire schedule of flights to and from Alaska march 27 and 28 and flew only a partial schedule on March 29. United canceled 35 Alaska flights between March 27 and 29. No serious disabling ash encounters occurred during this time.

GENERATION AND DISTRIBUTION OF GRAPHICAL DEPICTIONS OF VOLCANIC ASH PLUMES

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The Mt. Redoubt eruption episodes showed that National Weather Service (NWS) products on volcanic debris were most effective when distributed in graphical form. At the beginning of the eruptions, most of the products generated were either in alphanumeric form or hand drawn graphics. The graphical presentations were then distributed by slow telefax. The aviation community found the graphical depictions of ash plumes to be very valuable. The list of users rapidly grew to over 90. The slow-telefaxing method was found insufficient for distribution.

The Federal Aviation Administration (FAA), the primary user of the graphic products, provided a digital graphics system that allowed for rapid interactive generation and distribution of predicted volcanic plume trajectories to many users in the aviation community. The NWS reaction to future eruptions and use of the graphics-distribution system is described in detail.

VOLCANIC HAZARDS VIDEO

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Volcanic eruptions vary widely in type, magnitude, and effects. The hazards associated with eruptions, however, are not well understood by most people. The principal types of volcanic activity that can adversely affect people and property include ash falls from ash clouds, ash flows, mudflows, volcanic landslides, volcanic tsunamis, lava flows, and volcanic gases. Of these hazards, ash clouds are the primary hazard to aviation safety. People living near volcanoes are more likely to take steps to avoid the deadly consequences of eruptions if they understand the hazards associated with these types of volcanic activity. Toward this end, a videotape has been produced that ·amatically shows the destructive power of volcanic activity. Spurred by the eruption of Nevado del Ruiz (Columbia) in 1985 (more than 22,000 people were killed by mudflows), the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) sponsored production of the video program Understanding Volcanic Hazards in cooperation with the United Nations Educational Scientific and Cultural Organization, the United States Geological Survey, and other national organizations. The videotape will be available through IAVCEI in a variety of video formats and languages, including English, Spanish, Italian, Indonesian, and Japanese.

VOLCANIC-HAZARD DETECTION WITH TOMS

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The Total Ozone Mapping Spectrometer (TOMS) instrument is capable of unique identification of volcanic eruption clouds from space. This capability can aid in location of aviation hazards associated with volcanic ash during the early phases of an eruption and with sulfate aerosols during later phases of the eruption cloud. The instrument is presently flying in a polar orbit on the Nimbus 7 spacecraft. Four more instruments are scheduled to be launched on new Soviet, American, and Japanese polar orbiting spacecraft during the next six years. NOAA operational satellites will carry additional instruments during the next decade. A conceptual design study has been conducted on a geostationary TOMS instrument. Such an instrument would provide time resolutions of 15 minutes compared with 24-hour resolution from polar-orbiting satellites.

The technique makes use of the absorption of sunlight by sulfur dioxide, a gaseous constituent of volcanic plumes, at near-ultraviolet wavelengths, which are used for ozone mapping. A data-processing algorithm separates the ozone and sulfur dioxide quantities. The instrument produces full global surveys of ozone and sulfur dioxide each day with ground resolutions of about 50 km.

The 35 volcanic eruptions detected with TOMS since 1978 include Mount St. Helens, El Chichon, Alaid, Nyamuragira (Zaire), Galunggung, Una Una, Ruiz, Redoubt, Hekla, and several volcanoes in the Galapagos Islands. Research is underway to improve the detection algorithm and to understand the variations of sulfur dioxide in eruption clouds.

MITIGATION OF THE EFFECTS OF VOLCANIC ASH ON AIRCRAFT OPERATING AND SUPPORT SYSTEMS

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On 18 May 1980, Mount St. Helens erupted, covering 50% of Washington with approximately 1 km^3 of ash. Government agencies, airports, utilities, and private corporations within the affected areas were all forced to cope with ash deposits (ranging in depth from 3 mm to 75 mm) in maintaining essential services and in carrying on normal activities. In-depth interviews with equipment users, service companies, airport operators, utilities, and others affected by the ash elicited detailed information on ash-related damage and on mitigation methods.

Volcanic ash is abrasive, mildly corrosive, and (especially when wet) conductive. Also, it may carry a high static charge for up to two days. The ash is finely divided, easily entrained in the air by wind or vehicle movement, and may remain suspended in the air for many minutes. Due to the combination of these qualities, volcanic ash is pervasive. It can penetrate all but the most tightly sealed enclosures and can be very difficult to remove from electronic components.

The ash easily absorbs water and can weigh up to 1,400 kg/m^3; water laden ash may collapse or damage flat roof. Wet ash is very slippery and can cause traction problems. Dry ash blown into the air reduces visibility and piles up on roads, runways, and taxiways. Ash must be physically removed and controlled after removal to prevent re-entrainment. Ash deposited on electronic components can cause arcing, short circuits, and intermittent failure due to its conductive nature. High-voltage circuits and components are especially vulnerable. Ash dampened by rain can cause arcing, flashovers, and pole fires on electrical-distribution systems. Resulting outages may hamper mitigation techniques that require electrical power.

Techniques for reducing the effects of volcanic ash are basically "low tech" and can be grouped into three broad categories: keeping the ash out, controlling what gets in, and disposing of the ash. Mitigation actions will be required on a continuous basis as long as ash is present. Settled ash is easily re-entrained, and 2 mm layer can be as troublesome as a 50 mm layer.

The most effective technique for reducing ash-related damage or upset to equipment is to avoid using it: shut down, close up, keep inside, or seal off until the ash can be removed. Unfortunately, this tactic is acceptable only for short periods of time; operations must be resumed at some point. Effective mitigation depends on prior planning and preparation, mobilization of resources, and persistence.

VOLCANIC PRODUCTS AND AVIATION SAFETY: MODELING THE GAS-PARTICLE CONVERSIONS

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Volcanic plumes are mainly formed of fine grains of exploded rock: "volcanic ash". Plumes also include solid and liquid aerosols resulting from cooling and condensation of the high-temperature eruptive gases, which contain acids, halogens and metals. Aerosols can be both free or absorbed on the ash surface. Free volcanic gases can persist in the cold plume for hours before dilution; aerosols can persist for days.

A high-temperature volcanic-gas cooling model has been developed and will be used to predict the composition of volcanic aerosols. The model was tested using the examples of Mt. Etna and Mount St. Helens. Mt. Etna gases contained H_2O=91.9, H_2=0.7, CO_2=1.4, CO=0.0007, SO_2=2.8, H_2S=0.6, HCI=2.5, HF=0.5, NA= 1.2, K=1.2 plus 19 other trace elements detected (as collected at 928°C at the source of a side lava flow).

Mount St. Helens contained H_2O=98.6, H_2=0.4, CO_2=0.88, CO=0.002, SO_2=0.067; H_2S=0.09, HCI=0.07, HF=0.02, Na 0.0004, K=0.0003 plus 40 other elements detected (as collected in the crater at 710°C.

In both cases, plumes are very acid rich, but on Etna the plume is very rich in NACI and KCI; H_2S is oxidised to S gas and converted into metallic sulfurs. On Mt. St. Helens, NA and KCI are 1000 times less abundant and SO_2 is oxidised to form elemental solid sulfur. These reactions occur in a few seconds when the magmatic gases enter the atmosphere, then slower reaction of oxidation will occur in the cold plume taking a few hours or days. This mixture of gas, ash and aerosols can be sintered in the engine by heating, compressing and dehydration. It can affect the windshields or contaminate the kerosene.

However, the great variability of the actual volcanic-gas source composition makes it very difficult to predict the actual volcanic-plume composition before having samples from the source itself. The modeling makes it possible to predict the behaviour of different hypothetical gas mixtures starting with 20 elements and considering 900 final products.

MOUNT REDOUBT: TRACING VOLCANIC ASH PLUMES FROM SPACE

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Volcanic ash and debris are extremely hazardous to aircraft, with several craft experiencing near-catastrophic inflight damage as a result of flying through the debris. To respond to these potentially catastrophic events, the Federal Aviation Administration (FAA) and National Oceanic and Atmospheric Administration (NOAA) have established a cooperative Volcano Hazards Alert Program. The program encompasses all volcanic debris reaching at least 5 km altitude within U.S. airspace or international airspace designated as a U.S. Flight Information Region (FIR).

Upon detection or notification of an explosive volcanic eruption, NOAA's National Environmental Satellite, Data, & Information Service (NESDIS) has the responsibility to coordinate information (i.e., satellite-imagery analyses, trajectory forecasts, pilot report summaries, etc.) directly to primary FAA and NOAA facilities responsible for flight safety and warnings, including: NWS Meteorological Watch Offices, NWS National Aviation Weather Advisory Unit, National Meteorological Center, and FAA Central Flow Control Facility. These primary facilities have the responsibility of issuing "significant meteorological warnings" (SIGMET) to all aviation interests.

Mount Redoubt in Alaska began a series of explosive volcanic eruptions on 14 December 1989. Since the initial event, geostationary and polar-orbiting environmental satellites have been used to track ash and volcanic debris from over twenty eruptions of Redoubt. During the 15 February 1990 eruption, a pyroclastic surge resulting in a serious mudflow along the Drift River was detected in "real time" using AVHRR HRPT data, and timely warnings were issued to the hydrologist in Anchorage, Alaska. Multispectral imaging from polar spacecraft offers enhanced potential for monitoring ash plumes, even when debris is not apparent using single-channel visible or infrared data.

This paper briefly reviews the history of volcanic ash tracking in NESDIS (dating back to Mount St. Helens in 1980), the recent history of Mount Redoubt, and analysis techniques being planned and implemented.

STATISTICAL APPROACH IN ASSESSMENT OF VOLCANIC HAZARD FOR AIR TRAFFIC: AN APPLICATION TO VESUVIUS

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Release and dispersion of ash as a consequence of plinian or subplinian eruptions could seriously affect flights in the proximity of a volcano. We present a method to quantify hazard for flights so that realistic measures can be adopted, such as planning and designing for engineering systems to prevent the absorption of volcanic particles into engines. An example is presented for Vesuvius (Italy). The expected eruption (Macedonio et al., 1990, J. Volcano. and Geo. Res. 40, p. 327-342; Barberi et al., 1990, Nature, 334, p. 142-144) is taken into consideration for this volcano and a numerical model (Armienti et al., 1988, JGR, 96, B6, p. 6463-6476; Macedonio et al., 1988, JGR, 93, B12, p. 14817-14827) is used to compute ash concentration in the air. Eruption durations (T_e = 3*h*, 12*h*, 24*h*) are considered and, for each case, four subcases are analyzed: concentration in the air at times t - $0.5T_e$, T_e, $1.5T_e$, $2T_e$. Wind profiles (3125 different ones), recorded in the past years in the region, have been used in the simulations. More exactly for each time (for example: $t = T_e$), for each duration (for example: T_e = 12*h*) and for each wind profile, spatial ash distribution is computed. Letting t and T_e unchanged, the surfaces corresponding to isoprobability to have concentration greater or equal to given thresholds are computed, as obtained by using all the past available wind profiles. The directions and heights of ash clouds in a range of a few hundred kilometers around the volcano are then outlined.

USE OF METEOROLOGICAL SATELLITES FOR DETECTING AND TRACKING VOLCANIC CLOUDS

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Meteorological satellite data have been used to detect volcanic eruptions and monitor the subsequent ash clouds since 1976. Imagery and digital data can be used in conjunction with conventional radiosondes to determine the altitude of a volcanic eruption, the size, speed, and position of the ash cloud, and the direction the ash is moving. However, it can be difficult to distinguish a volcanic ash cloud from meteorological clouds due to similar spectral characteristics. Work was done to distinguish the two using multispectral techniques. Currently there are four geostationary meteorological satellites providing global coverage between latitudes 60N and 60S using visible and thermal infrared sensors. There are also several U.S. and Soviet polar-orbiting meteorological satellites with visible and thermal infrared sensors that provide daily global coverage and multiple overpass times over all volcanic areas. Using these satellites and enhanced detection techniques, it is possible to operationally monitor volcanic eruptions for any part of the Earth.

THE SMITHSONIAN'S GLOBAL VOLCANISM NETWORK: FACILITATING COMMUNICATION OF ERUPTION INFORMATION

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The Smithsonian Institution's Global Volcanism Network (formerly SEAN, the Scientific Event Alert Network) has gathered and disseminated information about the world's volcanic activity since 1975. In the succeeding 15.5 years, GVN has reported activity at more than 275 volcanoes, including history's smallest recorded eruption, which ejected 26 m^3 of lava from an Icelandic geothermal borehole in 1977, the globe-circling stratospheric cloud produced by Mexico's El Chichon in 1982, and Colombia's tragic Ruiz eruption that killed more than 20,000 people. Information is provided by a worldwide network of about 1500 correspondents -- scientists, government officials, airplane pilots, and others with knowledge of volcanic activity -- who receive a monthly *Bulletin*. The *Bulletin* is available by subscription through the American Geophysical Union, on electronic mail systems OMNET and KOSMOS/Pinet, and summaries are published in *Bulletin of Volcanology, EOS,* and *Geotimes*. Scientists and officials are quickly notified of eruptions that provide significant opportunities for research and/or threaten life and property.

News of an eruption that may affect aviation is immediately forwarded to NOAA's satellite service and the Federal Aviation Administration. Local volcanologists are consulted for information about the eruption, and Smithsonian resources are searched for data about the volcano's geography and eruption history. Observations from satellites and aircraft are in turn forwarded to volcanologists studying the eruption and to the officials responsible for the safety of people living nearby. Only by exchanging information among many sources -- volcanologists, atmospheric scientists, satellite observers, pilots, and air-traffic control facilities -- will the necessary perspective be available to the officials who must make informed decisions about the response to an eruption. Improved communications are needed to facilitate information exchange. For example, geologists presently have no direct, rapid access to volcano-related *Notices to Airmen* and pilot reports of eruption clouds. Assessment of the threat posed by volcanoes to air traffic is also hampered by the lack of maps that combine volcano locations with air routes. Interagency and interdisciplinary cooperation should be able to solve these and other problems, even in a time of limited funding.

VOLCANIC-TREMOR AMPLITUDE CORRELATED WITH ERUPTION EXPLOSIVITY AND ITS POTENTIAL APPLICATION FOR A VOLCANIC-ASH WARNING SYSTEM

Stephen R. McNutt, *Sacramento, CA*

New data on volcanic-tremor amplitudes define an empirical relation between tremor amplitude and eruption explosivity: as the explosivity increases, the tremor amplitude increases. Tremor data for over 50 volcanoes were normalized to their reduced displacement amplitudes, thereby permitting quantitative comparison. Amplitudes for a well-studied subset of data were compared with eruption styles yielding the following (in order of increasing explosivity): hydrothermal, 0.05-5 cm^2; strombolian, 2-30 cm^2; vulcanian/pelean, 20-150 cm^2; and plinian, >100 cm^2. The eruption styles overlap with each other, and, similarly, the tremor amplitudes overlap. Thus, tremor amplitudes alone cannot unambiguously define eruption styles, but clearly the amplitudes increase with increasing explosivity.

A rapid assessment of the explosivity could help determine hazards from airborne ash. Thus, tremor amplitudes could help form the basis of a warning system. The tremor amplitudes are recorded in real time as the volcanic materials exit the vent. It then takes many seconds to several minutes for the ash to reach altitudes where it would pose a hazard to aircraft. Therefore, tremor amplitudes could help determine the size of an eruption and the amount of ash before the ash reached hazardous altitudes. Tremor duration could be used to estimate the likely duration of an eruption. This information, coupled with information on wind speed and direction, would significantly improve the capabilities of a near-real time semi-automated volcanic-ash warning system.

VOLCANIC ASH FROM THE EXPLOSIVE ERUPTIONS IN KAMCHATKA AND KURILES AS A SOURCE OF POTENTIAL HAZARD FOR AVIATION

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Twelve volcanic eruptions of different types (Ksudach, Bezymianny, Shiveluch, Tolbachik and other volcanoes) taking place in the 20th century and having a volume of erupted pyroclastics of up to 2 km^3 and the range of tephra dissemination of several hundred or thousand kilometers, were studied in detail. More than 20 analogous and larger eruptions have been established to occur during the last 10,000 years. Data on the distribution, volume, chemical composition, mineralogy and grain size have been obtained for volcanic ash generated by historic and prehistoric eruptions. Studies on the dynamics of the eruptive clouds have shown that a considerable part of the volcanic ash was transported towards the Pacific Ocean.

The data obtained can be used as a model for calculating the movement of eruption clouds of future eruptions and for providing aviation safety in the region of the Northern Pacific.

VOLCANIC ASH AND AIRCRAFT OPERATIONS

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The aviation community has been subjected to volcanic eruption hazards on several occasions over the years, usually in rather dramatic fashion. Volcanic dust, a by-product of many volcanoes, though not all of them, is often injected into the stratosphere with an explosive eruption and is left to spread laterally in the upper level flow. The dust is abrasive and capable of causing serious damage to aircraft engines, control surfaces, windshields and windows, and landing lights. The dust can also clog the pitot static systems that help calculate airspeed and altitude for the pilots, and it can damage sensors that deliver electronic data to automated systems used to fly modern aircraft. Mixed with weather-associated clouds, the ash becomes difficult and sometimes even impossible to identify.

Recent events have reminded us with alarming regularity that aircraft and volcanic ash do not mix. Windshields have been rendered opaque, engines have failed, and severe damages have left air carriers with aircraft useless to them without costly repair. Most recently, the Boeing 747-400 of a Dutch airline encountered volcanic ash from the Redoubt Volcano in Alaska and suffered a simultaneous four-engine flameout. The most advanced example of that aircraft type was an expansive glider for several minutes, despite its state of the art technology.

This paper will explore the surface detection, reporting, and dissemination of information critical to crew members operating in the vicinity of known volcanoes. It will also discuss other operational needs of flight crew members. Pilots need to be educated about hazards of volcanic ash. Pilots need two tools in coping with volcanic ash: a copy of the ICAO Volcanic Activity Reporting Form and a chart portraying air routes and locations of known volcanoes. This chart is not yet available.

THE 1989-90 ERUPTION OF REDOUBT VOLCANO: CHRONOLOGY, CHARACTER AND EFFECTS

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Redoubt volcano, a remote 10,200-foot-high stratovolcano 110 miles southwest of Anchorage, began its third major eruption this century on December 14, 1989. An initial eruptive phase (December 14-19) consisted of numerous and repeated vent-clearing explosive events that generated ash-rich eruption columns rising to over 40,000 feet. Airborne ash generated by these events was carried by prevailing winds east and north toward the populous parts of the Cook Inlet region shutting down air traffic for 3 days. On December 15, a 747 jet passenger airliner lost all 4 engines after encountering an ash cloud 80 miles north of Anchorage; the engines wee later restarted and the aircraft landed safely. The second phase of the eruption, consisting of episodic lava dome emplacement (similar to Mount St. Helens) and destruction, began on December 22: 13 such lava domes were emplaced over the next 120 days. Each was destroyed by brief (<20 minute) explosive events that produced ash clouds which also effected air traffic but for a much shorter time than in the initial phase.

Alaska Volcano Observatory, through its seismic monitoring network and field observations, recorded all of the explosive eruptions and predicted several of them. Eruption notification and hazards were communicated to the airline industry through an agency call-down list, daily updates, and a color-coded hazard alert.

Six major explosive eruptions have occurred from Redoubt and neighboring Spurr and Augustine volcanoes in the past 38 years. All three of these Cook Inlet volcanoes are now monitored seismically so that their future eruptions can be reported immediately and in some cases predicted. West of Cook Inlet, the 39 active volcanoes that occur spaced along a 1500-mile-long arc from the Alaska Peninsula through the Aleutian Islands (and average one eruption per year) are not presently monitored. These otherwise remote volcanoes do, however, present a continuing hazard since several great circle air routes parallel or cross this arc.

NOAA'S RESPONSE TO THE MOUNT REDOUBT ERUPTIONS OF DECEMBER 1989

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The National Oceanic and Atmospheric Administration (NOAA) is responsible for monitoring the ejection of volcanic ash into the atmosphere and the subsequent forecast of where the ash is likely to be dispersed. NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) is responsible for the monitoring of an notification of ash eruptive events in real-time. NOAA's National Weather Service's (NWS) responsibility is to provide forecast information on the location and predicted track of volcanic ash. This guidance is provided in real-time through the issuance of Significant Meteorological Messages (SIGMETs) by NWS forecasters. NOAA's responsibility is stated in the memorandum of understanding between the Federal Aviation Administration and NOAA on Volcanic Hazards Alert.

As shown by the KLM event on December 15, the ability to monitor and forecast the volcanic-ash cloud dispersion in the atmosphere was inadequate. NOAA was asked to review the situation and generate a proposal for improving the volcanic-ash monitoring and forecast program. NOAA was able to pull together its various elements and generate a proposal within a few weeks. The Alaska Volcano Project consists of various components: new observing capabilities, new computer and communications equipment, and studies to enhance the numerical modeling systems. The presentation will provide a review on the progress of the Alaska Volcano Project.

USING A PERSONAL COMPUTER TO OBTAIN PREDICTED PLUME TRAJECTORIES DURING THE 1989-1990 ERUPTION OF REDOUBT VOLCANO, ALASKA

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J.F. Paskievitch, *U.S. Geological Survey, Anchorage, AK*

The Alaska Volcano Observatory (AVO) and the Anchorage Weather Service Forecast Office (WSFO) daily obtain predicted plume trajectories (PPTs) for Redoubt Volcano, Alaska. Data for the PPTs are produced on a National Oceanic and Atmospheric Administration NAS/9000 computer. It models measured and forecasted winds to predict the path of a weightless-particle release at various pressure altitudes above a specified location. The paths are assumed to indicate the general direction and speed that ash from an eruption at that location will travel.

In response to the Redoubt eruption, we programmed an IBM AT-style computer to dial the NAS/9000 and obtain the PPTs. The program enables AVO and WSFO to easily collect the day's PPTs each morning. Thus, the PPTs are immediately available in the event of an eruption later in the day. The PPTs are plotted on a map of Alaska, showing the predicted location of the ash at three-hour intervals for different altitudes between 5k and 53k feet. The plots are easily telefaxed to interested parties. The program has been modified to enable the user to obtain PPTs for other US volcanoes.

AIRBORNE RADAR DETECTION OF VOLCANIC ASH

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Detection of volcanic-ash clouds is highly desirable by both ground-based and airborne radar systems. Airborne radars would provide coverage in regions where ground-based radar coverage is not available, allowing for real-time pilot reaction to a potentially dangerous situation. Present airborne weather radars are inadequate for detection of volcanic-ash particles or clouds due to the power/aperture and sensitivity limitations of these systems.

This paper will analyze three different airborne radar configurations, X-Band (9.5 GHz), Ku-Band (16 GHz) and millimeter (95 GHz), to determine their effectiveness for detection of volcanic ash. Volcanic-ash cloud detection and signal-to-noise ratio will be evaluated as a function of operating frequency, radar cross section, range, and azimuth angle. Along with performance evaluation, antenna parameters (gain, beamwidths and sidelobes) and waveform parameters (PRFs, pulsewidths and coding) will be developed.

The practicality of modifying existing airborne radars to improve their detection capability will be addressed. Limitations of an airborne radar based on hardware constraints will be discussed. The paper will also identify advances in technology that will improve volcanic-ash detection in future radar systems. Recent advances in radar technology developed for the detection of low observable targets will be considered.

VOLCANIC-EVENT NOTIFICATION AT MOUNT ST. HELENS

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George J. Theisen, *USDA Forest Service, Vancouver, WA*

During the 1980-86 eruptions of Mount St. Helens, hazard information was quickly disseminated through a U.S. Geological Survey/USDA Forest Service notification system. Written and verbal statements issued jointly by the U.S. Geological Survey and University of Washington were released to the Forest Service for telephone call-down to governmental agencies and private interests. These statements were also entered into a computer-information system accessible to agencies on the call-down list. Once the call-down was in progress, public- and media-information tapes were updated and press releases issued. Since most of these eruptions had recognizable precursors, a series of information statements and eruption forecasts was issued during the weeks to hours before an eruption, providing advance warning of volcanic activity and associated hazards.

Hundreds of small gas and ash emissions also occurred during 1980-86, most without recognizable precursors. The lack of precursors made advance warning of these events impossible; instead, information statements were issued after the larger, more visible events. When small emissions were frequent, the possibility of more small emissions was stressed. However, when these events were infrequent, governmental agencies and the public were often surprised and frustrated by the lack of instantaneous information.

The occurrence of occasional small, unpredictable ash-producing explosions at Mount St. Helens during 1981-1991, coupled with increased concern about the hazards of volcanic ash to aviation, prompted CVO to develop a seismic-alarm system that triggers on small volcanic events. This alarm system activates CVO's 24-hour beeper. In addition, the Federal Aviation Administration (FAA) can call the beeper to report possible volcanic activity. These two modifications should decrease CVO's response time for non-predictable, sudden-onset events and help the FAA quickly verify pilot reports of possible volcanic plumes.

VOLCANOES AND ATMOSPHERIC TEMPERATURE

Reginald E. Newell, *MIT, Cambridge, MA*

The eruption of Mount Agung in 1963 produced increases in tropical stratospheric temperature measured with radiosondes of about 6^{O}C with possible decreases in the tropical troposphere of about 0.5^{O}C. The sudden temperature increases were the largest in that region since radiosonde records began in the early 1950's. The pattern of aerosol-induced temperature change in a latitude-height plane was similar to that of the pattern of radioactive dust from nuclear weapons' tests; both are controlled by the large-scale mean and eddy motions in the lower stratosphere. The eruption of El Chichon in Mexico in 1982 produced an aerosol cloud with similar extent and was also accompanied by an increase in tropical stratospheric temperature. In addition to radiosonde data, satellite data from microwave sounding units (MSU) was available for El Chichon and verified temperature increases for the lower stratosphere. This paper reviews observational studies of volcanic clouds and temperature changes carried out since the eruption of Agung engendered interest in this topic and raises the question: can significant information about the extent of volcanic clouds in the lower stratosphere be obtained from MSU data?

AVIATION SAFETY FOR ASH CLOUDS IN JAPAN AND JAL'S SYSTEM FOR SAKURAJIMA'S ERUPTIONS

Saburo Onodera, *Japan Air Lines, Tokyo, Japan* and Kosuke Kamo, *Sakurajima Volcanological Observatory, Kagoshima, Japan*

Japan Meteorological Agency (JMA) continuously watches 19 of 83 active volcanoes in Japan by means of monitoring volcanic clouds, seismic events, tilt changes, and other field observations. The information on volcanic activities that could affect safe operations of aircraft is issued by and based on JMA criteria, while satisfying that of ICAO SIGMET. The air-traffic control authority and the operators take their own countermeasures to prevent the volcanic-ash hazards. The following incidents by volcanic ash have been reported from the respective volcanoes in Japan since 1973; nine incidents for Sakurajima, four at Izu-Oosima, three for Usu and one for Asama.

Kagoshima Airport is located 25 km north of Sakurajima volcano which has been at unrest in the explosive activity for 35 years. Planning has been carried out to establish an aviation safety system for the ash clouds. This project is divided in two stages. The first one is to detect the volcanic explosions using the data of explosion-quakes and air-shocks and the second one to simulate the diffusion of ash clouds with the data of the meteorological condition above the volcano. The simulation will be started automatically after detecting and determining that an explosion occurred. The first stage of the plan is completed and operating. The second stage is under planning

GRAIN IMPACTS ON AN AIRCRAFT WINDSCREEN: THE REDOUBT 747 ENCOUNTER

David Pieri, *Jet Propulsion Laboratory, Pasadena, CA and* Robert Oeding, *PDA Engineering, Costa Mesa, CA*

In December 1989, a Boeing 747-400 aircraft intercepted an ash cloud from an eruption of the Redoubt Volcano. The encounter caused strong abrasion on leading edges and windscreens, and severely impaired engine function. To better understand the nature of the ash cloud, its remote-sensing signature, and the encounter itself, we have obtained an abraded 150 kg polycarbonate-laminate front windscreen of the 747, to analyze quantitative characterizations of the impact pits, in terms of the size-frequency distribution, areal density, and orientation. Ultimately, we would like to relate the impact signature to in-situ ash-cloud volume densities, and thus to its appearance in orbital imaging. In our analyses, we use (a) 747 slip-stream and boundary-layer characteristics, and (b) polycarbonate-laminate blanks, abraded by Redoubt ash at selected mass-flux rates in the laboratory for count calibrations.

Inspection of the windscreen shows the following: (a) Strong abrasion zonation dependent on azimuth from the direction of flight, ranging from complete destruction (opaque frosting) of juvenile windscreen material near the centerline (15% of windscreen area), to the onset of inter-pit juvenile material at about 45 degrees from the centerline, to only occasional elongated pits on the surface parallel to the direction of airflow (opaque frosting occurred within the inferred forward pilot line-of-sight); (b) Strong shadowing effects due to the presence of obstacles in the slipstream path--washer pylons and wiper blades appear to have interrupted the impact trajectory enough to have shielded small areas, even in the zone of head-on impact, suggesting mitigation of frosting by appropriate baffling upward of the area to be protected. This work was partially carried out under the NASA Solid Earth Sciences Program at the Jet Propulsion Laboratory, California Institute of Technology.

DETECTION AND DISCRIMINATION OF VOLCANIC-ASH CLOUDS BY INFRA-RED RADIOMETRY I: THEORY

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Volcanic-ash clouds with a high concentration of silicate particles exhibit optical properties in the infra-red (8-13 μm) that can be used to discriminate them from normal water/ice clouds. In principle, a simple radiometer equipped with at least two channels with appropriate passbands may be used to identify volcanic clouds. In this paper, we lay down the theoretical basis for such a radiometer. We solve the radiative-transfer problem in a cloudy atmosphere by using a discrete-ordinates model and present results for a variety of viewing conditions. These include vertical viewing downwards (from a satellite), horizontal viewing (from an aircraft) and vertical viewing upwards (from the ground). We also present some LOWTRAN-7 calculations for representative atmospheres that include height variation of temperature, cloudiness, water vapor and other trace gases.

Finally, we present results showing the effect of particle size and shape on the radiative transfer in an idealized volcanic cloud.

VOLCANIC-ASH CLOUD WARNINGS IN THE AUSTRALIAN REGION

Rodney J. Potts and Frank Whitby, *Bureau of Meteorology, Melbourne, Australia*

As part of its routine operations the Bureau of Meteorology provides warnings to the aviation industry for volcanic-ash clouds over the Australian region and the region to the near north. This service has been an important component of Bureau operations since its introduction in 1982 when several aircraft suffered engine failure after encounters with volcanic-ash clouds over Indonesia.

The warnings issued by the Bureau are based on notification of a volcanic eruption from the relevant neighbouring country, aircraft reports and unambiguous evidence on hourly Japanese Geostationary Meteorological Satellite images.

There are inherent difficulties with the provision of this service as the discrimination of volcanic-ash clouds from water/ice clouds on present GMS satellite imagery is difficult and the ability to assess the dispersion and residence times of a volcanic-ash cloud is limited.

The feasibility of using AVHRR Channel 4 and 5 data from the NOAA polar-orbiting satellites to discriminate volcanic-ash clouds from water/ice clouds has been previously demonstrated. The Bureau is in the process of installing an AVHRR antenna at Darwin and this antenna will enable good satellite coverage over the region north of Australia. The operational benefits provided by AVHRR data for the detection of volcanic-ash clouds is to be evaluated.

Numerical models enable a forecast trajectory for the volcanic-ash cloud to be determined and this is to be developed using models run by the Bureau.

IMPACT OF VOLCANIC ASH FROM REDOUBT VOCANO ERUPTION ON GE CF6-80C2 TURBOFAN ENGINES

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The 1989-1990 eruption of Redoubt Volcano, Alaska, and the near tragedy of KLM Flight 867 on 15 December

1989 underscore the threat to aircraft safety from volcanic ash clouds.

Between December 1989 and February 1990, at least 4 commercial jet liners suffered damage from encounters with ash clouds from Redoubt Volcano. The most serious incident occurred on 15 December 1989 when a new Boeing 747-400 aircraft equipped with GE CF6-80C2 engines encountered an ash cloud as the aircraft descended from the north for a scheduled landing in Anchorage. An eruption of Redoubt at 10:15 am (AST) produced an ash-rich eruption column which climbed to approximately 40,000 feet altitude. Wind speeds at the time were 100 knots in a northeasterly direction. At approximately 11:46 am (AST), KLM Flight 867 entered the volcanic ash cloud at approximately 25,000 feet altitude, 150 nautical miles northeast of Redoubt. Immediately upon entry into the cloud, the aircrew increased power and attempted to climb out of the ash cloud, gaining nearly 3,000 feet additional altitude before all 4 engines stalled. The aircraft descended approximately 13,000 feet during the next 8 minutes before the pilots restarted the four engines and resumed flight to Anchorage. While there were no injuries to passengers, the damage to engines, avionics, and aircraft structure from this encounter was significant. Similar engine thrust loss and engine and aircraft damage was experienced by two Boeing 747 aircraft during 1982 volcanic eruptions of Galunggung Volcano in Indonesia. Other encounters between jet aircraft and ash clouds from Mount Redoubt on 15 and 16 December 1989 and 21 February 1990 did not result in engine thrust loss.

The primary cause of engine thrust loss in the volcanic ash ingestion events in Indonesia in 1982 and at Redoubt was the accumulation of melted and resolidified ash on the stage 1 turbine nozzle guide vanes. These deposits reduced the effective flow area causing an increase in the compressor operating line and compressor surge. Compressor airfoil erosion contributed to the loss of surge margin. Turbofan engines tested operating at high combustor discharge temperatures, and exposed to high concentrations of sand/dust with low melting point, exhibit symptoms and conditions similar to those of engines exposed to volcanic ash. Operation at low-thrust level while in an ash cloud significantly reduces the rate of engine performance degradation.

RADAR REMOTE SENSING OF VOLCANIC-ASH CLOUDS

William I. Rose and Alexander B. Kostinski, *Michigan Technological University, Houghton, MI*

Ground-based airport radar systems designed many years ago for meteorological purposes have been have demonstrated capable of tracking volcanic-ash clouds (Harris, et al., 1981, *U.S. Geological Survey Professional Paper 1250, 323-333*; Harris and Rose, 1983, *J. Geophys. Res., 88: 10969-10983)*. Among the useful information that results from their use is the duration of eruption, particle concentrations in ash clouds, the total mass of erupted materials, magma eruption rate, potential ashfall mass, ashfall locations and times, durations and amounts of ashfall.

The reflectivity factors for very dense ash clouds (3-10 g/m^3) on meteorological radar systems are several orders of magnitude less than for severe storm clouds that those radar systems are designed to detect. We estimated the ash concentrations likely to have been present in ash clouds encountered by aircraft based on our knowledge of eruption rates and plume dispersion models. These data suggest that volcanic clouds, much less dense than meteorological radar stystems are designed to detect (<0.2 g/m^3), are a severe hazard to aircraft. Could a ground-based radar provide data for mitigation of ash cloud aircraft hazard?

One effective approach to using radar as an instrument for ash cloud tracking of Alaskan eruptions, would be to place a ground-based system on the Kenai Peninsula, which is between Anchorage and the several historically active nearby volcanoes. A system that could map thin ash clouds (0.1 g/m^3) with small (<10 µm) particles over a long range (up to 500 km) would be most useful. Power generation is more expensive for long range radar systems with wavelengths less than 3 cm, but the trade off between better sensitivity and more expensive power at shorter wavelengths will be discussed. One consideration is that reposes between eruptions are long and eruptive events are rather short-lived. Besides its utility as a cloud tracking instrument, the radar would provide data that would help solve many unknown scientific problems concerning volcanic-ash clouds and ash transport. The incorporation of meteorological Doppler radar in order to measure Doppler shifts of ash clouds would be a useful addition for cloud track forecasting, because it could detect ash fallout and determine the particle size distributions within the clouds. A method might be devised for distinguishing volcanic and meteorological clouds using the doppler spectral width. Also, polarization diversity can provide additional information about ash particles and fallout mechanisms.

REGIONAL MONITORING OF VOLCANIC ASH CLOUDS BY GEOSTATIONARY METEOROLOGICAL SATELLITE

Yosihiro Sawada, *Shizuoka Meteorological Observatory, Japan*

Visible and infrared images from GMS (Geostationary Meteorological Satellite) have successfully detected widely dispersed ash clouds caused by big volcanic explosions, 1981 Alaid, 1981 Pagan, 1982 Galunggung, 1982 Soputan, 1983 Una Una, 1984 Mayon, 1984 Soputan, 1986 Chikurachki, 1986 Izu-Oshima, 1988 Kie Best, 1988 Banda Api and 1990 Kelut. GMS's detection rate of ash clouds was about 14%. Limitation of the ground resolution and difficulty of discrimination of ash cloud from ambient atmospheric clouds with GMS's detector prevent the further improvement of its detection rate, but it is possible to monitor ash clouds caused by big explosions which threaten aviation safety. Height of the ash cloud's top can be estimated from the coldest temperature on the surface of the ash cloud and the profile of air temperature around the volcano, and the intensity of the explosion can be evaluated with thermal energy release estimated from image data analyses. However, there are still unsolved differences between estimated and observed top heights of ash clouds, and some examples that may show active thermal discharge on the ascending ash cloud's surface.

UTILITY OF AVHRR SENSOR FOR REMOTE SENSING OF ALASKAN ERUPTION CLOUDS

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The 1989-90 eruption of Redoubt Volcano and the 1986 eruption of Augustine Volcano have provided an opportunity to test and refine the use of the advanced very high resolution radiometer (AVHRR), a multispectral sensor which is aboard two polar-orbiting NOAA weather satellites. Each satellite furnishes twice daily coverage of Alaska at a spatial resolution of 1.1 km, allowing a synoptic view of volcanic eruption clouds. A comprehensive collection of seventy images, representing a wide variety of eruptive and environmental conditions, have been studied during these two recent eruptive events. Seismic monitoring, direct observations of eruptions, ash-fallout information, radiosonde measurements, and ground weather observations provide ground truth, which helps us evaluate the satellite data. In addition, our work has included spectral reflectance studies of ash samples in the laboratory.

At the date of writing, study of the Augustine images is completed (Holasek and Rose, Bull. Volcanol., in press), while the more extensive Redoubt images are still being intensely studied. Highlights of the conclusions so far: (1) Volcanic eruption clouds are detectable in a variety of weather conditions, both night and day, and over land or water. (2) The multiple infrared channels of the AVHRR sensor are essential in algorithms used for the discrimination of eruption clouds. (3) A single algorithm that can detect all eruption clouds has not been developed. Potential uses of the satellite data include monitoring and tracking eruption clouds, as well as contouring particle burden within the clouds.

A MESOSCALE DATA ASSIMILATION SYSTEM ADAPTED FOR TRAJECTORY CALCULATIONS OVER ALASKA

Thomas W. Schlatter and Stanley G. Benjamin, *NOAA Forecast Systems Laboratory, Boulder, CO*

Soon after a volcanic eruption, it is relatively easy to locate the plume from satellite imagery, at least if the sky is clear. Later, however, as the plume disperses and thins, remote detection becomes more difficult. A series of analyses, feeding wind data to a trajectory model at frequent intervals, is one answer to the need for accurate tracking of the plume.

NOAA's Forecast Systems Laboratory has developed a Mesoscale Analysis and Prediction System (MAPS) for assimilating surface and tropospheric data over the contiguous United States every three hours. Designed to serve aviation and local nowcasting, MAPS is scheduled for implementation at the National Meteorological Center (NMC) within one year. It relies heavily on automated aircraft reports available by the hundreds every hour. It uses isentropic coordinates in the free atmosphere and terrain-following coordinates near the ground. Isentropic coordinates are well-suited for trajectory calculations because air remains on these surfaces in adiabatic flow.

MAPS has been adapted for use over Alaska. The previous definition of topography has been modified to allow for rougher terrain. A major obstacle must be overcome before the full potential of MAPS can be realized: automated aircraft reports over all of Alaska must be collected in real time so that the tropospheric and lower stratospheric wind field can be adequately defined every few hours.

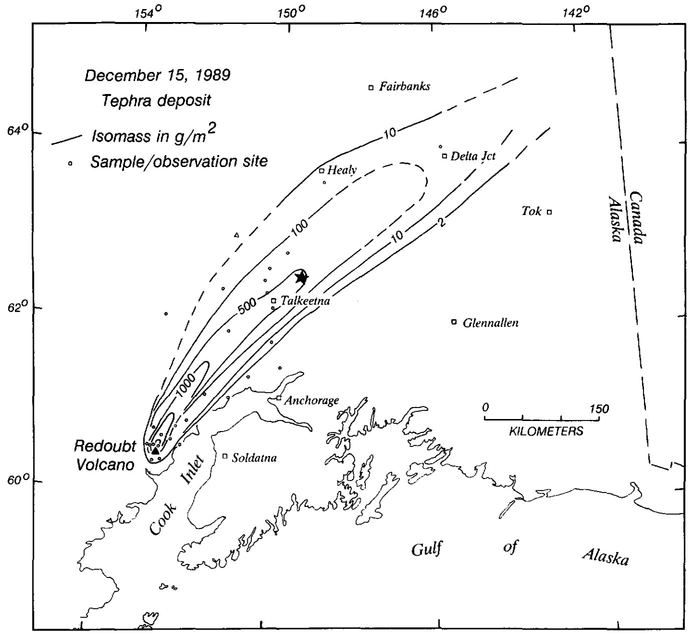
MASS, DISTRIBUTION, GRAIN SIZE, AND ORIGIN OF 1989-1990 TEPHRA-FALL DEPOSITS OF REDOUBT VOLCANO, ALASKA

William E. Scott, *U.S. Geological Survey, Vancouver, WA*, and Robert G. McGimsey, *U.S. Geological Survey, Anchorage, AK*

Twenty-one significant tephra falls occurred at Redoubt Volcano between 14 December 1989 and 26 April 1990. Although modest in size compared to such recent eruptions at Mount St. Helens 1980 and Galunggung 1982, these events inferfered with and imperiled air travel and disrupted life and commerce in south-central Alaska. Tephra plumes rose to estimated altitudes of 7 to more than 12 km; most drifted to the northeast, east, or southeast. Individual tephra-fall deposits extend maximum distances of 50 to more than 600 km from the volcano with mass concentrations ranging from 1 g/m^2 to 1.5 X 10^5 g/m^2. Mass estimates of individual deposits range from 6 X 10^7 to 4 X 10^{10} kg summing to a total dense-rock volume of about 4 X $10^7 m^3$.

The tephra fall of 15 December produced pumice- and crystal-rich deposits that were coarse grained near the volcano, whereas all subsequent events produced mostly ash-size deposits of lithic fragments and crystals (plagioclase, hornblende, pyroxene, and Fe-Ti oxides). Of the 19 events that produced lithic-crystal tephras, 17 involved at least partial dome destruction. This association, coupled with visual evidence from 4 events and lack of large ballistic fragments near the vent, suggests that much of the lithic-crystal tephra originated in ash clouds elutriated from pyroclastic flows formed by dome collapse.

Most 1989-1990 Redoubt tephra deposits other than proximal deposits of mid-December are composed of ash size material with mean grain sizes between 30 and 125 microns. Beyond 20 km from the volcano, little material is coarser than 500 microns; sorting is poor to very poor. Mean grain size decreases and sorting improves with transport distance. Grain size of many samples is polymodal; modes common to numerous samples occur at 63-125, 16-32, 8-16, and 500-1000 microns. These modes may be controlled by initial crystal-size distribution in the andesite of the dome.

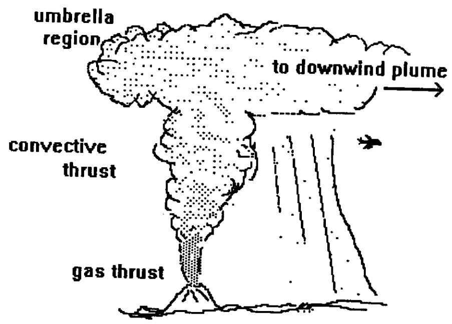


Volcanic ash deposits from the December 15, 1989 eruption of Mount Redoubt were detectable for more than 300 miles northeast of the volcano. The axis of the deposits passed through the town of Talkeetna. Methods used to construct this map are described in the paper by W. Scott and W. McGimsey (this volume). The star (*) indicates the position of the Boeing 747-400 airplane of KLM flight 867, enroute from Fairbanks to Anchorage, when it encountered the ash cloud. Map courtesy of William E. Scott.

ASH CLOUDS: CONDITIONS IN THE ERUPTION COLUMN

Stephen Self and George P. L. Walker, *University of Hawaii at Manoa, Honolulu, HI*

An eruption column is defined as the vertical or sub-vertical part of the emissions issuing from an explosive volcanic vent. Eruption columns range from very low, small-scale bursts to huge convective systems that rapidly transport ash, volcanic gases, and entrained air into the stratosphere. They have a lower gas-thrust part (the jet of material leaving the vent), that commonly represents less than 10% of the total height, and a convective thrust zone that constitutes most of the column but may be small in the Hawaiian-Strombolian types. Above this is the umbrella region, a zone of momentum-driven rise with considerable lateral spreading. Characteristics of eruption columns vary according to the style of explosive eruption, as summarized in the table below; rise rates shown are for the convective thrust region.



Characteristics of Volcanic Eruption Columns

CHARAC-TERISTIC	GLOBAL FREQUENCY PER YEAR				
	5-10	1-2	>10	0.1-1	<0.1
Max. ht/width (thou.'s of ft)	26-33/ 7-13	26-39/ 13-20	32-62/ 20-32	39-148/ 32-260	65-130?/262-490
Avg. rise rate (ft/s)	15-35	15-35	50-260	65-33	260-650
Duration (h); continuity	10-1000's; intermittent to semi-continuous	10-1000's; intermittent to semi-continuous	5-100's; extremely spasmodic to semi-continuous	<1-200; semi-continuous to continuous	? a few to ?100; semi-continuous to continuous
Ash content	Low- moderate	High	Moderate-high	Moderate-high	High
Other features	"Dry" volatile-bearing column; few fine particles; may be diffi-cult to detect visually	Wet, steam-laden columns; much aggregation of ash	Very common; widely variable style of activity; associated w/ small ash-flows	Coarse and fine particles in high column; often short-lived but maintained	Very high rise rates; large magnitude; infrequent
Recent examples	Kilauea, 1983-86; Pacaya, 1990; Oshima, 1986	White Island, 1976-82; Ukinrek, 1977; Surtsey, 1965	Redoubt, 1989-90; Sakura-jima (continuous)	Hekla, 1991; Mount St. Helens, 1980	small: Mount St. Helens, May 1980; big: Katmai, 1912
Type	Hawaiian/ Strombolian	Surtseyan (phreato-magmatic)	Vulcanian	Sub-plinian - Plinian	Ash flow (co-ignimbrite)

VOLCANOES: THEIR OCCURRENCE AND GEOGRAPHY

Tom Simkin, *Smithsonian Institution, Washington, DC*

The explosive volcanoes that threaten air safety tend to be in long, linear belts near continental margins. They cover less than 0.6% of the earth's surface. At least 1,200 volcanoes have erupted in the last 10,000 years and thus, since the lifetimes of most volcanoes are very long, are likely to erupt again in the future. Of these, however, only about 60 are active in a typical year, and that activity may range from the mild pyrotechnics of Italy's Stromboli to prehistoric catastrophes that dwarf recent eruptions such as Mount St. Helens 1980 or Krakatau 1883. As with earthquakes, the bigger eruptions happen less often than the smaller, with St. Helens-sized events perhaps once a decade and events like Redoubt 1989 and Ruiz 1985 two or three times a year. During the years 1975-1985 we found that over 100 eruptions penetrated the altitude range of air traffic, and at least 9 passed into the stratosphere where volcanic products are easily dispersed around the world.

Eruption durations were often not recorded historically, but they are known to range from minutes to thousands of years. The median duration is 2 months and few eruptions last longer than 3 years. Pulses of activity mark all but the shortest eruptions, and the paroxysmal event may come at any time from the first day (ca 45%) to months or even years after the start. Of particular importance for volcano hazards is the fact that unusually violent eruptions commonly occur after unusually long periods of repose. The historic record in many parts of the world is far shorter than the hundreds or thousands of quiet years that precede violent eruptions, meaning that some of our most dangerous volcanoes may be those not currently recognized as active. Of the 14 largest explosive eruptions in the 19th and 20th centuries, all but 3 were the first historic eruption known from the volcano. These factors emphasize the importance of communicating reports of new eruptions. We at the Smithsonian hope for more news from "eyes in the sky," and will do our best to disseminate volcano reports as we've been doing for nearly a quarter century (see McClelland abstract, this volume)

USE OF SATELLITE IMAGERY TO TRACK VOLCANIC ASH CLOUDS IN INDONESIA: A NEW POSSIBILITY FOR AVIATION SAFETY

Tumpal Situmorang, and Subroto Modjo, *Volcanological Survey of Indonesia, Bandung, Indonesia*

The Indonesian archipelago, which has 129 active volcanoes and is inhabited by 180 million people, has a high volume of air traffic. Most airline service between Asia and Australia must pass either through its principal air-traffic centers located near major volcanoes (Jakarta, Medan, Denpasar, Manado) or along air routes in Indonesian airspace. There were more than 100 explosive volcanic eruptions from 22 volcanoes during the last ten years (1980-1990). On the average, one major explosive eruption sends volcanic ash into the stratosphere and about ten less powerful eruptions occur every two years. The eruption products could threaten people directly in the hazardous zone, as well as having worldwide impact (e.g.: aviation disturbance, air pollution, unusual weather).

The remote sensing tools available include air photographs, radar images, earth-observing satellites images, thermal infrared images, and environmental satellite images. These offer new possibilities in surveys at various scales. In Indonesia, some of the satellite images (Landsat, GOES/NOAA, GMS) are received and distributed by LAPAN (the Indonesian Institute of Aeronautics and Space) Ground Station in Pekayon near Jakarta.

The volcanological science has benefited from use of remote sensing techniques. For tracking ash clouds, the very high temporal resolution images of environment satellites (GOES/NOAA, GMS) is most effective. Rapid acquisition and analysis of images allows us to issue an early warning for aviation safety and to the population living in the area that might be affected by ash fall. Images acquired by the GMS from a few hours to several days after the violent eruption of Kelut Volcano (East Java) on February 10, 1990, and Landsat images of East Java (covers Kelut, Semeru, Arjuno-Welirang, Lamongan volcanoes) taken on September 12, 1989, have been analyzed. Results are presented in this paper.

PREPARATION AND DISSEMINATION OF VOLCANIC ASH PLUME INFORMATION BY THE MONITORING AND AVIATION BRANCH OF THE NATIONAL METEOROLOGICAL CENTER

Arthur H: Smith, *National Meteorological Center, Camp Springs, MD*

Ash clouds produced by volcanic eruptions have a significant impact on aviation operations. This has resulted in the formulation of a multi-agency system to provide current and forecast information regarding the location, extent, and projected movement of the ash cloud to the aviation community. The Monitoring and Aviation Branch (MAB) of the National Meteorological Center (NMC) plays an important role in this support to the aviation community.

The functions of MAB include initiating the volcano response plan. This would be done by notifying the NESDIS Synoptic Analysis Branch when MAB receives information of a volcanic eruption from a Pilot Report or possibly a call from the Central Flow Weather Service Unit (CFWSU).

A second eruption-related function of the MAB is the preparation of high-level significant weather prognostic charts that depict the predicted volcanic ash plume or contain the disclaimer "Potential Volcanic Ash, See Local SIGMETS." The depiction of the plume on the prognostic chart is limited to those volcanic eruptions that are long-term and continuous.

The role of MAB's CFWSU in collecting volcanic ash plume observations and disseminating volcanic ash plume forecasts from and to the aviation community will be presented. The preparation, content, and dissemination of volcanic SIGMETS by MAB will be discussed.

MAB also has the capability to generate computer-prepared volcanic ash trajectory forecasts. These forecasts are used by MAB meteorologists in the preparation and issuance of volcanic SIGMETS and high-level volcanic ash plume forecasts. The method used to prepare the trajectories will be briefly discussed and examples of the trajectory forecasts shown.

VOLCANIC ASH DETECTION AND TRACKING SYSTEM APPLIED TO INDONESIA: A PROPOSED ALTERNATIVE

Indroyono Soesilo, *Agency for the Assessment and Application of Technology (BPPT), Jakarta, Indonesia*

A 10-month continuous series of volcanic eruptions of Mt. Galunggung, in West Java, Indonesia, during the period of 1982-83 disrupted the Singapore-Sidney air route corridor and forced jumbo jets of Singapore Airlines and British Airways to make safe emergency landings in Jakarta. No accident occurred; however, a real time information system network needs to be improved to cover this volcanically active 1700-island nation stretching 5100 km across the equator.

A computerized Indonesian Volcanic Hazard Information System (IVHIS) database should initially be developed, with the inclusion of geographic locations of 129 Indonesian active volcanoes and coastlines, islands, lakes, rivers, and administrative boundaries. Infrastructure digitized data (roads, cities, railroads, airports, etc.) would complement the database.

Volcanic ash detection and tracking activities are being simulated by the inclusion of real-time satellite and telemetric data into the IVHIS database within a designated period of time. Through a domestic telecommunication satellite network system, data are being shared by targeted agencies.

DISPERSAL OF ASH BY VOLCANIC ERUPTION COLUMNS

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Volcanic eruption columns consist of a rapidly ascending buoyant plume and a laterally expanding upper umbrella region. Concentration of volcanic ash is postulated to decrease exponentially with time in the turbulent column. For the umbrella region, the concentration of ash, C, decreases with distance from the vent, r, in a Gaussian fashion

$$C/C_0 = \exp[-r^2-r_1^2)\, v/Q]$$

where C_0 is the initial concentration, v is the terminal settling velocity of the particle, r_1 is the horizontal distance from the vent to the umbrella margin and Q is the flow rate. Q is determined by eruption column height and consequentially by discharge rate of magma. This simple theory shows good agreement with laboratory experiments on sedimentation from plumes and with field data from the Fogo A plinian deposit (Sao Miguel, Azores). The theory is valid for powerful eruptions with relatively weak wind. For the Fogo A eruption the theory has been tested down to 1/2 mm diameter. In a strong wind the same principles imply an exponential decrease of concentration with distance

$$C/C_0 = \exp[-dv/wh]$$

where w is the wind speed, d is the downwind distance, and h is the depth of the wind-transported plume layer. This result has not been validated in experiments, but is consistent with the overall exponential thickness decrease observed in most pyroclastic fall deposits. The model can be used to calculate particle concentration (mg/m^3) in plumes as a function of distance from source if assumptions are made about the initial particle grain size distribution and column height. Processes of atmospheric diffusion and particle aggregation will, however, modify concentration in downwind plumes in a manner that is not yet completely understood.

APPLICATION OF RADAR FOR THE OBSERVATION OF VOLCANIC ASH

Melvin L. Stone, *Lincoln Laboratory, Lexington, MA*

Radar detection and tracking of volcanic ash from Mount St. Helens demonstrated the usefulness of real time surveillance o the clouds (Harris, and Rose, 1983, JGR, 88, C15, p. 10969-10983). The radars used were operational NWS magneton systems. The low radar reflectively reported for volcanic ash clouds make the detection and characterization of the potential threat to aviation a formidable task. Both the NWS and the FAA are procuring pulsed Doppler radars with enhanced sensitivity. Contemporary airborne weather radars also have an improved detection capability. An overview will be presented of radar principles and technical issues related to various options for observing volcanic ash. Among the parameters to be considered are the operating frequency, power-aperture product, azimuth and elevation resolution, Doppler measurement, and update rate. The performance capability of currently operational and planned radar systems will be described. Candidate dedicated systems for proximate and stand-off surveillance will be suggested.

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MODELING VOLCANIC ASH TRANSPORT, DISPERSION AND DEPOSITION

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As required by a NOAA/FAA Memorandum of Understanding on Volcano Hazards Alerts, NOAA/Air Resources Laboratory (ARL) makes volcano ash trajectory forecasts. The three components of the present ARL product are (1) trajectory maps, (2) tables of 3-hour trajectory endpoints, and (3) written descriptions of the trajectories. It would be desirable for airline pilots to know more about the actual ash location with as much detail as possible. To expand the present product, ARL is developing a model to simulate ash transport. Meteorological data from the NOAA/Forecast Systems Laboratory Mesoscale Analysis and Predication System (MAPS) provide initial conditions and short-term forecast data; larger scale and longer term meteorological data is from the NOAA/National Meteorological Center (NMC). Dispersion and wet and dry deposition are also included in the model. Output describes the ash cloud in both space and time. Details of the model are described and example output shown.

CURRENT STATE OF VOLCANO MONITORING: STRENGTHS AND WEAKNESSES

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Perhaps 150 of Earth's 550 historically active volcanoes are monitored to some degree. The capability to monitor volcanoes and warn of impending eruptions has improved over the years but has reached neither an acceptable level of reliability nor an adequate geographic breadth to warrant satisfaction on the part of volcanologists. The most widely used and successful monitoring technique is the recording of earthquake activity from a volcano. Such *seismic monitoring* potentially provides real-time information on the state of a volcano, because data can be acquired and telemetered instantly from remote field sites to an observatory or crisis center. An increase in earthquake activity usually but not always precedes an eruption. Sophisticated procedures have been devised to analyze seismic information, but the single most crucial piece of evidence for warnings is simply the number of earthquakes per unit time. The newly developed ability to estimate seismic-energy release in real time is also very useful. The occurrence of false alarms (earthquake flurries with no eruption) is a significant weakness of seismic monitoring, so it is wise to augment that monitoring with other real-time methods to provide a more complete picture of the volcano. The two such methods most commonly used are *geodetic monitoring* and *gas monitoring*. Continuous geodetic monitoring is now effectively restricted to measurements of changing ground tilt with electronic tiltmeters, but in a few years Global Positioning System (GPS) instruments will become widely used for monitoring. Standard electronic-surveying techniques are often employed to detect swelling of the volcano, but they lack real-time capability. Geodetic monitoring, whether continuous or by repeated surveys, has proven useful at some volcanoes but is not a general panacea. Changes in Earth's gravity field can be monitored continuously but do not yet provide the basis for a dependable warning system. Real-time monitoring of volcanic gas composition and emission rate is conducted at a few volcanoes with mixed results, but this technique is evolving quickly and will become more useful. Thermal IR imaging is another technique whose promise has yet to be fulfilled.

Volcanoes are such remarkably complex natural systems that warning of impending eruptions is difficult under the best of circumstances. Under the worst, as in areas for which monitoring is limited or absent (such as in the Aleutians), warning is generally impossible. Volcanology has far to go before either the timing and or the style of each significant eruption can be foretold; meanwhile, the public should be aware that both large and small eruptions can and will take place unannounced at volcanoes around the world.

THERMAL PROPERTIES OF VOLCANIC ASH

Samuel E. Swanson and James E. Beget, *University of Alaska, Fairbanks, AK*

Melt quenched to a glass is a common phase in volcanic ash. The melt represents the most chemically evolved part of the magma with compositions typically 10-20 wt. % higher in SiO_2 than the condensed lavas. For example, bulk compositions of lavas from the 1989-90 eruption of Redoubt Volcano are high-silica andesites (SiO_2 = 58 to 63 wt. %), while groundmass and tephra glasses are rhyolitic (SiO_2 = 69-78 wt. %). Other volcanoes near Redoubt show similar relations (Augustine: lavas 51 to 63 wt. % SiO_2, glass 75 to 78 wt. % SiO_2; Iliamna: lavas 51 to 61 wt. % SiO_2, glass 79 wt.

% SiO_2; Spurr: lavas 54 to 63 wt. % SiO_2, glass 59 to 73 wt. % SiO_2).

The rhyolitic melts plot close to the pressure minimum in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2. Liquidus temperatures (1 bar, dry) of these glasses are about 960°C. Operating temperatures of commercial jet engines (600-700°C) are below the melting temperatures of these rhyolitic glasses, but above the glass transformation temperature (Tg, about 630°C) of the rhyolitic glasses. Above the Tg, "glass" behaves as a supercooled liquid and has considerable translational mobility. When ingested into an operating jet engine, glass particles will be heated, soften, and adhere to the engine parts. Annealing of the particles and flow of the glass will produce a glassy coating, thus creating operational problems for the jet engine.

PERFORMANCE DETERIORATION ON AIRCRAFT JET ENGINES WITH PRESENCE OF SOLID PARTICLES

W. Tabakoff, *University of Cincinnati, Cincinnati, OH*

Commercial and military airplanes are often exposed to foreign objects such as birds, hailstones, ice slabs, runway gravel, and others which are ingested into engine inlets. The ingestion of particulate matter such as sand and dust leads to the deterioration of these engines both structurally and aerodynamically. Some of the mechanisms that cause foreign-object ingestion are: (a) the vortex from engine inlet to ground during high power setting, with the aircraft standing or moving on the runway, (b) sand storms transporting sand to several thousand feet altitude, (c) thrust reverser efflux at low airplane speed may blow sand, ice and other particles into the engine inlets, (d) the most dangerous environment for jet engines is particulated clouds from the eruption of volcanoes. This paper will present the methods and results of several theoretical and experimental investigations concerning the effect of the presence of solid particles on the performance of turbomachines.

DEVELOPMENT OF A PREDICTION SCHEME FOR THE VOLCANIC ASH FALL FROM REDOUBT VOLCANO

H. L. Tanaka, *University of Alaska, Fairbanks, AK*

A volcanic plume prediction model has been developed for Alaska volcanoes including Redoubt Volcano. This is a 3-dimensional Lagrangian-diffusion model with gravity fallout of volcanic plume particles. The near real-time and forecasted upper-air data are provided by the NMC global model product through the Unidata program.

The model has been tested with Redoubt Volcano eruption records and compared with the NOAA AVHRR satellite data analyses. The 3-dimensional distributions of the plume dispersal are displayed on the computer screen as functions of time after the eruption. The simulation results agree reasonably well with the AVHRR satellite data analyses.

The model predictions have been demonstrated routinely at the Alaska Volcano Observatory (AVO) for daily hypothetical eruptions. These demonstrations show that the model is capable, within 6 minutes after any eruption report, to display traveling plume locations and dispersal for the following several hours. The prediction will be especially useful during dense-cloud situations when the visual monitoring is difficult, a common condition in winter at the Gulf of Alaska.

The model products are immediately available for aviation purposes through computer networking and FAX transmission supervised by the AVO. Because the model is operational at the AVO, it can offer the timely predictions important to aviation and public safety.

VOLCANO OBSERVATORIES AND VOLCANIC ASH WARNING

R. I. Tilling, *U.S. Geological Survey, World Organization of Volcano Observatories [WOVO], Menlo Park, CA,* T. J. Casadevall, *U.S. Geological Survey, Denver, CO,* G. Heiken, *Los Alamos National Laboratory, Los Alamos, NM,* and G. E. Sigvaldason, *University of Iceland [WOVO], Reykjavik, Iceland*

Incidents of aircraft encountering volcanic ash clouds have become more common in recent decades as air traffic has greatly increased worldwide. Airborne volcanic ash poses an infrequent but growing threat to aviation safety, particularly in the circum-Pacific region. Since 1986, the Volcanic Ash Warnings Study Group, under the aegis of the International Civil Aviation Organization (ICAO), has addressed the problem of ash-aircraft encounters, resulting in some improvements in pilot education, information flow, and reporting/warning procedures (ICAO regulatory documents). Beginning in 1988, in cooperation with ICAO, the World Organization of Volcano Observatories (WOVO), a commission of the International Association of Volcanology and Chemistry of the Earth's Interior

(IAVCEI), attempted to launch an *International Airways Volcano Watch*, a voluntary network established to improve communications between volcano observatories and other institutes that monitor volcanoes, meteorological offices, flight-control agencies, and pilots. Members of WOVO--about 40 institutions in 19 countries--were requested to initiate meetings with the civil aviation and meteorological offices in their regions to develop contacts and procedures so that information, including warnings about volcanic eruptions, could be exchanged on a timely basis. In return, volcanologists would have greater opportunity for access to pilots' real-time observations of eruption phenomena otherwise reported. To date, only a few observatories have participated in *Volcano Watch*, and WOVO is working to encourage wider participation in this voluntary international endeavor. Nonetheless, promising progress has been made in Indonesia, Japan, New Zealand, Papua New Guinea, and the U.S.A. Successes achieved during the past decade indicate that volcanologists and volcano observatories can, and should, take a more active role to further mitigate the risks posed by volcanic ash-aircraft encounters in the 1990s--designated the *International Decade for Natural Disaster Reduction* by the United Nations.

CURRENT PROCEDURES FOR IN-FLIGHT ADVISORIES REGARDING VOLCANIC ERUPTIONS AND ASH IN DOMESTIC AIRSPACE

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The National Weather Service has established policies and procedures for issuing In-flight Aviation Weather Advisories regarding conditions associated with volcanic eruptions. This was in response to user concerns regarding the potentially disastrous consequences of jet aircraft encounters with material from volcanic eruptions, and in coordination with international efforts to address the same issue. This paper discusses the procedures, the underlying policies, and the problems associated with using the Significant Meteorological (SIGMET) Advisory program for a nonmeteorological event. Current procedures recognize a user requirement for two basic types of information, notification that an eruption has occurred, and information regarding the location, extent, and movement of hazardous volcanic material. Current policy is to provide a one-time-only eruption advisory as rapidly as possible, followed by a volcanic ash "hazard" advisory as soon as sufficient information is available. There are several problems associated with the latter product. The most urgent type of advisory message, a SIGMET, is the chosen vehicle for this information. Unfortunately, all of the other criteria for issuing a SIGMET are <u>always</u> hazardous while volcanic material is not. This creates a potential for "over warning" which negatively impacts aircraft operations and damages the credibility of the advisory program. There is also no known correlation between current airborne material detection capabilities and the extent of the actual hazard. Events such as the Mount St. Helens and Mount Redoubt eruptions have demonstrated the tremendous variability in volcanic events and in the hazards they create. Procedures to provide useful advisories in any eventuality are extremely difficult to develop. The existing procedures are detailed and their rationale explained. The prerequisites for improvements are also briefly discussed.

THE AERONAUTICAL VOLCANIC ASH PROBLEM

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The International Civil Aviation Organization requires warnings and flight planning information about one of the most potentially hazardous but non-meteorological aeronautical phenomena that exists, volcanic ash. This paper discusses the provision of required information based upon the experiences Mount St. Helens and Mount Redoubt in the United States. The frequency and duration of the eruptions as well as the lack of guidelines about ash concentrations affecting aircraft has made it difficult to meet the requirements for supporting both safe and efficient aeronautical operations with available information messages. The paper also reviews the requirements and current support in the U.S. and suggests improvements in meeting them. Meeting the aeronautical information requirements for this nonmeteorological phenomenon requires cooperative research and development among various disciplines to attain not only safe but also efficient operations.

AIRCRAFT AVOIDANCE REGIONS FOR VOLCANIC ASH

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This paper describes a methodology for the prediction of a region that aircraft should avoid when the air contains dust from recent eruptions of volcanoes. The methodology consists of two parts, the dust model and the avoidance-area model. The dust model predicts the locations of ash particles from volcanic clouds. The avoidance-area model uses the predicted particle locations to determine an avoidance region of minimal areal extent. The methodology is PC based and can predict such avoidance regions in near real time. A model such as this could link a volcano observatory, a weather station, and an aircraft operation center

The avoidance area model uses predicted particle locations to define a volume in space of minimal cross sectional area. This region contains all possible cloud particles at the time of interest. The avoidance region can be defined for a single altitude or a range of altitudes.

The dust model includes key elements that affect the prediction of particle locations. Key elements include: the specification of cloud initial conditions and a three dimensional wind field; the transport and dispersion characteristics of the atmosphere; and the particle terminal fall velocities. The initial conditions of the cloud consist of a description of the cloud geometry, mass distribution, and particle size distribution. This initial cloud is represented by a number of horizontal wafers. Each wafer contains the mass and effective radius of each of the particle sizes. The location of representative particles are computed with a modified Euler method using a time dependent wind field. Dispersion is modelled by an empirical correlation. The fall rate of a particle is determined from its local terminal velocity, which is a function of size and altitude.

Mount St. Helens ash deposition data have been used in a study to assess the adequacy of the model. Reasonable agreement was found between predictions and measurements.

VOLCANIC ASH AS AN INGESTION HAZARD

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This topic will illustrate the relative engine ingestion hazard of volcanic ash compared to other more common hazards such as birds, sand, tires, ice, and severe weather. The causes of other ingestions will be shown to relate to their occurrence rates. The relationship of the ingestion event itself to economic damage as well as the more important aspect of flight safety will be stressed. The relative effects of the ingestion on risk to safety of flight will be explained and put into perspective relative to occurrence rates of the ingestion event itself. Finally areas of minimization and/or mitigation of operational impact will be discussed.

NEW ROLES FOR AIRPORTS IN RESPONSE TO VOLCANIC DISTRIBUTION

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On December 15, 1989, Mount Redoubt, a volcano located on the Alaska Peninsula, experienced a major eruption. This event, and numerous subsequent events, had a dramatic disruptive impact on the civil air transportation system in Alaska, exacerbated by the fact that it occurred during one of the busiest travel periods of the year. Almost immediately, air carriers began cancelling flights, leaving passengers stranded and airport revenues greatly reduced. The Alaska International Airport System (AIAS), which owns and operates both Anchorage and Fairbanks International Airports, was faced with a crisis.

The response of AIAS management to this crisis illustrates of the challenges facing airport management, and the possible pro-active steps that may be taken to mitigate the impact on the travelling public, the airlines, and ultimately to the revenue stream. The actions that may be selected by the airport can be divided into two groups: direct and indirect. It is important to point out that the airport, with respect to events of this nature, is not one of the central participants, those roles being held by the federal government and the air carriers. The direct actions primarily involve airfield and terminal management, and will not be discussed in depth. The indirect actions place the airport in a unique role; that of facilitator. This role will be discussed in depth.

ASH-FALL DEPOSITS FROM LARGE-SCALE PHREATOMAGMATIC VOLCANISM: LIMITATIONS OF AVAILABLE ERUPTION COLUMN MODELS

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Several models consider the structure and dynamics of eruption columns, and can be used to estimate the column height and discharge rate of prehistoric eruptions from the dispersal characteristics of their ash-fall deposits. These models are very successful in characterising deposits from "dry" eruptions (i.e. where the explosive activity is driven solely by release of volatiles dissolved in the magma, typically <6 wt% H_2O). They also provide accurate and useful predictions of the size and growth rates of "dry" eruption ash clouds.

However, some historical eruptions are known, and an increasing number of prehistoric deposits recognized to be from "wet," or phreatomagmatic, activity where external water (e.g. sea, lake, or groundwater) in various proportions (>10 wt%) interacted with the magma. The 22,500 year old Oruanui eruption (New Zealand) is of this type, and several features of its greater than 500 km^3 ash-fall deposit suggest that available eruption-column models cannot be applied to large "wet" eruptions, where column dynamics are dominated by latent heat associated with evaporation or condensation of water. Existing eruption-column models imply that involvement of water will decrease column height and vigor, yet some fall units in the Oruanui deposit have such extremely wide dispersal that they plot beyond all known examples of "dry" fall deposits. This contradiction between implications of low column height (and vigor?) from existing models and improbably high columns implied from dispersal characteristics of the Oruanui ash-fall beds suggests that other factors such as unusually rapid expansion of, or significant internal turbulence within, the eruption ash clouds must be invoked. These factors have to be considered before accurate modelling can be made of "wet" eruption columns and assessment made of the resulting threats to aviation.

EFFECTS OF VOLCANIC ASH ON AIRCRAFT POWERPLANTS AND AIRFRAMES

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This article is about the use of and the effects on aircraft used as a research platform to penetrate and sample volcanic eruptions. The article will discuss fouled plugs, oil sample analyses, and damage to the windscreen, airframe, and rotating equipment. The plane used for research was a Beechcraft Queen Air Model B-80 powered by two Lycoming IGSO-540 reciprocating engines. Two trips were made to Central America to sample three active Guatemalan volcanos, one in February 1978, and again in February 1980. On March 26, 1980 Mount St. Helens became active, the aircraft was re-instrumented, and on April 2, 1980, ferried to Portland for research flights through Mount St. Helens' plumes. There was considerable information available about the contents of volcanic eruptions, but little was known how direct sampling would effect aircraft performance and materials. On February 10, 1978, the volcano Fuego erupted, and the first direct flight through a dense volcanic cloud was accomplished. Thirty hours of flight time was logged during the 1978 program with an estimated 3-5 hours of flight in various types of ejected volcanic material. In 1980, between the Central America and Mount St. Helens projects another forty to fifty hours was flown with an estimate of 4-5 hours in volcanic-ash clouds of varying density.

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