The world’s busy air traffic corridors pass over or downwind of hundreds of volcanoes capable of hazardous explosive eruptions. The risk to aviation from volcanic activity is significant—in the United States alone, aircraft carry about 300,000 passengers and hundreds of millions of dollars of cargo near active volcanoes each day. Costly disruption of flight operations in Europe and North America in 2010 in the wake of a moderate-size eruption in Iceland clearly demonstrates how eruptions can have global impacts on the aviation industry. Airborne volcanic ash can be a serious hazard to aviation even hundreds of miles from an eruption. Encounters with high-concentration ash clouds can diminish visibility, damage flight control systems, and cause jet engines to fail. Encounters with low-concentration clouds of volcanic ash and aerosols can accelerate wear on engine and aircraft components, resulting in premature replacement. The U.S. Geological Survey (USGS), in cooperation with national and international partners, is playing a leading role in the international effort to reduce the risk posed to aircraft by volcanic eruptions.

In cooperation with national and international partners, the U.S. Geological Survey (USGS) Volcano Hazards Program is playing a leading role in the global effort to reduce the risk of aircraft encounters with ash through timely eruption forecasts and warnings, education about the hazard, and scientific investigation of volcanic processes and ash-cloud properties. Hundreds of active volcanoes around the globe have the potential to severely affect aviation operations, and each year dozens of these volcanoes erupt explosively. On a global basis, volcanic ash is a daily con-
cern to aviation. Volcanic ash clouds are carried by prevailing winds and can drift in different directions at many flight levels for thousands of miles from the erupting volcano. The hazard is complicated by the fact that ash and aerosol clouds from volcanoes can remain aloft at cruise altitudes for days to weeks. These clouds are difficult to distinguish visually from weather clouds and are invisible to air traffic control and aircraft radar. Volcanic activity can also have serious impacts on low-altitude aircraft and on airport operations.

**Hazards and Risks**

Volcanic ash consists of small (less than 2 mm or 0.08 inch across) solid, sharp-edged fragments of quickly cooled volcanic glass and minerals blasted at high velocity into the atmosphere during explosive eruptions. This material is abrasive and melts at the high operating temperatures of modern jet engines. When ingested into a jet engine, volcanic ash erodes turbine blades, and the melted ash can adhere to critical parts, causing engine failure (“flameout”). Any forward-facing surface of an airplane engulfed in a volcanic ash cloud is likely to be eroded, including the cockpit and forward cabin windows and landing-light covers. Cockpit windows may become so abraded that pilots have a serious loss of forward visibility. Ash entering sensitive aircraft electronics can interfere with navigation and other onboard systems. As a result of electrical disturbances within the ash cloud, a flight crew may also lose the ability to transmit a distress call.

Sulfur and other gases released in large eruptions also affect aircraft and their occupants. Acidic aerosols formed by the hydration of these volcanic gases produce a corrosive mist that may cause respiratory problems for passengers and flight crews and accelerate deterioration of vulnerable aircraft components. Over a period of many years, such exposure can significantly increase aircraft maintenance costs. Chronic “degassing” of nearby volcanoes upwind of airports can also affect ground operations or even close airfields for years.

Volcanic ash and aerosol clouds above airports and ash falling on and near airports can be hazardous to aircraft on approach and departure, as well as to operations on the ground. Ash on runways reduces braking effectiveness of aircraft, and wet ash is extremely slippery. The fine particles can be resuspended by surface winds and air-

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**ONE AIRCRAFT’S HARROWING ENCOUNTER WITH VOLCANIC ASH**

For more than 4 terrifying minutes on December 15, 1989, a powerless Boeing 747 with 231 passengers aboard plunged in silence towards the rugged, snow-covered mountains 90 miles north of Anchorage, Alaska. Fine ash and a strong odor of sulfur filled the cockpit and cabin as the flight crew donned oxygen masks and initiated emergency procedures to restart all four engines, which had flamed out when the aircraft inadvertently entered an eruption cloud from Redoubt Volcano 150 miles away. Radio transmissions to Anchorage Air Route Traffic Control Center record the severity of the event:

“KLM 867, we have flame out... all engines....and we are descending now.”

“KLM 867 heavy, we are descending now....we are in a fall!”

Although the crippled jet’s engines were restarted, and it ultimately landed safely in Anchorage, it suffered more than $80 million in damage ($140 million in today’s dollars, about half the price of a new Boeing 747). This incident was another “wake-up call” to volcanologists, industry representatives, and aviation officials worldwide. Following this encounter, coordinated efforts to address the hazard of airborne volcanic ash and implement more effective detection tools and warning systems around the globe accelerated.

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Glassy—melted and then resolidified—volcanic ash adheres to the leading edge of a high-pressure-turbine stage-1 nozzle guide vane inside a jet engine that encountered a volcanic ash cloud at 25,000 feet. The patch of dark glass shown here is about 1 inch across. (Photo courtesy of General Electric.)

KLM Flight 867 after landing safely.
Volcanic ash falling on and near airports is a hazard to aircraft on approach and departure, as well as to operations on the ground. Ash accumulation of more than a trace amount (~1 mm or the thickness of a dime) requires complete removal for airports to resume full operations. Ash does not simply blow away and disappear; it must be disposed of in a manner that minimizes remobilization by wind and aircraft. Case studies of cleanup methods are online at http://www.avo.alaska.edu/pdfs/cit2773.pdf. Recommended procedures for the protection and cleanup of ash-contaminated airports are given by the International Civil Aviation Organization (ICAO) in the Manual on Volcanic Ash, Radioactive Material, and Toxic Chemical Clouds (Document 9691-AN/954, 2002), available online at http://www2.icao.int/en/annex/met-aim/met/iaawpsg/Documents/Forms/Allitems.aspx.
Volcano observatories are a source of important hazard information for aviation users. Airlines can use warnings of impending or ongoing volcanic activity to select safe and efficient routes that avoid ash-contaminated airspace. Aviation Color Codes are used by all U.S. Volcano Observatories to indicate the status of volcanoes and are recommended for use worldwide by the International Civil Aviation Organization (ICAO).

<table>
<thead>
<tr>
<th>Color</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GREEN</td>
<td>Volcano is in typical background, noneruptive state or, after a change from a higher level, volcanic activity has ceased and volcano has returned to noneruptive background state.</td>
</tr>
<tr>
<td>YELLOW</td>
<td>Volcano is exhibiting signs of elevated unrest above known background level or, after a change from a higher level, volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.</td>
</tr>
<tr>
<td>ORANGE</td>
<td>Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, or eruption is underway with no or minor volcanic-ash emissions [ash-plume height specified, if possible].</td>
</tr>
<tr>
<td>RED</td>
<td>Eruption is imminent with significant emission of volcanic ash into the atmosphere likely or eruption is underway or suspected with significant emission of volcanic ash into the atmosphere [ash-plume height specified, if possible].</td>
</tr>
</tbody>
</table>

Volcano observatories are a source of important hazard information for aviation users. Airlines can use warnings of impending or ongoing volcanic activity to select safe and efficient routes that avoid ash-contaminated airspace. Aviation Color Codes are used by all U.S. Volcano Observatories to indicate the status of volcanoes and are recommended for use worldwide by the International Civil Aviation Organization (ICAO).

**EDUCATION AND COORDINATION**

To inform the aviation industry and flight crews about the hazards of volcanic ash, the International Civil Aviation Organization (ICAO) has produced a variety of educational and resource materials, including the poster below. In addition, professional aviation organizations, such as the Air Line Pilots Association, have also made a sustained effort to promote understanding of the hazard and methods of ash avoidance—http://www.alpa.org/Portals/Alpa/VolcanicAsh/VolcanicAsh.htm. Scientists with the USGS Volcano Hazards Program also give briefings to pilots, dispatchers, controllers, and others in order to familiarize the aviation community with volcano monitoring, hazards, and warning systems. In addition to the education of aviation personnel, effective coordination among volcano observatories, air traffic control authorities, and aviation meteorology services is essential to reduce aircraft encounters with ash clouds.
(continued from page 3) To address this, a consortium of pilot organizations, the FAA, aircraft manufacturers, and other aviation interests have developed and promoted operating procedures for flight crews whose planes inadvertently enter a volcanic ash cloud. This guidance is now part of flight crew training and emergency checklists for many airlines.

During a volcanic eruption, flight crews are important partners in disseminating warning information to keep aircraft safe. Often pilot reports are the first direct observations of a volcanic event. Details of such observations are of great help to volcanologists trying to interpret data from distant eruptions and to meteorologists and aviation managers who issue warnings and may have to restrict air space. Flight crews can greatly assist in these efforts by relaying key descriptive information contained in the Volcanic Activity Report Form (VAR) to air traffic control (ATC) centers.

Communicating the Hazard—The Aviation Color Code and the VONA

Volcano observatories provide important volcano hazard information for meteorological and aviation authorities who are responsible for issuing SIGMETs (advisories of Significant Meteorological information), NOTAMs (Notices To Airmen), and other warning products. Airlines can use warnings of impending or ongoing volcanic activity to select safe and efficient routes that avoid ash-contaminated airspace. In 1990, USGS scientists at AVO developed a four-color alert system for volcanic activity. This system was used to quickly inform the aviation community about the severity of hazard and level of activity at a volcano. ICAO has adopted a modified version of this color code system as the recommended guideline for volcano observatories worldwide. A change in the color code (either up or down) or a significant change within a color code prompts USGS volcano observatories to issue a specialized message for aviation users called a VONA—Volcano Observatory Notice for Aviation—that summarizes hazard information for pilots, aviation managers, controllers, and dispatchers in concise text.

VOLCANIC ASH ADVISORY CENTERS (VAAC)

Because volcanic ash clouds travel long distances, official response to an ash-cloud threat must be coordinated internationally. Under the auspices of the World Meteorological Organization (WMO) and the International Civil Aviation Organization (ICAO), nine regional Volcanic Ash Advisory Centers (VAACs) provide advisories to international Meteorological Watch Offices (MWOs) about the location and movement of ash clouds. The VAACs are located in Anchorage, Buenos Aires, Darwin, London, Montreal, Toulouse, Tokyo, Washington, D.C., and Wellington. VAACs use volcano-observatory reports, pilot reports, geostationary and polar-orbiting satellite data, and ash-dispersion models as the bases for their advisories. As an ashcloud drifts downwind, responsibility for issuing advisories generally passes from one VAAC to the next. The map shows volcanoes of the world (red triangles), areas of responsibilities for VAACs, and simplified major global air routes (white lines). Dotted regions are not covered by any VAAC because of satellite or other infrastructure limitations.
The Future

The worldwide growth of air traffic, especially in volcanically active regions such as the Pacific Rim, means that volcanic ash will remain a serious hazard to aviation. Furthermore, the expected introduction of “free-flight” air traffic operations by the FAA and increased use of twin-engine aircraft across remote areas of the planet (areas having few alternate landing sites) make timely detection and reporting of eruptions, ash-cloud movement, and anticipated ash fall essential to flight safety. The 2010 Icelandic eruption highlighted this and many other remaining challenges facing safe and efficient aviation operations during an explosive volcanic event.

Keys to reducing the risk to aviation are (1) increased ground-based volcano monitoring (only a very small percentage of volcanoes that threaten aviation are currently considered well-monitored with modern instrumentation) and improved eruption forecasts; (2) development of new and improved tools and techniques to detect, track, and characterize volcanic clouds that are a hazard to aviation; (3) improved forecasting of ash-cloud movement and expected ash fall; (4) research and education to better quantify and build awareness of the hazard; and (5) refinement of protocols to ensure rapid communication of ash-hazard warnings to flight crews. Scientists in the USGS Volcano Hazards Program are continuing to work with national and international partners to accomplish these goals and improve flight safety and efficiency around the world.

REMOTE SENSING OF VOLCANIC ASH CLOUDS

Remote sensing by satellite is a powerful tool used to detect and quantify volcanic clouds, especially in remote areas of the globe. Volcanic clouds containing ash (mineral and glass fragments) and gases such as sulfur dioxide (SO₂) absorb energy from different wavelengths of the electromagnetic spectrum in different amounts than weather clouds—this allows satellite sensors to differentiate the various cloud constituents. Volcanic ash is detected by comparing the intensity of radiation at two thermal infrared wavelengths, creating images of “brightness temperature difference,” while SO₂ is typically detected using several wavelengths of ultraviolet energy. Limitations of these techniques are frequency of image acquisition (geostationary satellites provide images approximately every 15 minutes, but others may provide data only a few times a day), the amount of water vapor in the atmosphere, daylight (for ultraviolet satellite data), and masking effects of weather clouds for some sensors. New sensors developed in the past decade hold great promise for better real-time tracking and characterization of volcanic clouds.

Satellite images showing the usefulness of the thermal infrared brightness temperature-difference technique and the ultraviolet absorption technique for discriminating volcanic ash and SO₂, respectively, in volcanic clouds that are physically mixed and visually indistinguishable from weather clouds. These images from August 2008 show an ash cloud from Alaska’s Kasatochi Volcano over the northern Pacific, about 2 days after the eruption. Shorelines (red) are enhanced for reference. A shows a thermal infrared brightness-temperature image. B is an enhanced image showing volcanic ash detected using a two-wavelength thermal infrared brightness temperature difference. C shows the corresponding SO₂ cloud as indicated by the ultraviolet wavelength absorption technique. (Images processed by D. Schneider, USGS.)