Assessment and Characterization of Volcanic Ash Threat to Gas Turbine Engine Performance

Craig R. Davison
Gas Turbine Laboratory,
National Research Council Canada,
1200 Montreal Road,
Ottawa, ON K1A 0R6, Canada
e-mail: craig.davison@nrc-cnrc.gc.ca

Timothy A. Rutke
Gas Turbine Laboratory,
National Research Council Canada,
196 Forsyth Road,
Newmarket, ON L3Y 7Y1, Canada
e-mail: timrutke@gmail.com

Multiple volcanoes erupt yearly propelling volcanic ash into the atmosphere and creating an aviation hazard. The plinian eruption type is most likely to create a significant aviation hazard. Plinian eruptions can eject large quantities of fine ash up to an altitude of 50,000 m (164,000 ft). While large airborne particles rapidly fall, smaller particles at reduced concentrations drift for days to weeks as they gradually descend and deposit on the ground. Very small particles, less than 1 μm, can remain aloft for years. An average of three aircraft encounters with volcanic ash was reported every year between 1973 and 2003. Of these, eight resulted in some loss of engine power, including a complete shutdown of all four engines on a Boeing 747. However, no crashes have been attributed to volcanic ash. The major forms of engine damage caused by volcanic ash are: (1) deposition of ash on turbine nozzles and blades due to glassification (2) erosion of compressor and turbine blades (3) carbon deposits on fuel nozzles. The combination of these effects can push the engine to surge and flame out. If a flame out occurs, engine restart may be possible. Less serious engine damage can also occur. In most cases the major damage will require an engine overhaul long before the minor damage becomes an operational issue, but under some conditions no sign of volcanic ash is evident and the turbine cooling system blockage could go unnoticed until an engine inspection is performed. Several organizations provide aircrew procedures to respond to encounters with a volcanic ash cloud. If a volcanic ash encounter is suspected, then an engine inspection, including borescope, should be performed with particular attention given to the turbine cooling system. [DOI: 10.1115/1.4026810]

Introduction

Volcanic ash is propelled into the atmosphere during eruptions that can occur with little or no warning. The ash can damage aircraft engines, windshields, probes, and lubrication systems. Volcanic ash bears no resemblance to the ash that is produced by combustion of organic products. However, it is similar to sand and dust and some of the prior knowledge in those domains can be transferred.

The first significant reported commercial encounter of an aircraft with a volcanic ash cloud was a British Airways Boeing 747 in 1982 near Galunggung, Indonesia. The aircraft experienced a loss of engine power, problems with airspeed indication, and abrasive damage that obscured the windshield. A new 747 encountered volcanic ash from the Redoubt volcano in Alaska in 1989. It experienced a flame out on all four engines within 80 s of entering the ash cloud but was able to restart and land safely. The estimated repair cost was $\$80 \times 10^6$.

These encounters occurred close to the erupting volcano within a short time of initiation. At the other end of the spectrum is clear air, but in between is a range of conditions with uncertain effects on aircraft. Civil aviation has taken an approach of not flying in visible ash, which some organizations have set at 2 mg/m^3. Visible ash is hard to define and depends on atmospheric conditions and particle size. For military applications a higher level of risk may be acceptable depending on the mission required.

The April 2010 eruption of Eyjafjallajökull in Iceland, shown in Fig. 1, and the subsequent shut down of European air space moved the potential danger of volcanic ash to the forefront of discussion. Civil aviation is driven by profit to determine the level of ash that can be tolerated. This includes both aircraft safety and increased maintenance costs. The military, however, has missions of differing levels of importance. In some cases, any additional damage and resulting cost is not worthwhile and the mission can be delayed or cancelled, but in some situations even the scrapping of an aircraft may be acceptable if the mission is successfully completed and the pilot returns safely.

Engine tests have been performed at high particulate concentrations, but to date little data are available on engine tests at mid to low concentrations. However, NASA is leading a partnership that includes the United States Air Force, the Federal Aviation Administration (FAA), and industrial members in preparing for an on-wing ash ingestion test of a F117-PW-100 engine.

To understand the issues of volcanic ash and its effect on turbine engines a basic understanding of the relevant volcanology is required. The first part of this paper presents the types of volcanoes, chemical composition of ash, estimated dispersal rates, and expected particle sizes and concentrations. Subsequently, the effects of ash on gas turbine performance are presented. This includes literature on inflight experiences and engine testing. Finally, recommended actions when encountering an ash cloud are summarized from the open literature. This paper is a condensed version of a more extensive literature survey completed for the Canadian Department of National Defense [1].

Volcanology

Volcano Activity. The solid surface of our planet is made up of noncontinuous tectonic plates, which move relative to one another. The boundaries of these plates form less stable regions that are more prone to earthquakes and volcanoes. Figure 2 shows the major tectonic plates and volcanoes around the world. Most of

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Fig. 1 Eyjafjallajökull erupting in April 2010 [2]

the volcanoes form along the plate boundaries. At convergent plate boundaries, one plate is pushed down under the adjoining plate were it is melted back into the core and is referred to as a subduction zone. The Aleutian Trench, seen in Fig. 2, is one example. At divergent plate boundaries, such as the Mid-Atlantic Ridge, two plates move apart and new crust is formed to fill the ensuing gap. The Icelandic volcanoes are a result of this action. At a transform fault two plates slide horizontally past each other. The San Andreas fault zone in California is an example of this type.

Geologists have identified approximately 1500 volcanoes above water that have erupted in the last 10,000 years. An even larger number have erupted under the sea and have not been identified. Between 10 and 15 volcanoes are continually erupting above water, and these are periodically joined by others. During the 1990 s, 50–60 volcanoes erupted every year. Many eruptions occur with little or no warning, and it is difficult to predict, even once started, if they will produce a significant ash cloud [3].

Not all volcanoes are equal in their production of ash that would create a hazard to aviation. A summary of the major volcanic eruption types is provided in Table 1. Important characteristics include the eruptive plume height, which is the height that the volcanic debris is projected into the atmosphere, the amount of fine debris, and the dispersal area, which is how far the debris is spread.

Figure 3 provides images of eruption types and typical plumes. Clearly, many of the eruption types produce significant quantities of small debris that are projected up to the flight altitude of transport aircraft. Walker [4] defines fine ash as having a diameter less than 63 μm and dust less than 4 μm.

To affect operations on a large scale the eruption needs to be of the plinian type, as the effect of others is only local or regional. The vulcanian and surtseyan eruptions could disrupt operations in the vicinity of the eruption but should be easy to avoid. However, missions with an objective in the vicinity of this type of volcano could be affected. Finally, strombolian and Hawaiian eruptions pose no threat to aviation.

The ejecta of interest from an aviation perspective are the ash and dust. The fume is also a concern since it may contain sulfur in high enough concentrations to accelerate engine corrosion. The smell can also enter the flight deck and provide a warning of entry into a volcanic cloud, as reported by a C-130 aircrew as they entered the ash cloud generated by Mount St. Helens on May 25, 1980 [5]. However, at higher concentrations the smell disappears due to olfactory fatigue. Therefore the smell should only be relied upon as a sign of entry into a volcanic ash cloud, but the subsequent absence of the smell should not be taken as evidence that the cloud has been exited [6].

Ash Dispersal. Ash dispersal from volcanic eruptions is dependent on a variety of factors. The eruption type, described above, and the energy level within the type will determine the height to which the ash is projected and hence the distance it will travel. The eruption type also effects the particle size distribution,

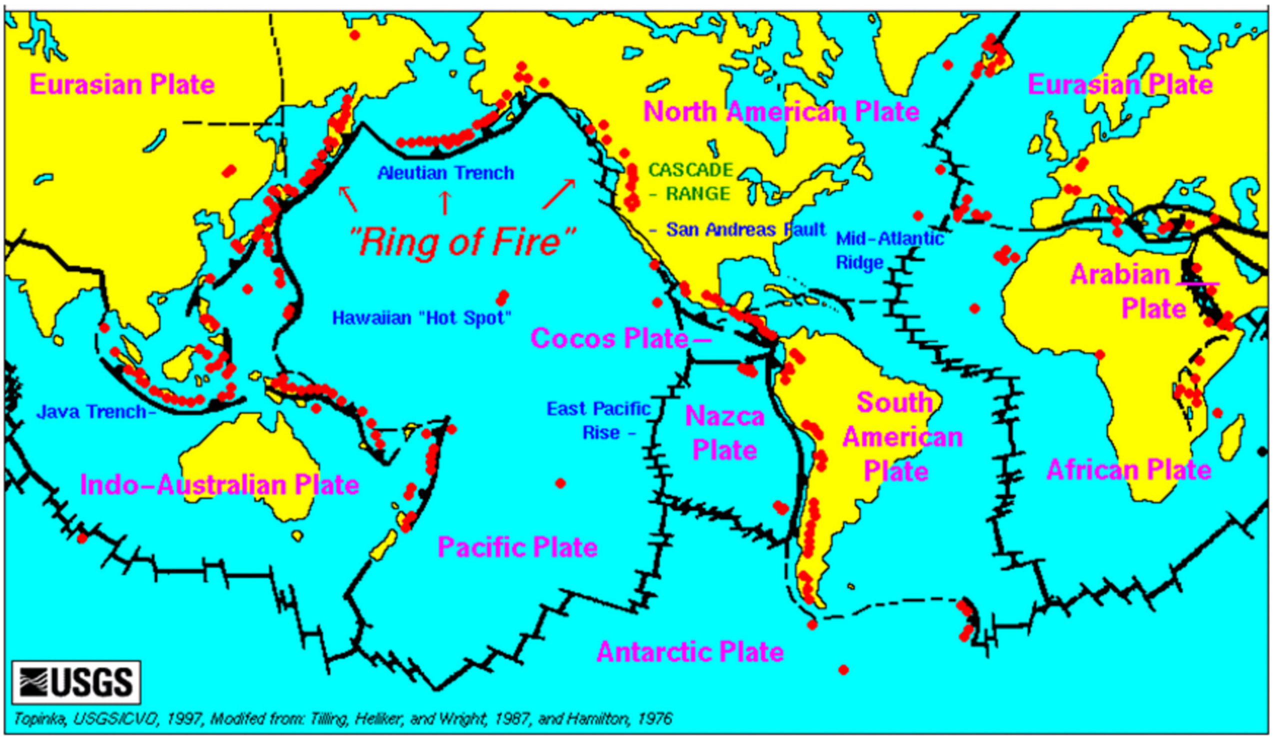

Fig. 2 World map showing volcanic "hot spots" (red dots) and tectonic plate boundaries (black lines) [7]

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Table 1 Explosive eruption types and their products[a]

Eruption type	Eruption column height (km)	Area affected by ash fallout (km^2)	Size of particles	Potential aviation hazard
Plinian	10–40	100–10,000 s	cm–μm	High; large regions
Plinian-hydrovolcanic	20–50	10,000–100,000 s	mm–μm	High; large regions
Vulcanian	0.3–3	10–100 s	mm	High locally; medium regionally
Strombolian	0.1–2	0.5–5	cm–mm	Low
Hawaiian	<0.1–0.5	up to 0.5	cm–mm	Low
Surtseyan	0.3–2	1–200	mm–μm	Medium locally

[a]Reference [8].

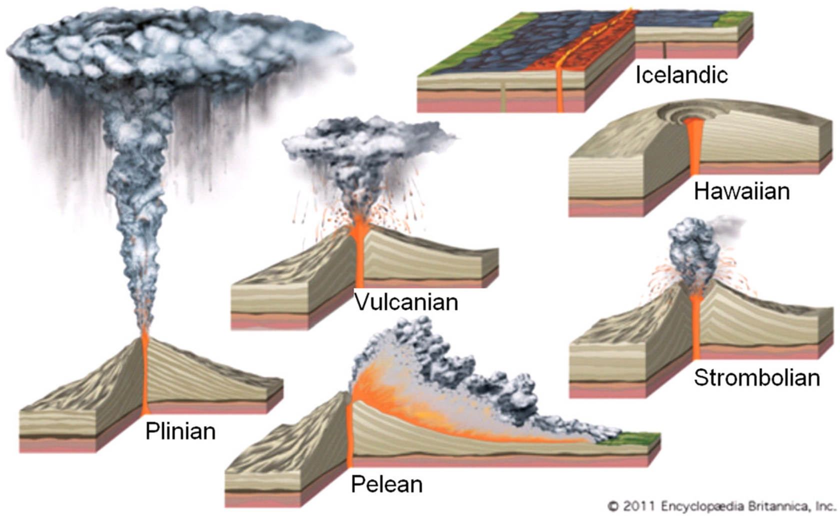

Fig. 3 Major types of volcanic eruptions and associated plumes [9]

which influences how long the particles remain aloft. Weather patterns direct the motion of the ash cloud and, at lower altitudes, rain may wash it out. Another factor is agglomeration of particles, which increases the rate of descent. At large distances from the eruption and at aircraft cruise altitudes the ash particle size will be less than 10 μm.

Gabbard et al. [5] presented a descent rate for ash particles but did not account for wash out or agglomeration and did not extend the analysis down to very small particles. After one day any particles greater than 50 μm initially ejected to a height of 20 km were predicted to have reached the ground. However, very small particles, approximately 0.3–0.5 μm, have been found to stay aloft for at least a year [10].

Volcanic cloud evolution can be broken into three stages [11]:

(1) High energy and growth: this is during and until a few hours after the eruption. The ash clouds resemble thunderstorms and most of the coarse material, greater than 50 μm diameter, falls out.
(2) Rapid physical and chemical changes: this occurs for approximately one day. Fine particle size concentrations decrease rapidly by at least an order of magnitude, likely due to aggregation or accretion of ice. Ice accretion is indicated by an increase of particle radii in the first 36 h after eruption and aggregation is assumed because the settling rates of the original particles are far too slow to explain the rate of fine ash decrease.
(3) Drifting aircraft hazard: this lasts for 3–5 days and can cover thousands of kilometers. Ash concentrations slowly decrease until they are below sensor limits.

The sulfur dioxide that often accompanies ash clouds remains in the atmosphere much longer, therefore the sulfur smell may not indicate the presence of ash particularly more than 10 days post eruption. Another point of interest is that large eruptions tend to have faster ash fall out, due to eruption plume dynamics, more electric charge leading to increased aggregation and higher plumes leading to more ice accretion [11]. The most immediate hazard with the largest potential for engine shut downs occurs during stage 1, especially since the eruption may be unreported at this time. Stage 3 is less likely to cause engine shutdowns but could cause undetected engine damage as an aircraft could fly unknowingly through it.

Bursik et al. modeled ash dispersal and looked at factors including particle size, wind speed, plume height, and aggregation [12]. This paper provides a basis for modeling ash dispersal. Not surprisingly, increased wind and plume height increased the dispersal distance while increased particle size and aggregation decreased it. Figure 4 gives their results and indicates that relative to the initial concentrations 4 μm particles can still be a significant factor 1000 km from the volcano. Such plots provide guidance only as the wind direction and initial conditions in the eruption strongly influence the dispersal.

During major eruptions forecasts are produced of volcanic ash location and altitude for use by the aviation community. Forecasting and even now-casting the location and concentration of ash clouds is still a challenging proposition. Servranckx and Chen break the problem down into three distinct components [13]:

(1) Volcanic ash source—this includes the quantity, and size distributions of the ash in both the horizontal and vertical directions. Large uncertainties often exist in this data.
(2) Meteorology—this uses standard weather prediction models. Horizontal resolution of these models is often not good but is important for ash deposition prediction and planning

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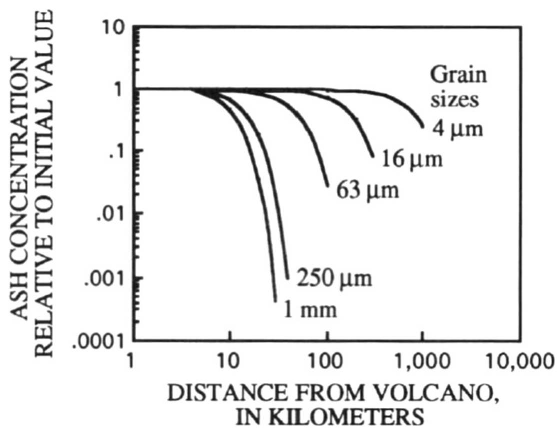

Fig. 4 Modeled ash dispersal in the absence of wind and aggregation for a plume height of 22.8 km [12]

aircraft routes. Parameterization also generates errors by applying simplifying assumptions particularly to small scale phenomena.

(3) Transport and dispersion—combines the inputs from the previous two components to displace and deposit the ash using the relevant removal and deposition mechanisms. All the above errors propagate into this section and are exacerbated by the different space and time grids used by the models.

Only a few of the modeling limitations are presented above and the reference should be consulted for a more in-depth discussion, but it is clear that a large degree of uncertainty exists in predicting even current ash conditions.

This uncertainty creates several problems. In the initial phase of the eruption it may not have been reported or detected, and aircraft may fly unknowingly into high concentrations of volcanic ash, causing engine flame outs. In a short period of time the ash cloud in the immediate vicinity of the volcano will usually be identified and the region avoided. Further out from the volcano, as the ash disperses, the uncertainty increases and determining a safe fly zone, even if a safe concentration level is well defined, becomes a difficult task.

Not only are attempts made to predict ash cloud locations and properties but they are also observed by satellites. Ash absorbs and scatters infrared radiation differently than clouds of ice or liquid water, allowing satellite imagery to assess ash concentrations. However, direct measurement of ash concentrations is hampered by water and ice coating the particles, the wide range of sizes, and the detection limits. In addition, satellites pass by at best every 15 min [14].

Chemical and Physical Morphology of Volcanic Ash. Volcanic ash particles vary in size, shape, chemical composition, and melting point. If the turbine inlet temperature (TIT) exceeds the melting point, then particles melt and can be deposited on the first stage turbine nozzles. The lower melting point of volcanic ash is 960 °C so a TIT below this should prevent deposition. In general the higher the silicate (SiO_2) concentration the higher the melting point [15]. Above 1177 °C an increase in the calcium content will increase the deposition making this another important element in determining the threat of a ash cloud [16].

A comparison of the chemical composition of volcanic ash and sand was performed based on compositions available in the literature [15,17,18] and presented by Davison and Rutke [2]. SiO_2 was the major constituent in all the samples and ranged from about 50% to 78%. The variation in composition within the ash samples was large, almost matching the total variation across all types. Even the variation for a specific volcano during a particular eruption was significant. As the ash composition is unknown until well after the eruption has occurred it is safest to assume the worst case of lowest melting point, which adversely affects the turbine, and the hardest, most erosive ash, which is worse for the compressor.

The comparison between ash and sand was close; indicating that some of the experience and knowledge gained with sand could be transferred to volcanic ash. The chemical composition of Arizona road dust and the ash from early in the 1989 eruption of Redoubt was very similar. SiO_2 differed by 1%, and Al_2O_3, CaO, MgO, and Fe_2O_3 by less than 1% [15,18]. Ash particle size ranges from submicron to millimeters in diameter. Ash hardness is typically 5.5 on Moh's scale but spans 2–7 [8]. Depending on the stage of the eruption the greatest discrepancy in transferring knowledge from sand to ash is likely the particle size and engine type. Sand usually affects turboshaft engines used in helicopters and volcanic ash turbofans in transport aircraft.

Aircraft Encounters With Volcanic Ash

Between 1983 and 2003, 100 commercial aircraft unexpectedly encountered volcanic ash and 8 of these suffered some loss of engine power [19]. The International Civil Aviation Organisation (ICAO) has published an ash encounter severity index, reproduced here in Table 2. It ranges from 0, where no damage occurs to the aircraft up to 5, where the damage causes a crash. Since at least 1973 no crashes due to volcanic ash have been reported.

Encounter of a Lockheed Hercules (C-130) With Volcanic Ash From Mount St. Helens. Gabbard et al. [5] reported on a Lockheed Hercules, or C-130, encounter with an ash cloud from Mount St. Helens in May 1980. The aircraft was equipped with four T56 turbo shaft engines. The aircraft took-off 50 min after the eruption began and 12 min later, between 3660 and 3960 m (12,000 to 13,000 ft), the crew noticed a smell in the cockpit. The engines were set to climb power and were reported normal. The captain reported seeing a "big cloud ahead of us and it goes way up." It was gray and looked more like a volcanic cloud than a weather cloud. Between 4570 m and 4880 m (15,000 and 16,000 ft) it got darker and the smell got stronger and at 4880 m (16,000 ft) the captain reported that he thought the smell was due to volcanic ash. The crew later reported the ash reduced the visibility in the cockpit.

Table 2 Ash encounter severity index[a]

	Criteria
0	Acrid odor (e.g., sulfur gas) noted in cabin Electrostatic discharge (St. Elmo's fire) on windshield, nose or engine cowls No notable damage to exterior or interior
1	Light dust in cabin; no oxygen used Exhaust gas temperature (EGT) fluctuations with return to normal values
2	Heavy cabin dust; "dark as night in cabin" Contamination of air handling and air conditioning systems requiring use of oxygen Some abrasion damage to exterior surface of aircraft, engine inlet and compressor fan blades Frosting or breaking of windows due to impact of ash Minor plugging of pitot-static system; insufficient to affect instrument readings Deposition of ash in engines
3	Vibration of engines owing to mismatch; surging Plugging of pitot-static system to give erroneous readings Contamination of engine oil hydraulic system fluids Damage to electrical system Engine damage
4	Temporary engine failure requiring in-flight restart
5	Engine failure or other damage leading to crash

[a]Reference [20].

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After 2 or 3 min, engine 4 began to stall and surge. The engine became uncontrollable and was shut down. Two minutes later engine 2 also surged and was shut down. At this time the captain started to descend. The aircraft soon cleared the cloud and the power on engines 1 and 3 was reduced. The aircraft landed 9 min after engine 2 was shut down.

Damage and effects to the aircraft included:

- all three forward windshields were severely abraded and required replacement
- air conditioning system components required replacement
- inside of cowlings and cockpit were covered in fine particles and dust
- tail pipes were black and blue and the bottoms contained approximately a 250 ml (1 cup) of shiny black grains ranging in size from fine sand to small peas

Damage varied by engine but was not correlated to time since overhaul. Engine 4 had extensive deformation of the first stage turbine nozzles due to deposition and erosion. Second to fourth stage nozzles had eroded airfoils and the rotor blade tips, shown in Fig. 5, were also eroded away. All 14 compressor stages had foreign object damage and erosion. The front compressor seal had damage-induced grooves and the air inlet housing had cracks.

Engine 2 had similar damage to engine 4 and also exhibited wear on two fuel nozzle air shrouds. Engine 1 had over-temperature damage to the turbine with 20 cracked and burned first stage nozzles and 12 second stage. 102 of the first stage blades had burnt and eroded leading edges. The compressor also had to be replaced and damage to the combustor was reported. Engine 3 also had over-temperature damage to the turbine but the compressor had only light erosion and was the only component used on a subsequent flight. Some of the depositions were thicker than 4 mm (5/32 in.).

The ash analyzed from the engines was irregular in shape and ranged in size from 50 to 500 μm. The melting temperature was 1200–1400 °C and it appeared that it had not been exposed to temperatures above 1100 °C in the engine. The ash had a hardness of 5–6 on the Moh's hardness scale and was considered by Gabbard et al. to be typical volcanic ash [5].

Encounter of a Boeing 747 With Volcanic Ash From Redoubt. On December 15, 1989 Redoubt volcano experienced a major eruption that lasted approximately 1 h [21]. Fifteen minutes after the eruption finished a Boeing 747-400 with four General Electric CF6-80C2 engines, which are high bypass turbofans, levelled off, and entered a heavy ash cloud.

The aircraft entered a maximum power climb, based on the mistaken belief that they could get above the ash, and after 1 min had reached 8500 m (27,900 ft) when all engines decelerated. Engines 1 and 3 decelerated to subidle core rotor speed (N_2) while 2 and 4 went to 80% N_2 for 20 s before rolling back to subidle. The engine roll back was caused by HPC stall, which resulted from the reduction in the high pressure turbine (HPT) nozzle flow area due to a resolidification and buildup of ash on the leading edges and pressure surfaces of the nozzle guide vanes (NGVs). This caused a flow and efficiency reduction. The engines were shut down to initiate a restart, which lowered the temperature and the built up material became brittle. The subsequent thermal, pressure and velocity transients during the restart attempts dislodged some of the deposits until enough cleared to allow the engines to restart.

The maximum power climb elevated the TIT possibly exacerbating the problem of glassification and deposition on the turbine nozzles. In addition to the engine rollbacks, a false cargo fire warning light occurred. Engines 1 and 2 restarted at 5240 m (17,200 ft) after five or six attempts. Engines 3 and 4 restarted at 4050 m (13,300 ft) after eight or nine attempts. After the engines restarted the aircraft was able to land safely.

Post flight inspection of the engines reported by Przedpelski and Casadevall did not indicate any erosion of the low pressure system including the fan, booster, and low pressure turbine. Also, minor compressor erosion was noted in the mid and aft rotating stages. HPT blade tips were ground down by 1.5 mm (0.060 in.es). Stage 1 HPT shrouds had a build-up of hard material and the HPT blade pressure surfaces had deposits of a thin hard material. The HPT cooling circuits were not plugged but fine, powdery, unmelted ash built up in the HPT rotor cavities. An 8% flow area reduction and a 7% efficiency loss were estimated. The HPC erosion resulted in a 1% efficiency and surge margin decrease.

Based on the rate of build-up on the nozzles the ash concentration was estimated to be 2 g/m^3. The particle size in the air was typically 10–100 μm, but size accumulated in the HPT passages was 6–10 μm. Ash with a melting point of 1200 °C was considered responsible for the rapid build-up of deposits on the NGVs but constituents with higher and lower melting points were also found.

High Altitude Encounter of a DC-8-72 With Volcanic Ash. Grindle and Burchman [19] reported an encounter of a NASA research DC-8-72 aircraft with a diffuse volcanic ash cloud in February 2000. During the encounter the aircraft was equipped to perform airborne chemistry research. The engines were CFM56-2 turbofans with a maximum EGT of 870 °C.

The source of the ash was the Mount Hekla volcano in Iceland. Its eruption column reached 13.7 km (45,000 ft) high. The most northerly location of predicted ash was 73 deg N but the NASA pilots observed ash at 76°11′N. The encounter was 320 km (200 miles) north of the predicted ash boundary, 1500 km (920 miles) from the volcano and 35 h after the start of the eruption.

The encounter lasted 7 min and atmospheric sulfur dioxide (SO_2) rapidly climbed from near 0 to 0.8 parts per million by volume (PPMV). SO_2 is important as it can have long-term effects on engines by increasing the rate of corrosion. The aircraft monitored the particle diameter in the 12 nm to 1 μm range. The measured value was less than 1000 particles/cm^3 before and after the encounter but rose to a peak of 26,000 particles/cm^3 with an average of about 24,000 particles/cm^3 during the encounter.

During the encounter there was no change in cockpit readings, any odor, smoke or St. Elmo's fire. No stars were visible during the encounter but they reappeared at the conclusion. However, this was no different than flying through a high cirrus cloud. After landing an external visual inspection did not reveal damage to either the engine or aircraft. After the ash encounter, the research program was carried out and the aircraft accumulated an additional 68 h of use before returning home and being examined by a borescope. The borescope inspection revealed clogged cooling passages and heat distress in the high temperature sections. Subsequent overhaul revealed a fine white powder throughout the engines, clogged cooling air holes, leading edge erosion, ash

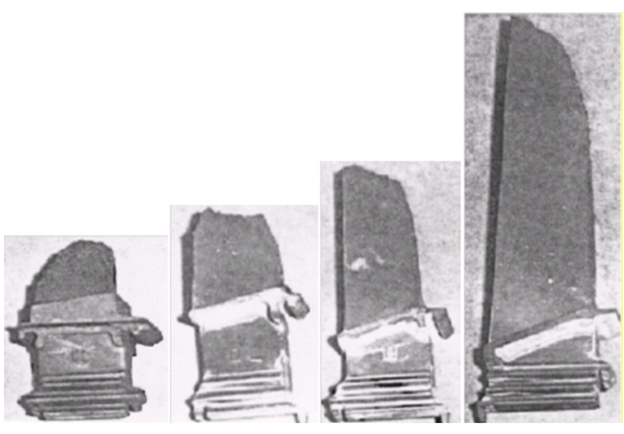

Fig. 5 First to fourth stage T56 turbine rotor blades after an encounter with Mount St. Helens ash cloud [5]

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buildup in cooling air passages, and blistered blade coatings. With the clogged cooling holes, remaining engine life may have been as little as 100 h, reduced from thousands.

Cruise snapshot data from each engine was taken on each flight and sent to the engine manufacturer for trending and analysis. After the ash encounter, the EGT was observed to drop slightly. This could be due to polishing of the compressor blades by the ash and the blocking of the cooling holes, which actually increases the overall engine efficiency by reducing the HPC bleed flow. Of course, the resulting elevated temperature of the turbine blades greatly reduces the engine life. Analysis of satellite data indicated that the ash particles may have been coated with ice, which would be less damaging to aircraft windscreens and leading edges, but the coating would melt in the engine exposing the hard ash. This may explain the damage found in the engine while the aircraft remained undamaged.

This encounter is important because without the research equipment on board there would have been no external evidence. Even a visual inspection of the aircraft failed to provide an indication of the damage that the engine had sustained. In addition, the engine damage was such that it did not reduce the performance but drastically reduced the life.

Major Effects of Volcanic Ash Ingestion and Mitigation of Damage in a Gas Turbine

The ingestion of volcanic ash into gas turbine engines causes damage through three major mechanisms: compressor erosion, fuel nozzle clogging, and ash deposition on the turbine NGVs. The rate and severity of the damage depend on the power level, particle concentration, particle size, and particle composition [22]. The engine type also affects the damage level. The following sections provide details on the three major damage mechanisms and correlations to engine operation.

Compressor erosion is caused by impacts of the volcanic ash particles with the blades and is dependent on the size and hardness of the ingested particles. Small volcanic ash particles closely follow the streamlines but large particles are more ballistic and impact intrusions in the flow, such as compressor stators and blades. These abrasive particles can initially polish the fan and compressor blades causing a slight efficiency increase in the compressor and engine, but at higher concentrations this quickly becomes detrimental erosion [19,23]. The polishing and subsequent erosion are more pronounced in the higher pressure stages [22]. Erosion of the compressor blades decreases the mass flow and efficiency and decreases the surge margin. Mitigation is limited to decreasing engine speed when encountering volcanic ash to slow the rate of damage accumulation.

Another effect of volcanic ash ingestion is material deposition in the fuel nozzle swirl vanes. During in-flight encounters [21] and stationary testing [22], the deposition of nearly pure carbon was observed. It is hypothesized that the carbon build-up is caused by a rich fuel to oxygen mixture due to the compressor system erosion [24]. These carbon deposits inhibit the atomization of fuel but not the total flow. Therefore, this deposition has a small impact on the steady engine performance but if the engine flames out it is extremely difficult to relight [20]. During flight, the fuel nozzles cannot be cleared of these deposits.

As the ash passes through the core of the engine, it can melt. The melting point for volcanic ash depends on silicate content and can be as low as 960 °C but is usually closer to 1100 °C. The TIT in modern aviation gas turbine engines often surpasses these temperature thresholds. Melting causes particles to agglomerate and adhere to surfaces which are impacted and this is often referred to as glassification. At low temperatures these deposits are brittle and can be easily removed by hand. The high pressure turbine NGVs are the first significant flow intrusions after the combustor, immediately followed by the HPT rotors. Consequently most of the glassification occurs in these locations as shown in Figs. 6 and 7. Glassification can also occur downstream of the first stage HPT, affecting multiple turbine stages. This was found during testing at the Calspan facility on a GE YF-101-100 engine [23].

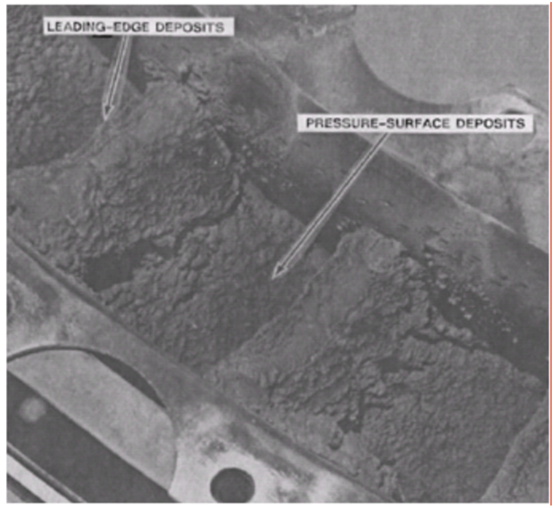

Fig. 6 Upstream view of first stage NGV deposits as a result of dust exposure (with black scoria) on a GE YF-101-100 engine [23]

The heaviest deposition occurs on the leading edges and pressure surfaces of the vanes, thus decreasing the throat area. The area reduction causes an increase in compressor discharge pressure (CDP) and reduces the flow rate of air through the core. The reduction in flow is approximately proportional to the decrease in throat area, since the flow is choked at this point. This is the dominant cause of surge margin reduction since at constant rotational speed surge margin is reduced as mass flow decreases. Surge causes erratic engine behavior, thrust loss, and flame outs.

A secondary effect is the cracking of the NGV trailing edges as a result of inadequate cooling due to material deposition on cooling holes shown in Fig. 7 [24]. This temperature effect has little impact on the immediate performance of the engine. The reduction in bleed air from the compressor, due to the clogged cooling holes, improves the performance, but the increased blade temperatures can reduce the engine life by an order of magnitude [19].

Dunn exposed a gas turbine engine, with a TIT of 1285 °C (2345 °F), to a 250 mg/m^3 simulated volcanic ash cloud, made up of black scoria, with a melting point of roughly 1100 °C [23]. All

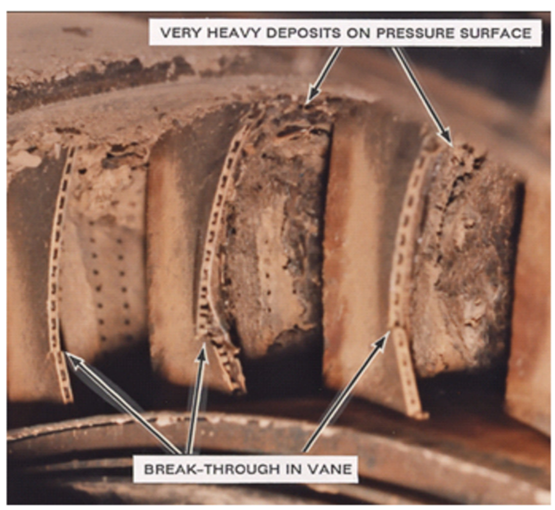

Fig. 7 Downstream view of first stage NGV deposits as a result of dust exposure (with black scoria) on a GE YF-101-100 engine [16, 23]

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the pressures and temperatures in the engine rose during the ash ingestion and the rate of pressure increase was approximately proportional to the dust concentration [24].

The response to the dust was immediate and reduced the fuel efficiency and surge margin. The fan turbine inlet temperature also increased, likely due to HPT efficiency loss and decreased airflow through the engine. The rate of occurrence of these detrimental effects was strongly dependent upon engine power setting, volcanic ash composition, and concentration.

The compressor pressure ratio increased during the dust exposure but appeared to level off as the test progressed. The shape of the pressure change curve was similar to the shape of a constant speed curve on a compressor map. The similarity of the two curves indicates that the pressure change was due to movement along the constant speed line as the mass flow was reduced. As the mass flow decreases a constant speed curve flattens out as it approaches the surge line. The pressure leveling off should not therefore, be taken as an indication that the rate of degradation is decreasing, but that the engine is approaching surge. When a similar test was repeated with a TIT of 1010 °C (1850 °F) which was below the melting point of the ash, the problems observed above were not seen [24]. The rate of deposition and therefore the approach to compressor surge was decreased to a level that would allow the safe return to an airport.

Dunn proposed a solution to deposition in the turbine to extend operation in volcanic ash while maintaining required thrust. To shed the deposited material and partially recover the surge margin, the engines can be "purged." A combination of temperature and pressure gradients, and ram air act to partially clear the engine. Shedding deposited material removes the NGV throat constriction which decreases the CDP and improves the surge margin. A purge cycle is performed by slowly reducing the PLA to idle position, dwelling for 30 s and advancing to full thrust. This process may have to be repeated multiple times for sufficient CDP recovery and should be done one engine at a time for multiengine aircraft. Operation was extended by approximately 13 min, but purging did not fully recover the performance and after the third purge the engine began to surge [24].

Increasing bleed airflow to all auxiliary systems can also delay the onset of surge by increasing the compressor mass flow, thereby decreasing the angle of attack of the compressor blades, and moving the operating point away from surge. However, increasing bleed airflow will also decrease power and increase hot end temperatures.

Minor Effects of Volcanic Ash Ingestion and Mitigation of Damage in a Gas Turbine

Minor damage mechanisms can contribute to engine failure, exacerbate the major damage mechanisms, and decrease the life of the effected components, but are less serious and require more time to cause an engine failure than the major damage mechanisms. Minor effects include material deposition in the cooling system, engine control system response, contamination of the lubrication, and environmental control systems.

Clogging of cooling holes in HPT blades and vanes can have a short term positive effect on engine performance as HPC bleed is reduced. This reduces the surge margin but increases the overall engine efficiency. However, the overheating of the nozzles and blades significantly reduces their lifetime from thousands to hundreds of hours [19].

Contamination of the cooling system is caused by the extraction of bleed air from the volcanic ash laden primary flow. Reports of cooling hole clogging without significant material deposition on NGVs and HPT blades from the contaminated core flow are uncommon but can result from exposure to low volcanic ash concentrations. The contaminants can become heated to over 500 °C in the HPC section of a modern engine. At these temperatures the silicates in sand and volcanic ash become sticky and can agglomerate [25]. A portion of the main flow contaminated with these sticky particles is bled to the hot section of the engine for cooling purposes.

Agglomeration and clogging of cooling holes due to volcanic ash is similar to that caused by sand particles. Larger particles, higher concentrations and lower melting points increase the amount of blockage that occurs. As observed previously these conditions vary between eruptions and even within a particular eruption. In addition, the particle size and concentration will decrease with time since the ash was suspended. Engine conditions that effect the rate of blockage include cooling air and metal temperatures, and the cooling method [25].

With the presence of both impingement and film-cooling, Cardwell assumed that the orifice diameters of both cooling methods were equal. Therefore, the impingement liner acts as a filter to screen out larger particles which would otherwise cause orifice obstruction in the film-cooling wall [25]. This filtration is the case for particle ingestion at ambient conditions. An increase in metal and particle temperature increases the probability of particle adhesion and therefore adherence to cooling orifices and impacted upstream surfaces In this case, particles which do not adhere to the upstream surface or obstruct the orifices of the impingement liner are carried into the hotter impingement cavity. The particles subsequently impact the upstream side of the film-cooling wall with a greater probability of deposition due to increased metal temperature of the film-cooling wall with respect to the impingement liner [25].

Under certain conditions, such as those encountered by a NASA DC-8-72 research aircraft and presented previously, this clogging can be the dominant damage mechanism in the hot section of the engine but engine parameters may not change sufficiently to identify the event. Since the immediate effect of this damage mechanism is minor and the conditions can result in no visible effect on the aircraft, the first evidence of a volcanic ash encounter is likely to be from a borescope inspection or engine oil analysis. If an aircraft has been operated near a volcanic ash cloud, an engine inspection may be warranted.

Higher volcanic ash concentrations for a prolonged duration result in major cooling reduction through internal cooling air passage blockage and external deposition, resulting in severe damage. Figure 7 illustrate the cracking of the first stage NGVs and blade burn-through, respectively, as a result of excessively high metal temperatures. The engine was exposed to contaminant ingestion for 180 min [23]. In these conditions, film-cooling was inhibited for stages beyond the first, material deposition may not occur due to the air temperature decrease as energy is extracted but the lack of film-cooling increases the metal temperature, thus reducing the material hardness and rendering it increasingly susceptible to erosion.

Technology likely exists to clean the cooling air but the performance penalty for an event that occurs so rarely is likely to be unacceptable. Filtering would impose a backpressure increase dependent on resultant flow blockage therefore inhibiting cooling air flow. An inertial particle separator could not separate a significant amount of the contaminant from the flow due to small particle size and relatively low particle mass and is impractical on a transport aircraft. The practical solution is to reduce the power level which achieves the following:

- reduces temperature at the compressor exit, therefore decreasing the probability of particle agglomeration within the cooling system, and particle deposition on cooling system internals
- decreases the overall amount of contaminant particles which are ingested, further decreasing the probability of forming a blockage within the cooling system

During ingestion of volcanic ash and increasing flow blockage in the NGV, air flow and turbine efficiency decrease, resulting in a drop in power available to the fan and compressor causing a drop in their rotational speed and pressure ratio. To compensate, the engine control system increases the fuel flow and therefore the TIT and EGT, resulting in increased rates of deposition in the hot

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section of the engine and decreased aircraft range [26]. Obviously if a temperature limit is reached the power output will be affected.

Volcanic ash also affects sensory equipment. Engine static pressure sensors are usually unaffected by volcanic ash ingestion, since they are nonintrusive and there is no net through flow. Conversely, the pitot-static probes mounted on the fuselage surface intrude into the flow and the total probe is prone to clogging by volcanic ash. This can impact the engine control system as modern engines have different control schedules depending on speed and altitude [20].

Thermocouples are contained in protective housings, which protrude into the engine airflow, making them susceptible to erosion and material deposition. Erosion of the housing has a trivial effect on the temperature reading but material deposition can obstruct orifices that allow sufficient airflow to achieve the required response time [5]. When the orifices are clogged and the flow reduced, a significant increase in response time results and transient engine operation can result in an overshoot of the temperature limit at the turbine. Control outputs by the engine control system, such as fuel flow, engine speed, stator vane position, etc. based on faulty sensor readings can result in exacerbated engine damage and possible surge in a volcanic ash contaminated environment [26].

Oil in the engine lubrication system may be contaminated by volcanic ash laden HPC bleed air used to pressurize the oil sump, a method which is extensively used in modern gas turbine engines. Particles larger than approximately 30 μm are filtered by one or multiple oil filters and in turn inhibit the flow of oil by increasing backpressure, causing oil to be diverted to the sump away from the bearings. This lack of oil may cause rapid increase in bearing temperature and wear as a result of friction. Particles smaller than 30 μm are able to pass through the filter to the lubrication system and bearings. As abrasive volcanic ash particles work their way into the bearings, they can cause excessive wear and erosion and may cause them to seize with prolonged exposure [23].

The environmental control system (ECS) is fed by bleed air from the HPC and is used for cabin pressurization, which provides breathing air for the flight crew and passengers, and to cool electronics. The contaminated air may also erode vital ECS plumbing, allowing the bleed air to escape the system [22]. Dependant on the location of the plumbing erosion, engine performance may be adversely affected.

Safe Operating Levels and Procedures

Commercial safe flight conditions in volcanic ash have been established under a preventative no-flight guideline and a reactive flight crew procedure in case of inadvertent volcanic ash contact. A forecasted volcanic ash concentration of greater than 2.0 mg/m^3 in the flight path or surrounding area may result in an alteration of the flight path or delay in the mission in order to prevent problematic exposure to volcanic ash. Rolls Royce presented volcanic ash flight envelopes, shown in Fig. 8 [27]. Operation within the red region of ash concentration and ingestion should be avoided as it can cause catastrophic engine failure due to the major damage mechanisms. Testing at the Calspan facility, and flights KLM 867 and BA9 encountered concentrations and rate of ingestion levels sufficiently high to cause short term failure, falling within the red region. The 2.0 mg/m^3 level is as a boundary for safe is still under discussion in the community and further study is required.

Due to the uncertainty of current ash diffusion modeling, an envelope of possible operation was established, denoted by the yellow region. In this envelope it is possible that minor damage mechanisms, such as clogged cooling orifices and minor compressor blade erosion may occur. Therefore, borescope inspection and engine oil analysis are recommended to assess the damage to an engine exposed to this type of environment.

Indications of a volcanic ash encounter include [5,20,28]:

- a smoky discoloration of ambient air
- St. Elmo's glow around the windshield and engine inlets
- acrid odor similar to ozone from electrical discharge
- sometimes sulfur smell
- fine dust appearing in the cabin
- landing lights cast sharp distinct shadows on the volcanic ash clouds. This is in contrast to the indistinct fuzzy shadows cast on water clouds.
- impaired vision through the windshield due to "sandblasting"

A set of procedures for pilots upon encountering volcanic ash was originally proposed at the First International Symposium on Volcanic Ash and Aviation Safety [28]. Currently these procedures are upheld by the International Civil Aviation Organization (ICAO) and are referred to by aircraft manufacturers, such as Boeing [29] and Airbus [30]. Subsets of these procedures are used by these aircraft manufacturers, where specific procedures may differ

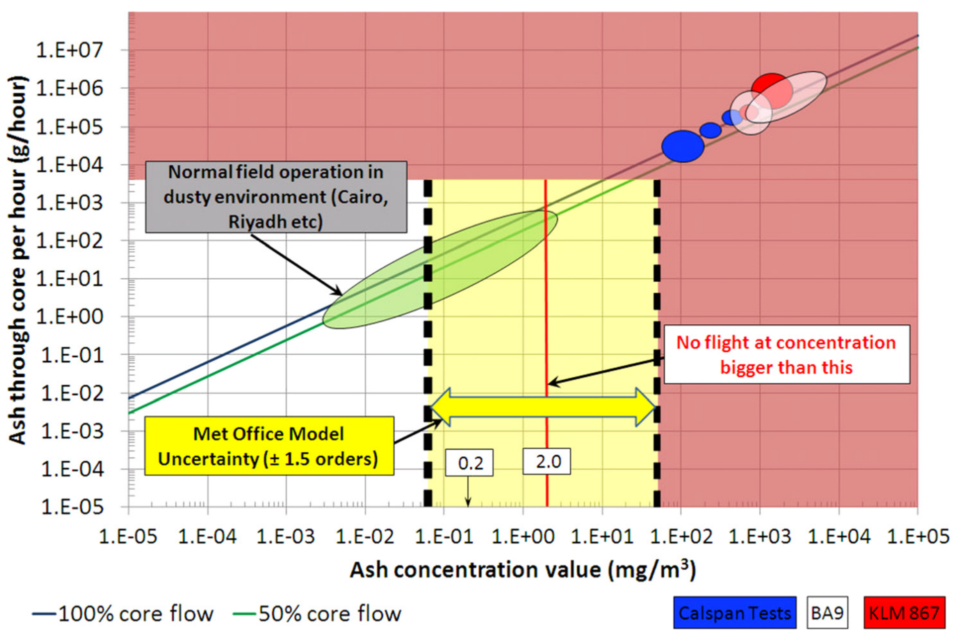

Fig. 8 Various incidents and current envelopes of operation in dust-laden environments from Rolls Royce, May 17, 2010 (adapted from [27])

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by aircraft avionics. The references above provide important details and the specific procedures provided by the aircraft manufacture should be followed, but the key actions include reduce engine power and exit the ash cloud. Often a 180° turn will be the most direct exit route. Attempting to climb above the cloud is not recommended as the cloud may be higher than the maximum flight altitude of the aircraft. The climb requires higher power which increases the ash ingestion and internal temperatures, both of which exacerbate the damage.

Recommended Maintenance. A detailed inspection of all engines on the aircraft including auxiliary power units is required upon landing after a volcanic ash encounter. Due to the range of engine damage possibilities, further aircraft and engine operation is not recommended prior to inspection. Inspection should not be delayed, as brittle deposits may dislodge from the NGV's and HPT blades resulting in a potentially nonrepresentative damage report.

A thorough borescope inspection of components indicative of the damage mechanisms given above should be conducted to assess the integrated damage to the engine. Inspection may require an engine teardown if the borescope results are deemed insufficient. During the borescope inspection particular attention should be given to the cooling holes since blockage can occur without effecting engine performance.

Engine oil change and analysis inclusive of sulfur should also be conducted, since volcanic ash exposure of any magnitude will show itself in terms of sulfur content [19].

Volcanic Ash Tolerant Engines

Modifications to make gas turbine engines more tolerant of volcanic ash generally decrease efficiency and increase emissions. High efficiency and decreased combustion emissions are achieved by reducing the engine core size, increasing pressure ratios, and increasing TITs [27]. A volcanic ash tolerant engine would feature the following:

- decreased TIT to decrease or inhibit the rate material deposition in the hot section of the engine
- decrease pressure ratios to decrease the contaminant particle concentration, thus decreasing the rate of material deposition in the hot section and the rate of erosion in the HPC section of the engine

Due to the infrequency of volcanic ash encounters it is very unlikely that engine manufacturers are going to adopt design criteria that would increase both operational cost due to increased fuel burn and emissions, making meeting new regulatory standards very difficult.

Summary and Conclusions

This report provided a brief introduction to volcanology and followed with a review of the effects of airborne volcanic ash on gas turbine engines and procedures to reduce damage. More details can be found in the report by Davison and Rutke [1] or by referring to the original sources. The primary effects caused by volcanic ash are:

(1) build-up of ash on first stage turbine guide vanes due to glassification
(2) erosion of compressor and turbine
(3) carbon deposits on fuel spray nozzles

In the short term these effects can lead to engine surge and flame out. Fortunately, engine restarts can shed deposits on the turbine which may allow the engine to relight, although multiple attempts may be required.

Secondary effects can degrade the engine and reduce its life. The blockage of turbine cooling passages has the potential to reduce the turbine blade life by an order of magnitude. To detect and quantify damage, a borescope inspection should be performed whenever it is suspected that the aircraft has encountered volcanic ash, even at low concentration.

If volcanic ash is encountered the aircraft manufacturers' procedures should be followed. These often include making a 180° turn and descending. Reversing course is often the shortest route out of the ash cloud and descending allows the engine power to be reduced. This reduces the TIT and ash deposition in the turbine.

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References

[1] Davison, C. R., and Rutke, T., 2012, "Assessment and Characterisation of Volcanic Ash Threat to Gas Turbine Engine Performance," National Research Council Canada, Ottawa, Canada, Report No. LTR-GTL-2012-0017.
[2] Adey, Alison, 2011, "Icelandic Volcano Sparks Ash Cloud Fears," Fabulous Travel Guide, http://fabulous travelguide.com/2011/10/volcano-katla-erupt-iceland/, accessed February 14, 2012.
[3] Wunderman, R., Siebert, L., Luhr, J., Simkin, T., and Venzke, E., 2004, "A Global Perspective on Volcanoes and Eruptions," 2nd International Conference on Volcanic Ash and Aviation Safety, Alexandria, VA, June 21–24.
[4] Walker, G. P. L., 1981, "Generation and Dispersal of Fine Ash and Dust by Volcanic Eruptions," J. Volcanology and Geotherm. Res., **11**(1), pp. 81–92.
[5] Gabbard, C. B., LeLevier, R. E., and Parry, J. F. W., 1982, "Dust-Cloud Effects on Aircraft Engines—Emerging Issues and New Damage Mechanisms," Defense Nuclear Agency, Washington, DC, Report No. DNA-TR-82-18.
[6] Wunderman, R., 2004, "Sulfurous Odors: A Signal of Entry Into an Ash Plume—But Perhaps Less Reliable for Escape," 2nd International Conference on Volcanic Ash and Aviation Safety, Alexandria, VA, June 21–24.
[7] Topinka, L., 1997, "Active Volcanoes, Plate Tectonics, and the 'Ring of Fire'," United States Geological Survey, Reston, VA, http://vulcan.wr.usgs.gov/Glossary/PlateTectonics/Maps/map_plate_tectonics_world.html, accessed February 17, 2012.
[8] Heiken, G., 1991, "Volcanic Ash: What It is and How It Forms," 1st International Symposium on Volcanic Ash and Aviation Safety, Seattle, WA, July 8–12, United States Geological Survey, Washington, DC, pp. 39-45.
[9] Encyclopædia Britannica, Inc., 2011, "Volcanic Eruption: Major Types," available at: http://www.britannica.com/EBchecked/media/3256/The-major-types-of-volcanic-eruptions
[10] Stothers, R. B., 2001, "A Chronology of Annual Mean Effective Radii of Stratospheric Aerosols From Volcanic Eruptions During the Twentieth Century as Derived From Ground-Based Spectral Extinction Measurements," J. Geophys. Res., **106**(D23), pp. 32043–32049.
[11] Bluth, G. J. S., and Rose, W. I., 2004, "Removal Process of Volcanic Ash Particles From the Atmosphere," 2nd International Conference on Volcanic Ash and Aviation Safety, Alexandria, VA, June 21–24.
[12] Bursik, M. I., Sparks, R. S. J., Carey, S. N., and Gilbert, J. S., 1991, "The Concentration of Ash in Volcanic Plumes, Inferred from Dispersal Data," 1st International Symposium on Volcanic Ash and Aviation Safety, Seattle, WA, July 8–12, United States Geological Survey, Washington, DC, pp. 19–29.
[13] Servranckx, R., and Chen, P., 2004, "Modeling Volcanic Ash Transport and Dispersion: Expectations and Reality," 2nd International Conference on Volcanic Ash and Aviation Safety, Alexandria, VA, June 21–24, pp. 3.1–3.5.
[14] Dehn, J., Webley, P., Cahill, C., and Peterson, R., 2011, "Remote Sensing Volcano Monitoring," TTCP Volcanic Ash Working Group Meeting 2011, Fairbanks, AK, August 22–25.
[15] Swanson, S. E., and Beget, J. E., 1994, "Melting Properties of Volcanic Ash," 1st International Symposium on Volcanic Ash and Aviation Safety, Seattle, WA, July 8–12, United States Geological Survey, Washington, DC, pp. 87–92.
[16] Dunn, M. G., 2012, "Operation of Gas Turbine Engines in an Environment Contaminated With Volcanic Ash," ASME J. Turbomach., **134**(5), p. 051001.
[17] Engelbrecht, J. P., McDonald, E. V., Gillies, J. A., "Jay" Jayanty, R. K. M., Casuccio, G., and Gertler, A. W., 2009, "Characterizing Mineral Dusts and Other Aerosols From the Middle East—Part 2: Grab Samples and Re-Suspensions," Inhalation Toxicology, **21**(4), pp. 327–336.
[18] Russell, J. A., Tosh, J. D., Newman, F. M., Greenberg, M. K., and Frazar, J. H., 1977, "Definition of Aviation Turbine Fuel Contamination Under Simulated Combat Conditions," Southwest Research Institute, San Antonio, TX, Report No. AFLRL-90.
[19] Grindle, T. J., and Burcham, Jr., F. W., 2003, "Engine Damage to a NASA DC-8-72 Airplane From a High-Altitude Encounter With a Diffuse Volcanic Ash Cloud," NASA, Report No. NASA/TM-2003-212030.
[20] ICAO, 2007, "Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds," 2nd ed., International Civil Aviation Organization, Montreal, Canada, ICAO Document No. 9691-AN/954.
[21] Przedpelski, Z. J., and Casadevall, T. J., 1994, "Impact of Volcanic Ash From 15 December 1989 Redoubt Volcano Eruption on GE CF6-80C2 Turbofan

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Engines," 1st International Symposium on Volcanic Ash and Aviation Safety, Seattle, WA, July 8–12, United States Geological Survey, Washington, DC, pp. 129–135.
[22] Dunn, M. G., and Wade, D. P., 1994, "Influence of Volcanic Ash Clouds on Gas Turbine Engines," 1st International Symposium on Volcanic Ash and Aviation Safety, Seattle, WA, July 8–12, United States Geological Survey, Washington, DC, pp. 107–118.
[23] Dunn, M. G., 1993, "Influence of Ingested Nuclear Cloud Dust and Overpressure Waves on Gas Turbine Engine Behavior," Defense Nuclear Agency, Alexandria, VA, Technical Report No. DNA-TR-93-2.
[24] Dunn, M. G., Baran, A. J., and Miatech, J., 1996, "Operation of Gas Turbine Engines in Volcanic Ash Clouds," ASME J. Eng. Gas Turbine Power, **118**(4), pp. 724–731.
[25] Cardwell, N. D., Thole, K. A., and Burd, S. W., 2010, "Investigation of Sand Blocking Within Impingement and Film-Cooling Holes," ASME J. Turbomach., **132**(2), p. 021020.
[26] Baran, A. J., and Dunn, M. G., 1994, "Response Models for the F101, TF33, and F107 Turbofan Engines to Dust Environments," Defense Nuclear Agency, Alexandria, VA, Technical Report No. DNA-TR-93-124.
[27] Emmott, P., 2010, "The Impact of Volcanic Ash on Aircraft Engines," Atlantic Conference on Eyjafjallajökull and Aviation, Keflavík, Iceland, September 15–16.
[28] Campbell, E. E., 1994, "Recommended Flight-Crew Procedures if Volcanic Ash is Encountered," 1st International Symposium of Volcanic Ash and Aviation Safety, Seattle, WA, July 8–12, United States Geological Survey, Washington, DC, pp. 151–157.
[29] Casadevall, T. J., and Murray, T. M., 2010, "Advances in Volcanic Ash Avoidance and Recovery," Boeing Commercial Airplanes Group, Seattle, WA, pp. 19–27.
[30] Airbus Flight Operations Support Services, 2006, "Flight Operations Briefing Notes: Operating Environment, Volcanic Ash Awareness," Airbus, Blagnac, Cedex France.

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