



# **VOLCANIC ASH TO FLY OR NOT TO FLY?**

Institution of  
**MECHANICAL  
ENGINEERS**

The Background Science  
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**THE ERUPTION  
OF EYJAFJALLAJÖKULL  
GROUNDED OVER  
100,000 FLIGHTS AND  
STRANDED 5,000,000  
PEOPLE AROUND  
THE WORLD.**

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This report has been written by a working party of Institution members in order to analyse the technical details behind the closures of airspace and to suggest what needs to be done to avoid similar difficulties in the future.

The Institution of Mechanical Engineers would like to thank the following for their time and contribution to this report:

**Professor Roderick A Smith FEng FIMechE**  
Imperial College London (Chairman)

**Dr Colin Brown FIMechE**  
Institution of Mechanical Engineers

**Dr Ricardo Martinez-Botas FIMechE**  
Imperial College London

**Peter Reading MIMechE**

**Stephen Tetlow MBE FIMechE**  
Institution of Mechanical Engineers

**Dr Peter Watson OBE FEng FIMechE**

# CONTENTS

02

**EXECUTIVE  
SUMMARY**

---

04

**BACKGROUND**

---

06

**DIVISION OF  
RESPONSIBILITIES  
AFTER A VOLCANIC  
EMISSION**

---

07

**EMISSION OF  
ASH AND GAS  
BY VOLCANOES:  
CHARACTERISATION  
OF SOURCE  
PARAMETERS**

---

10

**MOVEMENT  
OF VOLCANIC  
ASH CLOUDS**

---

14

**EFFECT ON  
AIRCRAFT:  
RECORD OF DAMAGE  
TO AIRCRAFT FROM  
PREVIOUS VOLCANIC  
ERUPTIONS**

---

16

**RISK**

---

17

**CONCLUDING  
REMARKS**

---

18

**RECOMMENDATIONS**

---

19

**BIBLIOGRAPHY**

---

20

**REFERENCES**

---

# EXECUTIVE SUMMARY

## The quiet skies of Europe

In April and May 2010, large areas of European airspace were closed due to the eruption of the Icelandic volcano, Eyjafjallajökull.

During this unprecedented time, 33 nations grounded over 100,000 flights, resulting in 5,000,000 travellers being stranded around the world. This disruption is estimated to have cost the European economy between €1.5–2.5bn.

So why was this volcanic eruption so disruptive?

## Why Eyjafjallajökull?

Unfortunately for Europe, Iceland's Eyjafjallajökull volcano erupted when the Jet Stream (a fast flowing current of air that moves from west to east) was directly overhead. The Jet Stream was unusually stable at the time of the eruption and maintained a continuous south-easterly heading and position. Finally, the explosive force of Eyjafjallajökull's eruption (intensified by melting glacial water flowing into the volcano) injected the ash directly into the Jet Stream, which was swiftly carried over almost all European airspace.

This combination of factors created a situation not experienced by many other eruptions. Previous volcanic events have generally allowed for the diverting of aeroplanes around the ash plume or cloud with the regulators closing any airspace where ash was thought to be present. On this occasion, with the Jet Stream spreading Eyjafjallajökull's ash across almost all of Europe and the regulators adopting the standard zero tolerance approach, almost all the major European airports were closed within days of the eruption.

By April 2010, the UK Civil Aviation Authority, in agreement with engine manufacturers, had set a revised ash density limit of 2mg per cubic metre of airspace. In addition, Time Limited Zones were created over Europe for areas that had ash concentrations between 2mg–4mg. However, airlines would only be permitted to enter these zones if they could produce certificates of compliance for their aircraft.

## What is the impact of volcanic ash on aeroplane engines?

In reality, the term 'ash' is misleading. Ash is generally defined as solid products produced as a result of combustion, whereas ash from a volcano is material that has been ejected by the eruption. Most volcanic ash comprises of silicates that can quickly wear propellers, turbo compressor blades and other aeroplane equipment.

For modern jet aeroplanes, the biggest concern is when volcanic ash is 'sucked' into the jet engine. Ash has a lower melting point, around 1,100°C, than the combustion occurring in a jet engine, which results in gas temperatures between 1,400°C -1,800°C. This causes the ash to melt and potentially stick to the internal components of the engine creating, substantial damage or even engine failure.

A well-documented example of the extreme effect of ash is British Airways Flight 9 over Indonesia in 1982. The Boeing 747-236B flew through an ash cloud and lost power to all of its four engines, descending over 24,000ft (7,000m) before the cooling caused the ash deposits to crack and spall off and thereby allow the engines to be re-started.



## Using history to predict the future

Predicting ash movement and dispersal has become ever more sophisticated over the years. In the UK, the Met Office uses the Numerical Atmospheric-dispersion Modelling Environment (NAME) computer model, developed after the Chernobyl accident in 1986. This model has tracked a number of atmospheric dispersion events, including the Buncefield explosion of 2005. Its purpose is to try and predict how far, and how concentrated, emitted particles will be dispersed using a number of factors, such as wind, rainfall, particle size etc.

Furthermore, the aircraft industry has documented over 126 incidents of encounters with ash clouds since 1935. These encounters have varied significantly and have helped in the creation of an ash-encounter (AE) severity index ranging from 0 (no notable damage to exterior and interior) to 5 (engine failure leading to crash). To date, on volcanic encounters using the AE severity classifications, no class 5 events have occurred but around 70% of encounters have been classed between 2 and 4.

The difficulty for regulators and the aerospace industry is in trying to predict what an exact safe level of ash concentration is for aeroplanes to fly through. For many, including the Dutch Pilots Union, "...100% safety (in the air) does not exist." and therefore past experience and the gathering of ever more data are our only guides when trying to make an informed decision in the future.

## Volcano chasing

As the risk of total aeroplane failure due to flying through volcanic ash is considered very small (especially when seen against the number of global daily flights over the past 50 years), the economic cost of substantially redesigning aeroplanes and their engines is just not a sensible course of action.

The Institution of Mechanical Engineers therefore recommends that the regulatory authorities continue to collect field data by test flying aeroplanes through volcanic eruptions around the globe. The aim would be to measure as far as technology will allow, the density and particle size distribution in conjunction with any effect they may have had by inspecting the aeroplane and its engines afterwards.

This form of 'volcano chasing', where data is collected on ash concentrations within the atmosphere, combined with subsequent aircraft and engine inspections, will mean that our understanding of the effects of ash on aircraft will gradually improve as will our approach of how best to manage future situations.

## IN SUMMARY:

- The position and stability of the Jet Stream directly over Eyjafjallajökull carried ash over most of Europe.

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- Regulators adopted the standard zero-tolerance approach to ash in the atmosphere and grounded all flights.

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- Later revisions of ash concentrations, up to 4mg per cubic metre, allowed flights to resume once all certificates of compliance for aeroplanes were in order.

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- Volcanic ash has a lower melting point than the combustion occurring in a jet engine. It therefore, melts and sticks to internal components of the engine causing damage or engine failure.

# BACKGROUND

Plumes of dense volcanic ash near active volcanoes present a risk to aircraft, especially for night flights, when the ash cloud is invisible. The term 'ash' is misleading. It does not refer to the solid products of combustion, it is instead solid or solidified material which has been ejected from the volcano. The ash is hard and abrasive and composed largely of silicates. It can quickly cause significant wear on propellers and turbo compressor blades, and scratch cockpit windows, impairing visibility. It contaminates fuel and water systems, can jam gears, and can block pitot tubes. It can get inside the cabin and contaminate everything there, and can damage the aeroplane electronics.

However, and most seriously for immediate safety, it can cause damage to the engines. The ash particles have lower melting point, about 1,100°C, than the temperatures in the combustion chamber of a jet engine, in excess of 1,600°C. The turbine blades are placed to take the air flow and potentially molten ash leaving this hottest section of the engine. The materials used (both for static vanes and for rotating blades) have melting points around 1200°C. A cooling air system in the engine is therefore devised to reduce the thermal loading on the components by about 400°C. The situation is partly alleviated by thermal barrier coating the components but the majority of the reduction is achieved by internal and external blade cooling using air piped from the later stages of the compressor (typically with temperatures below 700°C). Both the rotating and static components have a very large number of small cooling holes through which the colder compressor air ejects on to the very hot free stream thus providing a thin surface film which protects them. Given the high thermal loads, blockage of these cooling holes by ash would lead to a component failure of the relevant blade; substantial blockages would lead to a catastrophic failure of the entire turbine.<sup>[1]</sup>

In 1960, the operational temperature at the turbine entry was about 1,100°C. However, this temperature has increased steadily over the years with progress in turbine materials and technology made to increase fuel combustion efficiency. 1,400°C was passed in production engines before 1970. Today the temperature now exceeds 1,600°C. In this sense, the major safety issue is relatively new.

A serious incident of engine failure occurred in 1982, when British Airways 747 Flight 9<sup>[2]</sup> flew through an ash cloud, lost the power from all four engines, and consequently descended from 36,000ft (11,000m) to only 12,000ft (3,700 m) before the flight crew managed to restart the engines. A similar incident occurred on 15 December 1989 involving a KLM 747 Flight 867<sup>[3]</sup>. The restarts were possible because, on cooling the glass-like deposit with a lower thermal contraction coefficient, cracks and is blown clear, by the air jet through the engine.

With the growing density of air traffic, and the possibilities of encounters like this becoming more common, in 1991 the aviation industry decided to set up Volcanic Ash Advisory Centres (VAACs), dividing the world into nine regions, acting as liaisons between meteorologists, volcanologists, and the aviation industry<sup>[4]</sup>.

Prior to the European air travel disruption of April 2010, aircraft engine manufacturers had not defined specific ash particle density levels above which engines were considered to be at risk. The general approach taken by airspace regulators was that if the ash concentration rose above zero, then the airspace was considered unsafe and was consequently closed<sup>[5]</sup>.

The April 2010 eruptions of Icelandic volcano Eyjafjallajökull, and the subsequent closure of large areas of European airspace, caused sufficient economic difficulties that aircraft manufacturers were pressed to define specific limits on how much ash is considered acceptable for a jet engine to ingest without damage. In April, the CAA, in conjunction with engine manufacturers, set the safe upper limit of ash density to be 2mg per cubic metre of airspace<sup>[6]</sup>. From noon 18 May 2010, the CAA revised the safe limit upwards to 4mg per cubic metre of airspace<sup>[7]</sup>.

In order to minimise the level of further disruption that this and other volcanic eruptions could cause, the CAA announced the creation of a new category of restricted airspace called a Time Limited Zone (TLZ)<sup>[8]</sup>. Airspace categorised as TLZ is similar to airspace experiencing severe weather conditions in that the restrictions are expected to be of a short duration. However, the key difference with TLZ airspace is that airlines must produce certificates of compliance in order for their aircraft to enter these areas. Flybe was the first airline to conform to these regulations and their aircraft were permitted to enter airspace in which the ash density was between 2mg and 4mg per cubic metre<sup>[9]</sup>. Other airlines subsequently followed suit.

Currently, any airspace in which the ash density exceeds 4mg per cubic metre is categorised as a no fly zone: a restriction which carries forward to the future.

It is important to make a distinction between flight through (or in immediate vicinity of) the eruption plume and flight through so-called affected airspace<sup>[10]</sup>. Volcanic ash in the immediate vicinity of the eruption plume is of an entirely different particle size range and density to that found in downwind dispersal clouds which contain only the finest grade of ash. The ash loading at which this process affects normal engine operation is not established. Whether this silica-melt risk remains at the much lower ash densities characteristic of far field downstream ash clouds is currently unclear.

Observations have indicated that some damage does occur, which whilst not an immediate safety threat, needs careful monitoring and increased inspection and maintenance before its accumulative effect becomes critical. This is therefore a safety hazard which invites preventive risk management strategies in line with other comparable aviation risks, and a balance of the consequences of continued flight operations, including economic ones, in these uncertain conditions.

# DIVISION OF RESPONSIBILITIES AFTER A VOLCANIC EMISSION

There are essentially four aspects of this problem, each the responsibility of a different group of specialists but all closely interlinked.

The essential aspects are:

Emission of ash and gas by volcano. Estimation of ash volumes, composition and particle size ranges.

Modelling and measurement of ash dispersion: position and density

Effect on plane surfaces, systems and engines?

Regulation to fly or not to fly and for how long?

Broadly speaking, the identification and measurement of an erupting volcano is carried out by observers in the country in which it is situated, and the forecasting of the dispersion of the ash (and gas) cloud are the responsibility of nine Volcanic Ash Advisory Centres (VAAC) covering the world.

Observations of the progress of the ash are made by many groups in many ways, including observations by pilots, satellite images and radar soundings. The extent and strength of the cloud are passed over to the relevant aviation regulatory authorities who are responsible for making decisions about the safety of flying: the Civil Aviation Authority in the case of the UK, working in close contact with National Air Traffic Services (NATS) which is the organisation that separates aircraft on the ground or in flight within controlled airspace. The decision of allowing or suspending flying is informed by advice given by the engine and airframe manufacturers concerning the ability of their products to withstand exposure to ash.

Until the recent events of April 2010, this tolerance was set at zero. Unfortunately, this meant that European airlines, and aeroplanes bound for European destinations, could not fly around the ash cloud because, on occasions, it filled the sky above almost the entire continent. Put simply, they could not arrive or depart without flying through the ash cloud.

One of the consequences of applying the traditional technique of ash avoidance was that the aviation industry has never had to research the risk of damage, particularly to aeroplane engines, of flight through areas of widely dispersed upper airspace volcanic ash. In the past, most research had focussed on the impact of flights through the volcanic plume itself.

It is obvious that local to the volcano a 'near source field' exists where flying is extremely hazardous. It is a relatively simple matter to establish a no-fly zone extending from the volcano in the downwind direction. In this region the possibility of external damage to the aircraft and internal damage to the engines is highly likely. At night this volcanic soup may not be visible to pilots, hence the need of rapidly establishing exclusion zones when an eruption is detected. This zone may well be several hundreds of kilometres in extent.

At the other extreme, a long distance from the volcano in the 'far field', much of the ash will have dropped out and the remaining concentration is much reduced. However, as witnessed in April over European airspace, the affected area can be considerable and its detection, even in daylight, can be practically impossible.

This presents a real problem for both modelling and measurement of the extent of the ash. When is the concentration so small as to be of negligible danger? It is obvious that as the ash falls out with distance, the effects on an aircraft become smaller. Observations of actual damage in incidents reported to date substantiate this.



# EMISSION OF ASH AND GAS BY VOLCANOES: CHARACTERISATION OF SOURCE PARAMETERS

During volcanic eruptions, volcanic ash transport and dispersion models (VATDs) are used to forecast the location and movement of ash clouds. Those models use input parameters, called 'eruption source parameters', such as plume height  $H$ , mass eruption rate  $dM/dt$ , duration  $D$ , and the mass fraction  $m_{63}$  of erupted debris finer than  $63\ \mu\text{m}$ , which can remain in the cloud for many hours or days. Estimation of these parameters is by no means a trivial task and is specific to each eruption.

What made the eruption of the Icelandic volcano Eyjafjallajökull so disruptive to air travel was the combination of the following factors:

- the volcano's location was directly under the Jet Stream;
- the direction of the Jet Stream was unusually stable at the time of the largest eruption maintaining a continuous south-easterly heading;
- the volcano's explosive power was sufficient to inject ash directly into the Jet Stream some 8km above the volcano vent itself (more than 1,600m above sea level).

Finally, the eruptive phase took place under 200m of glacial ice. The resulting meltwater flowed back into the erupting volcano which created two further specific phenomena:

- the rapidly vaporising water significantly increased the eruption's explosive power;
- the erupting lava cooled very rapidly, which created a cloud of highly abrasive, glass-rich ash.

Without the specific combination of the above factors, the eruption would have been a medium sized, somewhat non-descript event that would have been of little interest to those outside the scientific community, or those living in the immediate vicinity. However, the above factors were exactly those required for the Jet Stream to carry the ash directly over Northern Europe and into some of the busiest airspace in the world.

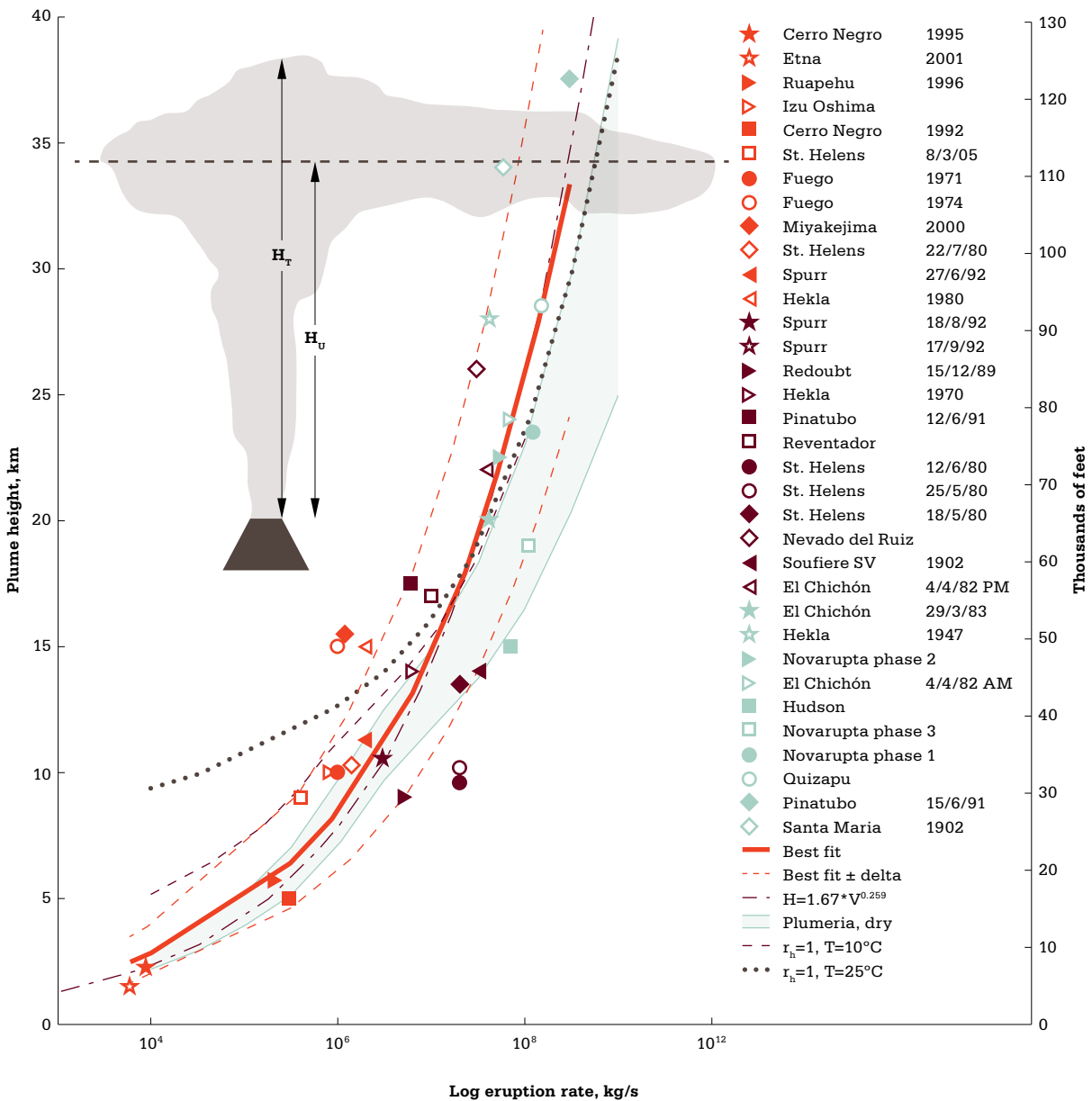
A recent paper<sup>[11]</sup>, reviews the situation regarding source estimation thus:

Observational constraints on the value of such parameters are frequently unavailable in the first minutes or hours after an eruption is detected. Moreover, observed plume height may change during an eruption, requiring rapid assignment of new parameters. This paper reports on a group effort to improve the accuracy of source parameters used by VATDs in the early hours of an eruption. We do so by first compiling a list of eruptions for which these parameters are well constrained, and then using this data to review and update previously studied parameter relationships. We find that the existing scatter in plots of  $H$  versus  $dm/dt$  yields an uncertainty within the 50% confidence interval of plus or minus a factor of four in eruption rate for a given plume height. This scatter is not clearly attributable to biases in measurement techniques or to well-recognised processes such as elutriation from pyroclastic flows [segregation of solid particles in the molten rock flow]. Sparse data on total grain-size distribution suggest that the mass fraction of fine debris  $m_{63}$  could vary by nearly two orders of magnitude between small basaltic eruptions ( $\sim 0.01$ ) and large silicic ones ( $>0.5$ ). We classify eleven eruption types; four types each for different sizes of silicic and mafic eruptions; submarine eruptions; 'brief' or Vulcanian eruptions; and eruptions that generate co-ignimbrite or co-pyroclastic flow plumes. ['Basaltic', 'silicic', 'mafic' and 'ignimbrite' refer to different chemical compositions of volcanic rock.] For each eruption type we assign source parameters. We then assign a characteristic eruption type to each of the world's approximately 1,500 Holocene volcanoes. These eruption types and associated parameters can be used for ash-cloud modeling in the event of an eruption, when no observational constraints on these parameters are available.

**Figures 1 & 2** on pages 08 and 09 are taken from the same paper. The point of reproducing these detailed figures here is to emphasise that the basic input data for the complex modelling of ash distribution is imperfectly known and subject to much scatter illustrated on the logarithmic scales of these figures. To this uncertainty might be added the variability of the composition of the ash particles from different volcanoes.

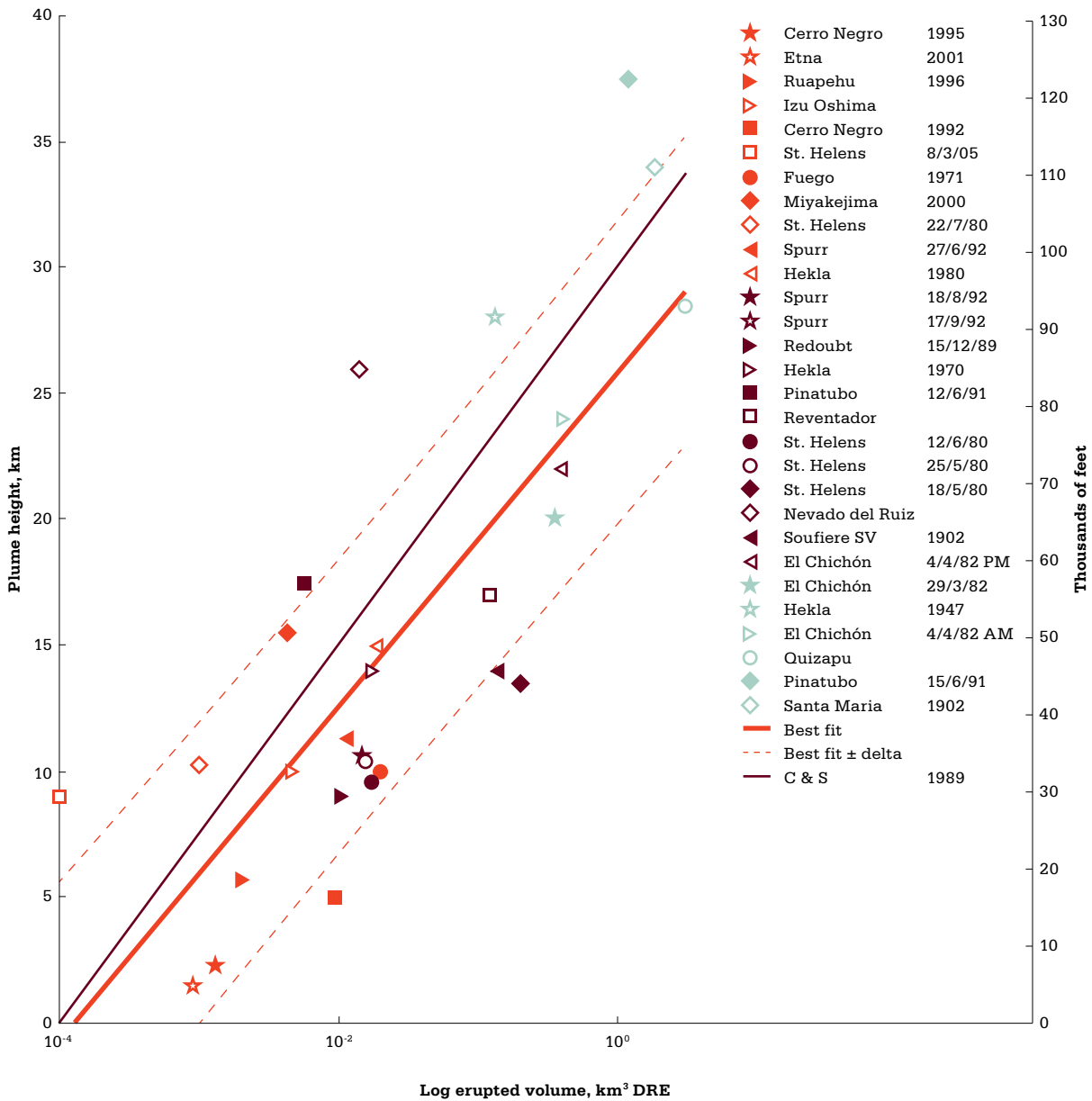
**Figure 1** illustrates the relationship between plume height and mass eruption rate<sup>[11]</sup>. (Height is taken as the elevation at which most ash spreads laterally from the plume.)

**Figure 1**



**Figure 2** illustrates the relationship between plume height and ejected volume<sup>[11]</sup>.

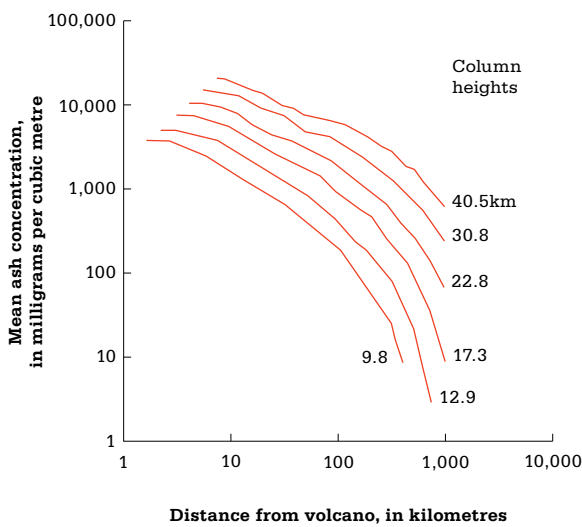
**Figure 2**



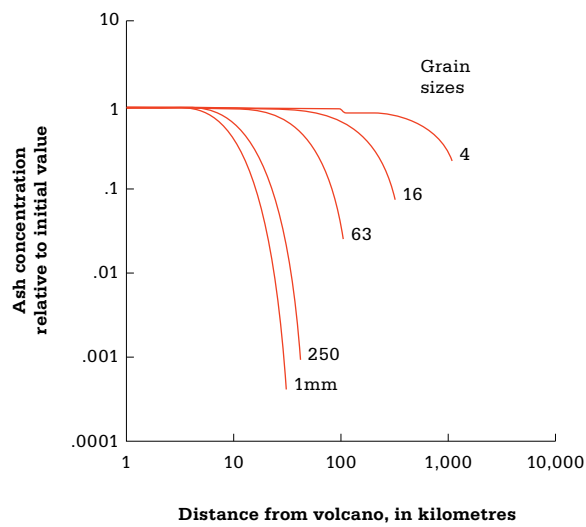
# MOVEMENT OF VOLCANIC ASH CLOUDS

The movement of the volcanic ash cloud from the volcano site depends on a combination of its natural dispersion in the atmosphere and its transport as an entity by the upper tropospheric and stratospheric winds. Ash is deposited by gravity and by scavenging by rainfall. The possibility of agglomeration of particles exists, but little detailed information is known. Depending on wind profile with height, it is possible for the ash cloud to shear and move in different directions at different levels of the atmosphere.

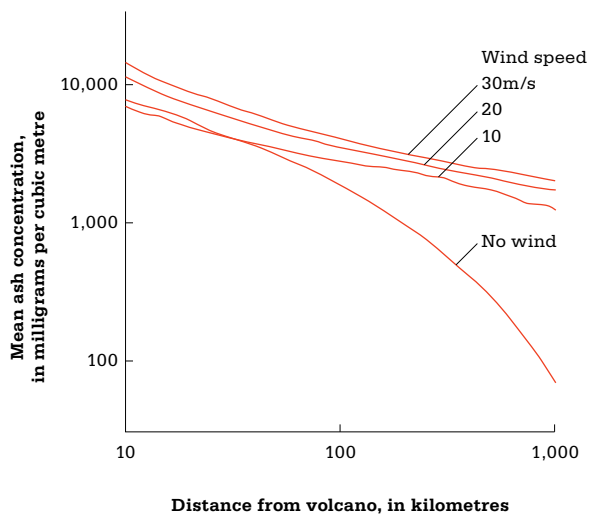
Now the strongest winds are usually in the higher levels of the troposphere and may include jet streams. This layer from 10km to 14km coincides with the cruise levels of most jet aircraft, increasing the possibility of an aircraft encountering ash clouds of significant concentration hundreds of kilometres from the volcanic source. The following figures illustrate typical calculated values of the fall out of ash with distance from the source<sup>[12]</sup>.



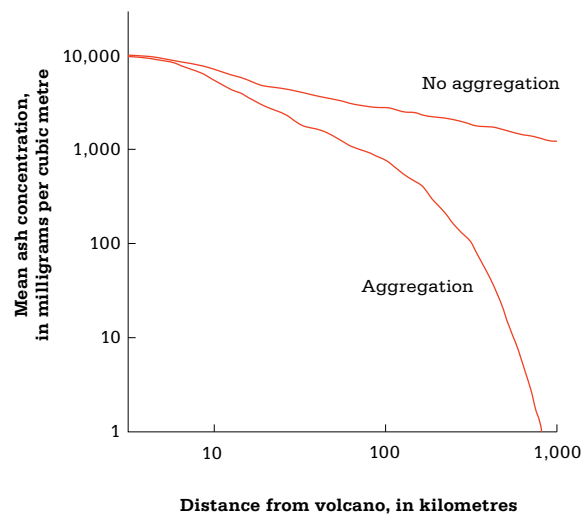
**Figure 3A:** Theoretical ash concentration in an umbrella cloud (in  $\text{mg}/\text{m}^3$ ) is plotted against distance for six different column heights and for dispersal in the absence of wind.



**Figure 3B:** Relative concentration of ash is plotted against distance for each grain size class for a 22.8km (75,000ft) high column in the absence of wind.



**Figure 3C:** Concentration of ash (in  $\text{mg}/\text{m}^3$ ) is plotted against distance for a 22.8km (75,000ft) high column erupted in no wind and for downwind transport of a layer 5km thick with its base at 15.9km (52,000ft) altitude for wind velocities of 20, 40 and 60kt, and for the case of no wind.



**Figure 3D:** Comparison of the downwind change in ash concentration between the case of individual fallout of all sizes and the case where particles less than 63  $\mu\text{m}$  aggregate. Calculations are for a wind speed of 20kt and a 5 km (16,000ft) thick layer with base at 15.9km (52,000ft). (from Bursik, Sparks, Carey and Gilbert<sup>[12]</sup>)

The Volcanic Ash Advisory Centre (VAAC) with responsibility for the UK and the north east Atlantic, is part of the UK Meteorological Office. VACC Toulouse covers Western Europe and Scandinavia. The volcanic ash transport and dispersion models (VATD) developed by the Met Office is the NAME (Numerical Atmospheric-dispersion Modelling Environment) computer model. The model began development following the Chernobyl accident in 1986 and has been used to model a wide range of atmospheric dispersion events over the years, including previous volcanic eruptions and the Buncefield explosion in 2005<sup>[13]</sup>. The model assumes an input of ash particles at the source and models the movement of individual particles subjected to gravity and wind forces. The basic physics of this Lagrangian process are well established (possibly with some reservations on the details of particle coalescence) and the modelling process is stable.

However, it is not necessary here to describe at length the details of this formidable modelling problem. The issues of defining the input have been discussed above. The huge distances over which results are computed and additional input of the wind forecast over large areas add to the difficulties. The accuracy of far field predictions of ash density as a function of height clearly depend on the accuracy of the input. It is unlikely that quantitative predictions of ash density in the far field are going to be better than say an order of magnitude. Thus the guidance given to aviation authorities should be regarded as extremely useful as regards special accuracy, but not particularly accurate regarding quantitative ash density levels.



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**THE ECONOMIC IMPACT  
OF THE WEEKLONG CRISIS  
HAD CAUSED LOSSES OF  
ESTIMATED AT BETWEEN  
€1.5–2.5 BILLION.**

SIIM KALLAS  
EU TRANSPORT  
COMMISSIONER







# EFFECT ON AIRCRAFT: RECORD OF DAMAGE TO AIRCRAFT FROM PREVIOUS VOLCANIC ERUPTIONS

Based on an updated compilation of information on encounters of aircraft with volcanic-ash clouds, at least 126 incidents from 1935 through 2008 have been documented<sup>[14]</sup>.

Since 1973 when jet travel became prevalent, the annual frequency of encounters ranges from 0 to 21, with an average encounter rate of approximately three per year. Thirty-eight source volcanoes for the ash clouds have been identified, with size of the eruptions ranging from small, brief episodes to major, sustained events.

The documented encounters vary greatly in the severity of effects observed by flight crews during the encounters, and of damage to the aircraft. A severity index has been developed, with 6 classes, ranging from 0 (minor sulphurous odour) to 5 (crash). **Figure 4.**

Fortunately, no class 5 encounters have occurred; ten class 4 encounters (temporary engine failure) have occurred from 1980–2006. Of the 109 encounters for which a severity class could be assigned, 75 (~70%) were damaging (classes 2–4). Aircraft exposures to ash-cloud hazards (defined by ash concentration and time in cloud) are not well defined in the available data. However, the data does show that most damaging encounters have occurred within two days of ash-producing eruptive activity. There have been no reported fatalities or injuries to passenger or crew.

A recent report from the British Geological Survey<sup>[15]</sup> reveals actual measurements on ash from Eyjafjallajökull which were found fallen to earth in the UK. Preliminary examination of the samples showed that the grains of ash were formed of both glass and crystalline phases. These ranged in size from less than 1µm up to 60µm in diameter. Some of them were found aggregated together in clumps with an average size of 85µm, the largest of which were 200µm across. This is considerably in excess of the sizes currently predicted by the analysis to be capable of travelling as far as the UK and underlines the challenge of the modelling problem.

**Figure 4:** Ash-encounter Severity Index

Class	Criteria
0	<ul style="list-style-type: none"> <li>Acrid odour (eg sulphur gas) noted in cabin</li> <li>Electrostatic discharge (St. Elmo's fire) on windshield, nose, engine cowls</li> <li>No notable damage to exterior or interior</li> </ul>
1	<ul style="list-style-type: none"> <li>Light dust in cabin; no oxygen used</li> <li>Exhaust gas temperature (EGI) fluctuations with return to normal values</li> </ul>
2	<ul style="list-style-type: none"> <li>Heavy cabin dust; 'dark as night' in cabin</li> <li>Contamination of air handling and air conditioning systems requiring use of oxygen</li> <li>Some abrasion damage to exterior surface of aircraft, engine inlet and compressor fan blades</li> <li>Frosting or breaking of windows due to impact of ash</li> <li>Minor plugging of pitot-static system; insufficient to affect instrument readings</li> <li>Deposition of ash in engine</li> </ul>
3	<ul style="list-style-type: none"> <li>Vibration of engines owing to mismatch; surging</li> <li>Plugging of pitot-static system to give erroneous instrument readings</li> <li>Contamination of engine oil hydraulic system fluids</li> <li>Damage to electrical system</li> <li>Engine damage</li> </ul>
4	<ul style="list-style-type: none"> <li>Temporary engine failure requiring in-flight restart of engine</li> </ul>
5	<ul style="list-style-type: none"> <li>Engine failure or other damage leading to crash</li> </ul>



The most alarming of these encounters, involving temporary engine failure, have naturally received disproportionate publicity. But the fact that only 10 such incidents have been recorded in 26 years gives an indication of their rarity. Although few quantitative details are available, it is clear that the most serious incidents have all occurred in the 'soup' relatively near the volcano.

A well documented example occurred on 15 December 1989 when a KLM Boeing 747-400 encountered flameout of its engines due to ash when flying near an eruption of Mount Redoubt in Alaska<sup>[16]</sup>. The damage was estimated to have cost some US \$80m to repair. There was 80kg of ash in each turbine and the calculated ash density was 2g/m<sup>3</sup>. Given the air ingestion rate above and if all the ingested ash was retained, then 6<sup>2</sup>/<sub>3</sub> minutes exposure would have been sufficient to collect 80kg. However for the limiting density on which the no fly ban was initiated, 4mg/m<sup>3</sup>, only 160g would have been ingested, emphasising the huge range of densities from the flame out magnitude down to the level of the flying ban.

But safety is not the only consideration. In 2007, it was stated that<sup>[17]</sup> *"the economic cost of volcanic ash to international civil aviation is staggering. This involves numerous complete engine changes, engine overhauls, airframe refurbishing, window re-polishing and/or replacement and pitot-static system repair, etc., and the inevitable loss of revenue due to aircraft down-time while the foregoing is accomplished. Delays to aircraft and their rerouting around volcanic ash has caused considerable expense to airlines operating in regions prone to volcanic eruptions. Also to be included is the cost of volcanic ash clearance from airports and the damage caused to equipment and buildings on the ground. Various estimates have been made, most citing costs to aviation well in excess of \$250 million since 1982"*.

The question of allowing or banning flying through the ash cloud proved to be difficult to answer on a rational and quantitative basis. The interaction of aviation technology, uncertainty in observation and modelling, economics and risk proved to be both difficult and messy. At best the answer to this question was subjective and changed as experience grew and the allowable density for flight was doubled. It is clear that the economic arguments for permitting flying became more compelling to the airlines as the length of the ban increased, and the patience of travellers became tested as they looked up into apparently clear skies. In the words of the vice president of the Dutch pilots union, "*We are asking the authorities to look at the situation because 100% safety does not exist. It is easy to close airspace because then it is perfectly safe, but at some time you have to resume flights.*"<sup>[19]</sup>

It will surprise many readers to learn that the huge disruptions to European air traffic in the spring and early summer of 2010 were occasioned by reaction to a potential risk that has neither killed or injured anyone in the past. It is superficially easy to be critical of such a decision. However, although flying is inherently very safe, the public perception is governed by the occasional picture of the wreckage of a disaster in which all perished. It is difficult to persuade either the public or indeed governments to be entirely rational about matters appertaining to aviation safety.

## The Risk of Death

The average life expectancy in the UK is around 80 years (~30,000 days). To a first approximation this is equivalent to saying that we have a 1 in 30,000 chance of dying each day. If there were a population 300 people then on average one person from that population would die every 100 days.

In comparison, we can imagine an aircraft carrying 300 people and assume that this group of people take an aircraft flight each and every day. We know from historical fatality statistics that on average 117 people have died for every 1,000,000,000 flights taken. In the 30,000 flights that this group of people could take in their lifetimes we would therefore expect that the cumulative number of extra deaths would be:

$$\frac{30,000 \times 300 \times 117}{1,000,000,000} = 1$$

i.e. on average any one person from this group might be expected to die every 80 years from daily flying rather than once every 100 days from all other causes.



# CONCLUDING REMARKS

The relatively high densities of ash needed to cause engine failure can be avoided by establishing a no-fly zone round the active volcano. The far field problem is much more difficult to deal with. The safety risk changes to an economic risk with distance from the source. Yet a quantitative assessment of this risk is not possible at present and awaits further information of the effect of ash on jet engines. Currently there is a factor of 500 between the far field ash densities on which the ban was based and the estimated concentrations near the source of a volcano that previously caused engine flame out.

In order to better inform any such decisions in the future, it is clear that more quantitative information is needed on the effect of ash at various densities, compositions and particle sizes on jet engines. It seems likely that density alone is not good enough to define the exposure.

Particle size clearly plays a role: larger particles are assumed to be centrifuged out by the action of the fan sweeping air into the engine. If particles move to the outside they will travel via the bypass and not enter the combustion process.

At the other extreme it is claimed that very small particles, in the order of microns in diameter, will be swept across surfaces in their passage through the engine and prevented from making contact by the boundary layer effect. It may be that these processes could be clarified by appropriate numerical fluid mechanics modelling. In addition to ash, volcanoes release gaseous material which disperses in a different manner to ash. In particular, sulphur dioxide may be a further problem when ingested into engines, therefore the effect of sulphur on some of the complex surface coatings used on turbine blades needs careful investigation.

Operationally it is recognised that the path and the time of passage of the aeroplane through the ash cloud defines the amount of ash injected. Because of the variations in density with height, coupled with the fact that the ash may form thin layers, modelling is unlikely to give sufficient precision to calculate the amount of ingested ash with flight path. Ideally this might be achieved by in flight measurement, but considerable improvements in technique are needed for this to be viable.

Experience of flying in ash of increasing density will allow data to be established on exposure rates and damage. Condition monitoring equipment carried on board already has sufficient capability to monitor deterioration in performance such as increasing fuel consumption which may be an early indicator of erosion damage to blades. Certainly ground inspection of the internal state of engines after ash exposure can be carried out by borescopes (optical devices on flexible tubes) to give a clear indication of internal engine damage.

The state of knowledge of volcanic emissions and the modelling of the dispersion of ash has improved considerably in recent decades. However, the uncertainties are such that modelling alone cannot be the basis for a quantitative decision about the boundaries of safe, and or economic flying. Developments in experimental measurement techniques for the variation of ash density in the atmosphere are taking place and in the future may have advanced sufficiently to become accurate indications of real conditions.

None of the above are trivial tasks and some will prove to be extremely expensive. Given the present delicate state of aviation finances, it is not clear how such an investigation will or should be financed. However, the cost of disruptions to flying is also high. With luck it may be many years before decisions to those made this summer have to be made using the limited information now available. On the other hand, history may repeat itself tomorrow and unless the necessary advances in knowledge are made, we will be still in the position of having to make decisions with far reaching consequences informed by incomplete information.

# RECOMMENDATIONS

The clear recommendation from this report is that every opportunity should be taken for the regulatory authorities to collect field data. This data should be from actual engine/volcano combinations generated by test flying and subsequent aircraft and engine inspection. In simple terms this form of 'volcano chasing' will mean that our understanding improves only for those conditions that actually exist and only at a rate that matches the actual number of times ash plumes interact with controlled airspace.

It would also be possible to call for significant investment and action in each of the three main areas of uncertainty highlighted in this review.

- a** Measurement of actual volcanic eruptions for their particle size, chemistry and ash volume together with improved modelling of the subsequent atmospheric dispersion over distance and time
- b** Extensive modelling and testing of aircraft, their systems and engines in exposure to a range of ash types and densities
- c** Establishment and review of clear procedures and responsibilities for who will balance and by what method all of the unknowns and probabilities to decide whether or not to allow flights in controlled airspace

These are clearly the priorities for action where time and resources allow. For example, computerised fluid dynamics modelling of particle behaviour in aircraft engines is a valuable engineering project that would yield a return. This should be undertaken immediately.

The reality however is that a definitive overall answer to the question of an aircraft's sensitivity to volcanic ash is not possible. The question has so many unknowns that attempts to answer it fully could absorb effort and resources out of proportion to the risk it poses.

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**Institution of  
Mechanical Engineers**

1 Birdcage Walk  
Westminster  
London SW1H 9JJ

T +44 (0)20 7304 6862  
F +44 (0)20 7222 8553

[transport@imeche.org](mailto:transport@imeche.org)  
[www.imeche.org](http://www.imeche.org)