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Abstract

As part of the cross industry efforts to get aircraft flying again during the April/May 2010 eruption of Eyjafjallajokull Rolls-Royce produced a chart that plotted examples of aircraft engine exposure to volcanic ash against the ash concentration the engines had been exposed to. This chart became known as the Rolls-Royce 'Safe-to-Fly' chart, and it was used to guide decisions on how the UK Met Office ash concentration charts for the Eyjafjallajokull eruption could be utilised to help aviators plan their flight paths. Over the period 2011–2013, this paper's authors reassessed the engine data that made up the 'Safe-to-Fly' chart, and in particular the data relating to two key exposure events at high ash concentrations, flight BA009 on 24 June 1982 and flight KLM867 on 15 December 1989. Through a combination of reassessment of the original engineering calculations carried out for these events (i.e. calculations based on evidence from engine hardware) and assessments of relevant volcanological and ash cloud visibility data, it has been concluded that these events are unlikely to have occurred at or near the 2000 mg/m^3 ash concentration arrived at in 2010; based on current evidence, it is more plausible that these events occurred in ash concentrations of around 200 mg/m^3. As a consequence, a revision to the 'Safe-to-Fly' chart is recommended. In addition, to more easily present the main considerations associated with flight within ash concentrations where the ash would start to become visible, a new chart is proposed that plots duration of exposure against ash concentration. The points plotted on this chart are the revised understanding of the BA009 and KLM867 events, other relevant engine exposure events and speculative regions where flight would be unsafe and where flight would be safe, but engines would be susceptible to long-term damage.

Keywords

Volcanic ash, aircraft gas turbine, turbine accretion, compressor erosion, ash visibility

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Introduction

In response to the Eyjafjallajokull volcanic eruptions of April 2010 the London Volcanic Ash Advisory Centre (VAAC) produced Volcanic Ash Advisories (VAA) and Volcanic Ash Graphics (VAG), using established procedures, which in conjunction with accepted guidelines of avoiding flight in volcanic ash, led to cancellations of flights over much of Europe. The economic cost and social disruption that resulted from these flight cancellations stimulated, at that time, discussions about whether it was necessary for aircraft to avoid all atmospheric volcanic ash; if an ash concentration could be established up to which safe flight can be undertaken, isolines, or contours, of this concentration might be produced and normal flight operations resumed outside of these contours. In response to these discussions, as well as direct requests from the UK Civil Aviation Authority (CAA), the UK Met Office (which runs the London VAAC) started using their Numerical Atmospheric-dispersion Modelling Environment (NAME) code to produce volcanic ash concentration contour charts.

The UK CAA also approached aircraft airframe and engine manufacturers to see if a volcanic ash concentration threshold for safe aircraft operation could be established. Consequently, Rolls-Royce undertook a review of the relevant gas turbine engine data that it had access to. The interpretation of these data was presented in 2010 on a chart of atmospheric ash concentration against the resulting mass flow of ash through an engine, a chart that became known as the Rolls-Royce 'Safe-to-Fly' chart (Figure 1).

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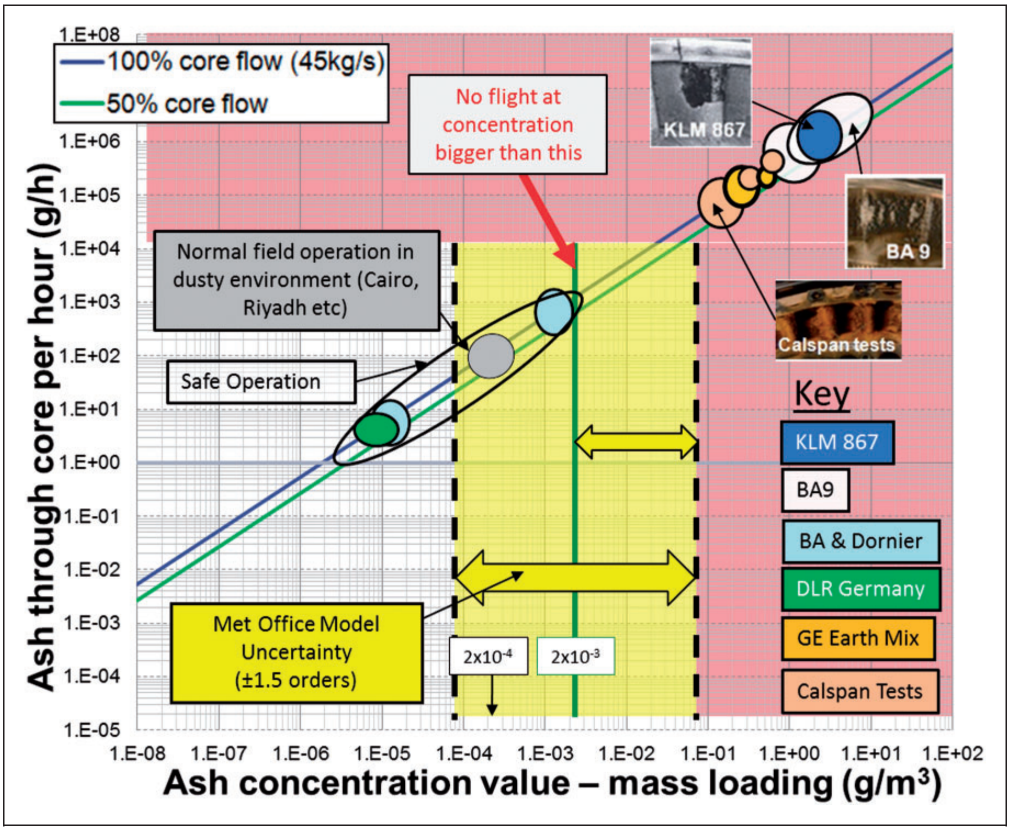

Figure 1. Original 2010 ‘safe-to-fly’ chart.

Information displayed on the chart was then, in effect, used to help satisfy aviation industry stakeholders that flight was safe up to a UK Met Office predicted ash concentration of 2 mg/m^3.

Since the end of 2010, the authors have gradually undertaken a review of the information presented on the original ‘Safe-to-Fly’ chart, including the assumptions and analysis that went into its construction. Supplementary data have also been used to make judgements on the uncertainty and relevance of the chart data points. The objective of this paper was to present the conclusions of these studies and what currently might be inferred from them.

2010 safe-to-fly chart

The original ‘Safe-to-Fly’ chart (Figure 1) was put together over a relatively short period of time in April and May 2010. Qualitatively, the effects volcanic ash has on gas turbine engines were already well known because they had been observed from previous aircraft volcanic ash encounters. Most of the gaps in the detailed understanding of the damage mechanisms were quickly filled in 2010 by revisiting original photographic and written evidence from these previous events. The Boeing training film ‘Volcanic Ash Avoidance’[1] made in 1992 gives a very good introduction to the subject. What was less easy to establish, because of a lack of good data, was a quantitative understanding of the damage mechanisms, that is to say the rate at which the damage progresses as a function of the concentration of ash ingested, the engine design and its power setting.

An obvious source of data from which to make quantitative assessments are the historical aircraft volcanic ash encounters. Unfortunately, only two ended up being of use; the 1989 Redoubt KLM867 event, a quantitative assessment of which had been attempted and reported to a degree in the early 1990s[2,3] and the 1982 Galunggung BA009 event, which involved Rolls-Royce RB211-524C2 engines, for which substantial data were still available. Both encounters involved Boeing 747 aircraft and in both cases power was initially lost from all four engines. In both cases, the aircraft landed safely; after a few minutes, power was restored to all four engines on the KLM867 aircraft; the BA009 aircraft landed with power from three engines. Data from the other seven serious events, where power was lost from at least one engine, and numerous less severe events were either unavailable to Rolls-Royce in 2010 or the data were insufficient to be of value. Included below is a brief description of the original 2010 assessments of the ash concentrations the KLM867 and BA009 aircraft encountered.

In addition to historical aircraft ash encounters which led to engine damage, there were data from test flights conducted during the 2010 Eyjafjallajokull eruption which did not lead to, as far as was known, detectable damage; a British

Airlines (BA) Boeing 747 flight, and flights by two research institution aircraft, the UK Airborne Research and Survey Facility (ARSF) Dornier 228 and the German Aerospace Centre (DLR) Dassault Falcon. The Dornier and Falcon aircraft had instruments fitted that could determine, to a reasonable accuracy, the ash concentrations they were flying in. The BA flight took a flight path similar to the Dornier flight such that the ash concentration it had flown through was inferred.

The observation that there are similarities between the effects mineral particulates (e.g. sand and dust) have on engines and the effects volcanic ash has on engines was used to broaden the pool of possible data sources. Engines that regularly fly in and out of sandy dusty airports, like Dubai, Riyadh and Cairo, gradually accumulate damage but do not fail between major overhauls. This experience was related to well-reported typical sand and dust concentrations at these types of location.

Although there were no known test bed engine studies with volcanic ash, there had been test bed studies where sand and dust was introduced into engines. Two such studies that appeared to be relevant were the Calspan dust cloud tests (carried out by Mike Dunn and co-workers in the 1980s and early 1990s) and the General Electric (GE) 'Earth Mix' tests, believed to have been carried out in the early 1990s. In these studies, known concentrations of mineral particulates were introduced into the engines and the engines run until they surged or flamed out, i.e. lost controllable power or shutdown.

In 2010, all the above sources of engine data were plotted on the 'Safe-to-Fly' chart. Note that for the encounters with atmospheric ash, the points are plotted against an average ash concentration for the aircraft exposure; it is likely that there would have been some, and possibly substantial, variation in the ash concentration the aircraft encountered.

Additional information was also included on the chart, such as the 2010 perceived uncertainty in the UK Met Office's NAME ash dispersion model, centred on the 2 mg/m^3 vertical line, and two lines of mass flow of ash through an engine core against ash concentration for two different engine core air flows; 45 kg/s and 22.5 kg/s. These core air flows are representative of large to medium civil turbofans at cruise powers. The choice of axes for the chart is worthy of comment, because there is a simple relationship between them; the mass flow of ash through an engine's core (the y-axis) is the concentration of ash in the air (the x-axis) multiplied by the ratio of mass flow of air through the engine's core to the density of air. Consequently, for a given engine power and altitude (i.e. both the mass flow of air through the core and the air density are fixed), whichever ash concentration a test or encounter occurred at the chart datum point can only lie on a diagonal line, such as the blue and green diagonal lines on the chart. In addition, because the chart is set out on a log/log scale, to get a significant distance away from these central diagonals will require either an enormous or a miniscule engine mass flow. Consequently, engines powering aircraft from the smallest business jet to the largest civil airliners will always appear very near to the central diagonal.

KLM867 event assessment

It is believed that an assessment of the average ash concentration flight KLM867 encountered on 15 December 1989 was carried out shortly after the event by the aircraft's engine manufacturers. Although some information is reported in Przedpelski and Casadevall,[3] there is insufficient detail to know the exact calculations. It appears that the mass of ash accumulated on the high pressure turbine stage 1 nozzle guide vanes (HP1 NGV) was approximated from the ash deposits left on the components when the engines were stripped. How reliable such an assessment might be is unknown because all four engines were restarted before the aircraft landed and there is evidence that a substantial amount of deposit was removed during the restarts and subsequent running. There are potentially other indirect ways of estimating the amount of ash deposited, but it is not known whether these were used (e.g. the aircraft and engines were relatively new, and the engines shutdown at a climb power – relating the required reduction in turbine flow capacity to loss of available compressor surge margin could in principle be used to estimate the mass of ash deposited).

Having established a mass of ash deposited (m_{ash}), using a knowledge of the altitude at which the encounter occurred (to get the air density, ρ_{air}), the mass flow of air through the engine core prior to shutdown ($\dot{m}_{air}$) and the duration of the ash cloud encounter (Δt), the average concentration of ash encountered (C_{ash} in g/m^3) can be calculated if the rate of ash accumulation at the HP1 NGV is known. The rate of ash accumulation is conveniently expressed as the proportion of ash entering the engine core that accumulates on the HP1 NGV, often referred to as the accumulation factor (ζ_{NGV}). i.e.

$$C_{ash} = \frac{m_{ash}\rho_{air}}{\dot{m}_{air}\zeta_{NGV}\Delta t} \quad (1)$$

The exact accumulation factor used in the calculation is again uncertain, the only comment in Przedpelski and Casadevall[3] being that it was based on values arrived at during the Calspan testing. Whatever value was used, the ash concentration for the encounter was calculated to have been around 2000 mg/m^3.

In 2010, workers at Rolls-Royce took the above concentration value, estimated the mass of ash accumulated on the HP1 NGVs from the reported throat blockage, the mass flow through the engine and the duration of the encounter, and calculated that the accumulation factor used must have been in the 1–5% range. This is consistent with the accumulation factors derived from some of the Calspan testing reported by Mike Dunn and co-workers in 1994.[4]

BA009 event assessment

In 2010, two methods were used to estimate the average ash concentrations for the BA009 Galunggung encounter on 24 June 1982, one on the amount of ash accumulated on the HP1 NGVs, in the same way as the KLM867 calculation above, and one based on the amount of metal eroded from compressor blades.

The ash concentration calculation based on the amount of ash accumulated on the HP1 NGVs made use of the fact that one of the aircraft's engines, despite initially being restarted after the first exposure to ash, repeatedly surged and was shut down without being restarted following the second ash exposure. (The BA009 aircraft first encountered ash whilst cruising at 37 000 ft, where all four engines shutdown, and left the ash cloud shortly before restarting the engines at 12,000 ft. The flight crew then attempted to climb to 15,000 ft but re-entered the ash cloud). As with the KLM867 engines, post strip evidence from the BA009 engines that were kept running during the second ash exposure indicated that a substantial amount of ash was removed from the HP1 NGVs during restart and subsequent running. The ash deposits on the HP1 NGVs of the engine that was not restarted after the second exposure were inspected and photographed once the engine had been removed from the aircraft and stripped.

Using the 1982 engine strip reports, it was deduced that the HP1 NGV throat area had been reduced by 10%. This information, combined with the distribution of ash on the HP1 NGVs, which was evident from photographs, and the assumption that the ash deposit density would have been similar to the density of an ash cloud particle (approximately 2500 kg/m^3), allowed a mass of accumulated deposit to be arrived at. Using this number along with an assumed encounter duration of 2 minutes, the engine core mass flow established from engine performance data and an accumulation factor of around 1% gave an average ash concentration in the region of 2000 mg/m^3. Interestingly an accumulation factor of 3% was considered to be, at the time, towards the upper limit of plausibility based on evidence from accumulation of sand and dust deposits typically found on engines operated in sandy dusty environments. This engine evidence suggested an accumulation factor of 1% was reasonable.

To get to an average ash concentration from the mass of material eroded from a single row of compressor blades (m_{ero}) the following parameters need to be established: (i) the erosion rate (ε), expressed as the mass of metal removed per unit mass of ash striking the blade, (ii) the proportion of ash particles that strike a single row of rotor blades – the incidence ratio (β), (iii) the mass flow of air through the engine, and (iv) the encounter duration. Thus:

$$C_{ash} = \frac{m_{ero}\rho_{air}}{\dot{m}_{air}\varepsilon\beta\Delta t} \qquad (2)$$

The mass of compressor blade metal eroded was estimated from photographs taken during the engine strips in 1982. It was assumed that the erosion rate would be the same as that for sand, for which experimental data was available, and the incidence ratio was assumed to be 10%. These values, along with an assumed encounter duration of 2 min and the engine core mass flow, also gave an average ash concentration of approximately 2000 mg/m^3.

In 2010, it was recognised that some uncertainty existed in both the above calculations and this was reflected in the size of the two bubbles representing the BA009 encounter on the 'Safe-to-Fly' chart, one bubble for each calculation method; the higher concentration bubble corresponds to the erosion calculation.

Re-evaluation of the BA009 and KLM867 encounters

At the beginning of 2011, two observations led the Rolls-Royce Engine Environmental Protection (EEP) team (i.e. the authors) to re-evaluate the assumptions that had gone into the construction of the 2010 'Safe-to-Fly' chart. It is well worth noting that an essential factor in the making of both observations was the recruitment by the EEP team of a volcanologist.

The first observation was that virtually all of the Calspan tests had not been conducted with pure volcanic ash, and that volcanic ash, with its high glass particulate content, is quite different in nature to general sand and dust. This observation alone warranted a detailed assessment of the assumptions that had been based on the Calspan results.

The second observation was that ash dispersion calculations produced by the UK Met Office using their NAME code for both the KLM867 and BA009 encounters,[5] so-called 'backcasts', produced average ash concentrations for both encounters about an order of magnitude less than the 2010 engineering calculations indicated; the peak concentrations calculated for the KLM867 and BA009 encounters were 70 mg/m^3 and 320 mg/m^3, respectively. Some in the engineering community have suggested that this was additional evidence of how inaccurate ash cloud dispersion modelling can be. There is a widely held view that the UK Met Office ash concentration forecasts of the 2010 Eyjafjallajokull eruption over-predicted the concentrations by up to 1.5 orders of magnitude, a suggestion backed up by the apparent lack of visual ash within the 2 mg/m^3 contours and assessments of the uncertainty in the prediction boundary conditions, the eruption source parameters in volcanology parlance. However, it seemed curious that the UK Met Office's backcasts appeared to under predict ash concentrations by an order of magnitude, whereas their 2010 forecasts appear to over-predict ash concentrations by around an order of magnitude. Over-prediction of forecasts and under-prediction of backcasts by relatively small factors might be understandable, but by greater than an order of magnitude is puzzling and justifies some explanation; reliable ash dispersion modelling is an important element to minimise air traffic disruption in airspace potentially contaminated with volcanic ash.

The atmospheric physics, volcanological and meteorological communities are engaged in ongoing activities to understand the limitations of, and improve, ash dispersion modelling. Notwithstanding these activities, a review of the engineering understanding also felt appropriate to see if this could help reconcile the puzzling tendencies in the NAME ash dispersion modelling. Was it possible that the engineering assessments could have over calculated the ash concentrations for the KLM867 and BA009 encounters? Could they have occurred at concentrations anywhere near 200 mg/m^3?

Engineering calculation assessments

The first engineering assumption to be reviewed was the high pressure turbine NGV accumulation factor for volcanic ash, and how this relates to the BA009 and KLM867 ash accumulation calculations. A review of the BA009 erosion calculations was then conducted. The final engineering assessment was to compare the time taken for engines to lose controllable thrust, or shutdown, during sand and dust ingestion tests with the time it took for the BA009 and KLM867 engines to shut down.

NGV ash accumulation calculations

There is some uncertainty in three of the parameters that are needed to derive an ash concentration from the accumulated deposit on the HP1 NGVs. The exact duration of both the KLM867 and BA009 events is difficult to establish. Flight KLM867 may have been exposed to lower concentration ash for a little time before the crew realised they had a problem and attempted to climb out of it. Flight BA009 certainly experienced two encounters at high power (i.e. cruise and climb), the first being at least 2 min long, and the second being between 3 and 7 min in duration (data taken from an internal Rolls-Royce report). The mass of ash deposited is calculated by estimating the deposit volume and by assuming an ash deposit density. There is probably a range of possible ash deposit densities, a plausible estimate being between 1000 and 2500 kg/m^3, depending on the deposit porosity. Because of the way the volume of ash deposited on the HP1 NGVs was estimated, there is substantial uncertainty in the mass of ash deposited for both the BA009 and KLM867 events. However, the parameter that probably has the greatest uncertainty is the NGV accumulation factor.

The primary source of data for the accumulation factor has been the Calspan tests. It should be noted that the original purpose of the Calspan studies was to look at the effects a post-nuclear explosion dust cloud would have on jet engines, and whether a way could be found of keeping engines running once they started to suffer significant damage. The dusts used for the engine tests were a synthesised mixture of crystalline sands and dusts, plus some glassy material. Although volcanic ash was used as one of the glassy material sources, the nature of the crystalline material and the nature and proportion of much of the glassy material in the Calspan dusts is significantly different from volcanic ash. Also, because of the way the Calspan engine tests were run, it is not possible to derive reliable accumulation factors from them. The only Calspan tests where such data can be derived were those run on the two Hot Section Test System (HSTS) rigs,[4] the combustors and HP1 NGVs from an Allison T56 engine and a Pratt & Whitney F100 engine; the rigs did not include the engine compression system or turbines. Figure 2 presents the results from these tests that are most relevant to the likely behaviour of volcanic ash.

A review of all the HSTS points indicated that although a number of parameters influenced the NGV accumulation factor, it is the combustor exit temperature (T4) that has the greatest influence, hence the choice of x-axis in Figure 2. Note that the dust concentrations quoted in relation to the HSTS tests are the equivalent ambient atmospheric concentrations that the engine would have been encountering. The exact origin of the Black Scoria is unknown; it is reportedly basaltic in nature,[6] but it may not have resulted from an explosive volcanic eruption (in mining terminology the glassy surface of mafic lava flows are also referred to as 'Black Scoria'). However, it does contain around 80–85% glassy material. Dust Blend #2 contains 42% Black Scoria, the remaining 58% being a mix of sands and clays; i.e. Blend #2 contains around 34% volcanic glass.

The key observations from the data in Figure 2 are:

- The accumulation factors for the two Black Scoria points are significantly larger than the Blend #2 points at the same T4, which are in fact below the threshold temperature at which Blend #2 starts to accrete on the NGVs.
- Two points – both the Blend #2 points at 500 mg/m^3, one run for 7 minutes the other for

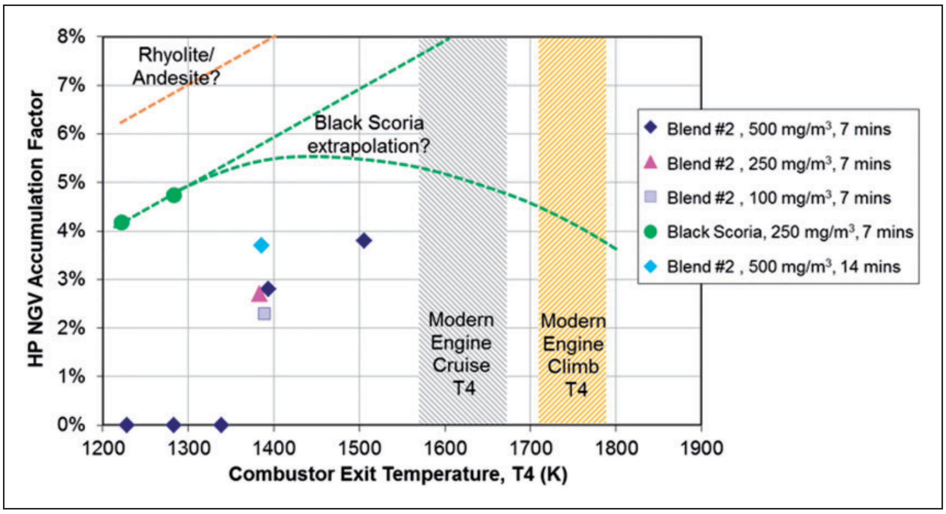

Figure 2. Accumulation factor results from the Calspan Hot Section Test System testing for Blend #2 and Black Scoria.[4]

14 minutes – indicate that the accumulation factor increases with exposure duration, and thus mass of material accreted.

- The accumulation factors for Blend #2, for a fixed 7 minute exposure, are not substantially influenced by the dust concentration, in the 100–500 mg/m^3 range.
- The 5 Blend #2 points at 500 mg/m^3 and the two Black Scoria points at 250 mg/m^3 suggest a strong correlation between increasing T4 and increasing accumulation factor.

All the above behaviours are rational, with the possible exception of the contrast in behaviour between Black Scoria and Blend #2 in the 1200-1350 K T4 range; it appears that the presence of the non-Black Scoria constituents in Blend #2 are preventing the 42% Black Scoria in Blend #2 from accreting.

Another observation from Figure 2 is that all the data points are at lower combustor exit temperatures (T4) than would be expected on a modern large civil turbofan at cruise or climb powers; see the cross hatched columns representing cruise and climb T4s. The equivalent T4s for the earlier generation of engines on flight BA009 would have been around 250 K cooler, which still leaves the cruise and climb T4s of these engines a little to the right of the Black Scoria point at 1280 K. The two broken lines through the two Black Scoria points are suggested extrapolations of this material's accumulation factor to these higher T4s.

A linear extrapolation would seem reasonable, but the lower curved extrapolation, indicating a peak accumulation factor as deposit removal rate gradually increases and ultimately equals the accumulation rate, is also plausible. The Calspan T56 HSTS tests reported in Kim et al.[4] suggest that a maximum in accumulation factor with increasing temperature may exist. These tests included two runs with Mount St Helens ash, both at a high ambient ash concentration of 1250 mg/m^3. The difference between the two runs was the T4 at which they were conducted; 1394 K and 1494 K. Unfortunately, in these tests, Mike Dunn and co-workers were unable to determine the NGV accumulation factors, but they did establish that the average accumulation rate was about 20% lower at 1494 K than at 1394 K. However, the evidence also indicates that this effect happens after a considerable amount of deposit has accumulated on the NGV, i.e. it is an effect dependant on a combination of exposure time and ash concentration. The occurrence of the effect will also be influenced by the temperature–viscosity relationship of the deposit, which is a function of the ash chemical composition.

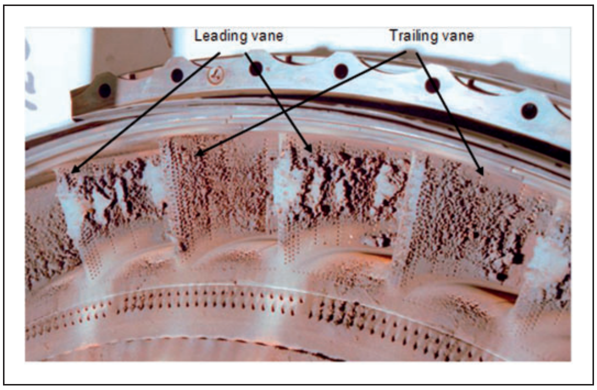

Figure 3. HP NGVs from the Flight BA009 engine that could not be restarted after second ash encounter.

Additional evidence of the trend in accumulation factor with increased temperature can be inferred from photographs of the BA009 engine that could not be restarted after the second ash encounter. Figure 3 is a photograph of the HP1 NGVs of this engine and it shows a distinctive pattern of ash deposit on alternative NGVs; the so-called leading vanes have substantially more deposit, by about 3–4 times, than on the trailing vanes. Assuming the ash particle concentration in the combustor gas just upstream of the NGVs is essentially the same for each vane position, the only plausible parameter driving the difference in deposit distribution is temperature. The best understanding available for these engine types is that the pressure surfaces (i.e. the visible surfaces in Figure 3) of both the leading and trailing vanes operate at roughly the same mean metal temperature; peak local surface temperature differences are no greater than ~20 K. However, the temperature of the gas the ash was in just upstream of the different vanes will have been something around 100–200 K hotter for the leading vane than the trailing vane, a typical combustor characteristic that is a function of its design. Consequently, it can be inferred that the accumulation rate increases by a factor of 3–4 over a 100–200 K increase in T4. This is a significantly steeper gradient than the Figure 2 linear extrapolation for Black Scoria, which gives the accumulation factor doubling from 4% to 8% between 1200 K and 1600 K

The final observation to make from Figure 2 is that as a low silica content basaltic material Black Scoria would be expected to have a relatively high melting temperature compared to more silica-rich and more commonly encountered volcanic ash, such as andesite and rhyolite; rhyolite has a melting temperature a few hundred K lower than basalt. It is believed that the glass in ash needs to substantially exceed its glass transition temperature and/or the bulk ash constituents need to approach a molten state before the ash can start to accumulate on the HP NGVs. If it is assumed that the difference in bulk softening/melting temperature between Black Scoria and andesite/rhyolite is similar to the difference in bulk softening/melting temperature between Blend #2 and Black Scoria, it is possible to put a tentative line where an andesitic or rhyolitic ash might appear in Figure 2; see the broken line in the top left hand corner of Figure 2. Gerbe et al.[7] indicates that by late June 1982, the ash from the Galunggung eruption was a phreatomagmatic basaltic andesite, with between 52% and 57% silica content. Bayhurst e al.[8] gives the proportion of silica in the ash from the 15 December 1989 Redoubt eruption at 69.9%, making it of dacite composition, a silica content midway between andesitic and rhyolitic ash. A linear relationship between T4 and accumulation factor over the 1250 K to 1500 K temperature range would suggest the accumulation factor for the BA009 encounter was at least 6% with the KLM867 encounter being significantly higher.

In an attempt to test the reliability of the suggestion that accumulation factors might be greater than the 1–5% taken for the original BA009 and KLM867 assessments, evidence was reviewed from two computational fluid dynamics (CFD) particle tracking studies conducted under the European Commission funded NEWAC volcanic ash programme (2010–2011).[9] One study by Chalmers University (Sweden) modelled the trajectories of representative ash particles through a combustor and HP1 NGV. Their results showed that the proportion of particles hitting the NGV pressure surface is ~11% for particles in the 1–2 µm size range, ~34% for particles between 2 and 4 µm, and ~95% for particles between 4 and 8 µm. From Calspan and other engine experience, typical average particle sizes at the compression system exit are around 6 µm; the ash particles entering the engine get broken into smaller pieces as they pass through the compressors. Note that the above particle hit rates should not be taken directly as accumulation factors. Two considerations will lead to a lower accumulation factor; (i) not all the ash entering the engine core will reach the combustor, some may be removed from the compressors in bleed air, as cabin air and cooling air (although cooling air is usually taken from inner annulus lines to limit contamination from particulates), and (ii) the Chalmers model did not include any representation of particle heat transfer or softening, so could not represent sticking or bouncing; in reality, a proportion of the particles hitting the NGV will probably bounce off.

The second NEWAC CFD study was conducted by Loughborough University (in the UK), a study that included a representation of the particle heat transfer, particle softening, potential bounce on contact with surfaces and an ash deposit shedding mechanism. The engine studied was a more modern engine than those involved in the BA009 and KLM867 events, dating from the early 21st century. The engine power setting investigated was climb with a T4 of around 1700 K and at these conditions Colantuoni et al.[9] quote an accumulation factor varying between 3.2% and 1.5% over an 8-min period. (Although not stated in Colantuoni et al.,[9] the accumulation factor was actually calculated to decrease from greater than 3.2% to 1.5% over the 8-min period.) Such a figure would appear to support the accumulation factor assumptions made in the original KLM867 and BA009 assessments, but the work reported in Colantuoni et al.[9] requires closer analysis.

Loughborough University is a Rolls-Royce University Technology Centre and a detailed description of the work has been included in an internal Rolls-Royce report. Initially, the CFD model was run without an ash shedding mechanism which resulted in a steady state accumulation factor for the same conditions as above of 34.5%. Believing this to be an excessively high value and being aware that deposit shedding was a possibility the analysts used the Kern and Seaton surface fouling model[10] and tuned it to represent the perceived behaviour of volcanic ash to represent the effects of deposit shedding. It was the use of this shedding model that resulted in the accumulation factors reported in Colantuoni et al.[9] Unfortunately, as implemented, the Kern and Seaton model led to some implausible results; (i) it predicted that sufficient deposit could accumulate on an HP NGV to surge the engine at 2000 mg/m^3 but at

800 mg/m^3, the engine could run indefinitely without accumulating enough ash to cause a surge and (ii) the accumulation factor would always reduce with time, which the limited Calspan data does not support, certainly over a 7- to 14-min time period. It is reasonable to expect some ash deposit shedding such that the accumulation factor for the conditions studied is less than 34.5%, but by how much is difficult to judge. It probably will be a function of ash composition, exposure duration, HP1 NGV surface temperatures, engine geometry and power setting.

Also included in the internal Rolls-Royce report of the Loughborough University NEWAC study were the results of a sensitivity study looking at the effects of varying ash particle size, density, Stokes number and spatial distribution. In the absence of a shedding model, these resulted in accumulation factors that varied between 15 and 38%.

Undoubtedly, both the above NEWAC CFD studies have their limitations, the absence of a reliable ash deposit shedding model being only one. However, it is difficult to see how these limitations can account for a discrepancy in the accumulation factors they generate and the value of 1% used for the 2010 BA009 analysis, a discrepancy greater than an order of magnitude.

Returning to the ash accumulation calculation carried out for the BA009 event, taking an accumulation factor of 6% and a longer exposure duration than the originally assumed 2 min, it is possible to arrive at an exposure ash concentration of around 200 mg/m^3. It is believed that the KLM867 engines run slightly hotter than the BA009 engines, and the evidence is that they attempted to climb out of the ash cloud at maximum power, which would have pushed the T4 even higher. These considerations, combined with the encountered ash type being a dacite, are plausibly all consistent with a higher accumulation factor than might have occurred on the BA009 engines. Assuming the accumulation calculation for the KLM867 event was originally carried out with an accumulation factor of 3%, but substituting an accumulation factor of 15% into the calculation gives an encounter concentration for this event of 400 mg/m^3. Any underestimation of the KLM867 encounter duration or over estimation of the mass of ash accumulated will reduce the encounter ash concentration further. However, if these possibilities are ignored, the available HP1 NGV ash accumulation evidence suggests that the KLM867 encounter occurred at a higher ash concentration than the BA009 encounter.

BA009 erosion calculation

Seeking additional evidence to test the suggestion that the BA009 encounter may have occurred at around 200 mg/m^3 rather than the original estimate of 2000 mg/m^3 attention was directed towards the compressor erosion calculation.

The assumption that ash erodes compressor aerofoils at the same rate as sand would appear questionable based on work carried out by Hamed et al.[11] which indicated that volcanic ash can be four times more erosive than sand. Another relevant source of data are a series of NEWAC erosion tests,[9] conducted on a variety of different rigs at different institutions, but all undertaken with ash collected from the 2010 Eyjafyallajokull eruption. These tests indicate that, depending on the impact incidence angle, the Eyjafyallajokull ash is equally erosive or up to 40% more erosive than the erosion rate taken for the BA009 calculation.

One of the weaknesses of the sand erosion data originally used in the BA009 calculation, and also the NEWAC data, is that they are for particles striking an aerofoil at its mid-height. Inspection of eroded compressor blades, including those from BA009, shows a high proportion of material loss at the tip. Discussions with one of the researchers involved in the sand erosion testing that provided the erosion rate for the original BA009 calculations concluded that the erosion environment existing at blade tips is probably quite different from those at the blade mid-height; particle incidence angles and velocities are likely to be substantially different, and abrasion exists at the tip – removal of material by particles interacting with two surfaces moving relative to each other, where a particle experiences multiple impacts.

The assumption that the ash particle incidence ratio is 10% can also be questioned. Experimental data generated by Rolls-Royce from a turning flow environment similar to that which exists in compressor rotor blades suggests that for particles in the 10–20 µm size range, the incidence ratio will be in the 40–80% range. It is believed that the overwhelming bulk of the ash mass entering the BA009 engine core compressors would have been in this size range or larger (based on the distance from the volcano where the encounter took place).[12]

The remaining parameter in the BA009 erosion calculation, the mass of metal eroded, is probably the most uncertain. A review of the method used to arrive at the mass eroded, inspection of photographs taken in 1982 of the damaged compressor blades (Figure 4), confirmed the level of uncertainty. A further complicating factor is that the engines had been in service for some time. Consequently, they would have experienced, as part of normal operation, occasional contact between the rotor blades and the compressor casing, known as tip rubs; tip rubs result in some material loss. Also, when engines surge, they tend to experience heavy rubs and greater material loss. How much of the material lost from the compressor blades was from normal operation, the surges they experienced during the ash encounter or from erosion/abrasion by the ash is difficult to quantify.

Assuming the mass of eroded metal was overestimated and taking the uncertainties in the incidence ratio, the possibility that the erosion rates originally assumed are a little low relative to what might be expected for the volcanic ash encountered and the encounter was greater than 2 min, it is possible to plausibly arrive at an ash concentration for the BA009 encounter in the region of 200 mg/m^3.

Times to engine surge and flameout

Although the Calspan engine tests were not run with true volcanic ash, the nature of the dust blends used do make them a useful reference point for judging how long a gas turbine engine can operate in volcanic ash before it loses controllable thrust or shuts down. The dust concentrations used for the Calspan engine tests were between 50 and 500 mg/m^3, however, it is over the 250–500 mg/m^3 range that engine surge behaviour is reported in some detail. It can be inferred from Dunn[13] that a F100 engine exposed to dust concentrations of 250 mg/m^3 and 500 mg/m^3 will run out of surge margin after about 6 min and 3 min, respectively. Informal discussions in 2011 with the Calspan lead researcher, Mike Dunn, confirmed this perception and that similar results were obtained from the Calspan YF101 engine tests.

Low bypass ratio fast jet engines run at ground level generally have more surge margin than high bypass ratio civil turbofans operating above 25,000 ft. The kind of manoeuvre a fast jet needs to be capable of requires greater operability margins in its engines than the engines of a civil airliner, where high fuel efficiency is more important. The need for ever greater fuel efficiency in civil turbofans is leading to higher pressure ratios and smaller, more compact, cores that run at hotter temperatures. These trends tend to lead to reduced surge margins. So, if a fast jet engine runs out of surge margin on the ground in 3 min when exposed to 500 mg/m^3 of a low glass content mineral dust (as with the Calspan tests), it would be reasonable to expect a high bypass ratio civil turbofan engine at 25,000–37,000 ft to run out of surge margin within 2–3 min when exposed to 200–500 mg/m^3 of a high glass content volcanic ash, *à la* BA009 and KLM867 encounters.

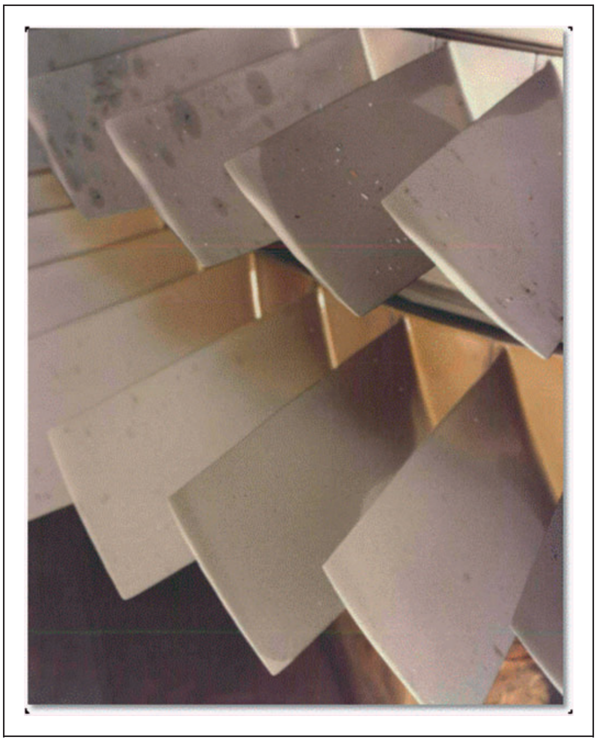

Figure 4. Damage to IP Compressor Stage 1 & 2 Blades from flight BA009.

Ash cloud modelling and measurement

The considerations covered in the preceding sections suggest the possibility that the BA009 and KLM867 encounters could have occurred in ash concentrations in the region of 200 mg/m^3. Additional sources of data that might be used to explore this possibility further are ash cloud dispersion modelling and direct measurement of ash cloud concentrations.

As commented on above a study by the UK Met Office[5] using their NAME dispersion code, the same code used to produce the 2010 ash concentration forecasts gives maximum concentrations for the two encounters at approximately 70 mg/m^3 for the KLM867 event and around 320 mg/m^3 for the BA009 event (see Table 1). The question of whether dispersion models such as NAME would consistently under-predict backcasts by an order of magnitude is being addressed by the appropriate stakeholders and is outside the scope of the current paper. However, discussions with the Met Office staff who are responsible for the NAME modelling indicated that, while there is a level of uncertainty in both NAME forecasts and backcasts, it is not currently easy to explain why

Table 1. Distance from volcano vent and magnitude of eruption for BA009 and KLM867 encounters.[5]

Event	Volcano	VEI	Distance from vent (km)	NAME backcast max. ash concentration[5] (mg/m^3)
KLM867	Mt Redoubt, 1989	3	~150	~70
BA009	Galunggung, 1982	4	~150	~320

Note: VEI is a logarithmic scale of explosive eruption magnitude.

backcasts would consistently under-predict concentrations by an order of magnitude or more.

An alternative type of model to NAME for calculating volcanic ash concentrations, and one that has been used by the aviation industry in the past as a guide to the likely atmospheric ash concentrations that might occur from different eruption scenarios,[14,15] was proposed by Bursik et al.[16] in 1991. Bursik et al.'s model uses in essence an integral approach to calculate the variation in ash concentrations with distance from the vent and was calibrated against data on ground deposit thickness variations and grain size distributions. The model results presented in Bursik et al.[16] cover a variety of eruption scenarios, but unfortunately none cover the exact conditions of either the 24 June 1982 Galunggung or 15 December 1989 Redoubt eruptions. It is possible using a series of extrapolations and interpolations of the results presented to arrive at a range of approximate average ash concentrations for the BA009 and KLM867 encounters. However, there are two key model parameters that influence these extrapolations and interpolations which are difficult to assess from the presented results; the vertical extent of the ash clouds and to what extent particle aggregation aids ash fall to the ground.

The authors have had many discussions with the world's leading volcanologists, including two of the authors of Bursik et al.,[16] concerning the likely impact of particle aggregation on the ash concentration 150 km from a 1982 Galunggung or 1989 Redoubt size eruption. Views are divided, some suggesting that field evidence indicates significant aggregation would have existed and thus concentrations of around 2000 mg/m^3 for the BA009 and KLM867 encounters would be very unlikely. Others though have suggested such a conclusion is not certain. Despite the uncertainty in the part aggregation played, it would still be instructive if the model from Bursik et al.[16] was set up and run specifically for the BA009 and KLM867 encounters.

Another potential source of data that might establish whether the KLM867 and BA009 encounters occurred at 2000 mg/m^3 would be actual measurements of ash concentrations 150 km from similar scale eruptions to the 1982 Galunggung and 1989 Redoubt eruptions. At the time of writing, the only measurement techniques that can directly measure ash concentrations involve instruments that need to be in close proximity to the ash cloud. Getting such instruments close enough to the ash clouds, e.g. on aircraft, is very difficult and very few measurements are available. A more widely used means of establishing ash cloud density is by measuring the interaction of visible and infra-red radiation with ash particles via satellite mounted instruments.[17] However, these techniques only give a direct indication of the total mass of ash in a column of atmosphere, that is, the total mass of ash suspended in the atmosphere per unit of ground surface area (i.e. g/m^2). To convert such data into an average ash concentration requires knowledge of, or assumptions about, the ash cloud vertical thickness. In addition, depending on a number of factors (predominantly ash particle size distribution, but also the presence of water cloud and the relative temperatures of the earth's surface to the ash cloud temperature), these satellite measurements typically detect 10–50% of the actual ash present, but can detect as much as 90% or as little as 1% of the ash present (personal communications with M I Watson, University of Bristol, School of Earth Sciences).

Accepting the limitations of satellite measurements, typical satellite measured total column ash loadings 150 km from the vent of volcanic eruptions similar in size to the 1982 Galunggung and 1989 Redoubt eruptions would be 1–100 g/m^2, with 100 g/m^2 being rare and very localised (personal communication, M I Watson, University of Bristol, School of Earth Sciences, 2012). There are obviously a number of assumptions that could equate such numbers to an ash concentration of 2000 mg/m^3 (see Table 2). The expert view is that the scenario listed in the first line of Table 2 is possible but very rare.

Satellite data from the 1982 Galunggung eruption measured peak column loadings between 15 and 20 g/m^2 (personal communication with A J Prata, 2012). The BA009 aircraft suffered its first set of engine failures whilst cruising at an altitude of 37,000 ft (11.5 km). With no engine power, the flight crew turned left and descended in a glide for about 12 min, whilst continuously being in the ash cloud. They finally entered clean air at around 12,000 ft, at which point they managed to restart all the engines. Jakarta Air Traffic Control then asked the crew to climb back above 15,000 ft so they could be seen on radar above the mountains of Java. Unfortunately,

Table 2. Combinations of assumptions that would result in ash concentration of 2000 mg/m^3.

Satellite measured column loading (g/m^2)	Proportion of ash detected by satellite	Ash cloud thickness (m)	Mean ash concentration (mg/m^3)
100	10%	500	2000
20	10%	100	2000
20	2%	500	2000

the aircraft re-entered the ash cloud and after between 3 and 7 min, at ~15,000 ft, engine number 2 started to surge and had to be shutdown. If the exposure was 3 min and the climb rate was 500 ft/min, this would put the ash cloud base at around 13,500 ft (4.1 km). An ash cloud of thickness 7400 m with an average ash concentration of 2000 mg/m^3 would seem unlikely. Two separate dense ash layers are certainly possible, and to only just cover both phases of the BA009 flight where the engines shutdown, the layers' thicknesses need to be; a 100 m thick layer at around 37,000 ft and a 500 m thick layer at around 13,500 ft – see second and third lines in Table 2. Both these scenarios are possible but highly unlikely.

The evidence from the BA009 event makes it difficult to be very precise about the ash cloud thickness during the encounter, but the evidence from the KLM867 event means that a minimum ash cloud thickness can be established, noting that a minimum ash cloud thickness gives an upper limit on the average ash concentration. The KLM867 flight crew first became aware they were in an ash cloud at 25,000 ft.[3] All four engines failed after they had climbed to around 27,900 ft. Thus, it can be inferred that where flight KLM867 encountered the ash cloud it was at least 884 m thick. (Note that the Redoubt eruption plume height on the morning of 15 December 1989 is believed to have been 39,000 ft[5].) To get to an average ash concentration of 2000 mg/m^3 within an 884 m thick ash layer would require a total column loading of 1768 g/m^2, which would need a scenario similar to that covered by the first line in Table 2.

To conclude this section, current ash cloud modelling capabilities and actual ash concentration field measurements have their limitations, but are still useful sources of evidence for understanding the ash concentrations the BA009 and KLM867 aircraft encountered. The evidence they provide does not preclude the possibility that in both encounters the ash concentration was as high as 2000 mg/m^3, but it suggests this would be very unlikely, whereas an ash concentration in the vicinity of 200 mg/m^3 would currently appear more likely. The many discussions the authors have had with the scientists engaged with ash cloud modelling and measurement generally support this view; however, further work in these areas would be very fruitful in understanding the ash cloud environments the BA009 and KLM867 aircraft encountered.

Visibility evidence

In addition to the engineering analysis and ash cloud measurement and modelling, another potential source of evidence for understanding the ash concentrations the BA009 and KLM867 flights encountered is the visibility in the ash clouds. Desert sand and dust storms are a useful reference point for visibility. There is a substantial amount of published information that puts the particulate concentration in an average dust storm concentration at around 2 mg/m^3 with the concentration being typically 20 mg/m^3 in a severe dust storm. Work by Dayan et al.[18] indicates that visibility is approximately 1 km in a particulate concentration of 1 mg/m^3, whereas the visibility in a severe dust storm is usually only a few 10 s of metres. Shao et al.[19] developed a validated model for relating dust concentrations to visibility in the dust storms of northeast Asian; for visibilities less than 3.5 km, the relationship between visibility (V) in m and the dust concentration (C_{dust}) in mg/m^3 is given by

$$V = \frac{4900}{C_{dust}^{1.19}} \tag{3}$$

Another useful source of visibility data is a presentation by the Environment Agency of Iceland which comprises a series of photographs of ash from the 2010 eruption of Eyjafjallajokull taken about 33.5 km from the volcano.[20] The photographs are of re-suspended ash gradually increasing in concentration over time, with the corresponding reduction in the visibility evident; ash concentration was measured directly while landmarks at known distances from the camera gradually disappear from view giving an indication of the visibility. Consequently, it is possible to relate visibility to ash concentration – see Table 3. Also included in Table 3 are the constants of proportionality derived for an inverse relationship between visibility and ash concentration and a law following Shao et al.'s[19] relationship for dust storms – equation (3) above. The constant of proportionality values suggest the data from Finnbjornsdottir and Mila[20] follows an inverse law.

Table 4 presents predicted visibilities at elevated ash concentrations using the Shao et al.relationship and an inverse relationship derived from Table 3 taking a visibility at 4 mg/m^2 of 400 m (i.e. $k_2 = 1600$). Both relationships give visibilities at 2000 mg/m^3 of less than a metre.

Recorded interviews and reports from flight crew and passengers on flight BA009 include comments about seeing flames coming out of the back of the engines and St Elmo's fire effects being visible in the

Table 3. Ash concentration and visibility data from the 2010 Eyjafjallajokull from the Environment Agency of Iceland.[17]

C_{dust} (mg/m^3)	V (m)	$k_1 = VC_{dust}^{1.19}$	$k_1 = VC_{dust}$
0.05	>50,000	–	–
0.075	20,000	917	1500
0.3	4000	955	1200
0.75	1600	1136	1200
1.5	1000	1620	1500
4	400	2082	1600

Table 4. Predicted visibilities at elevated ash concentrations using the Shao et al relationship and the inverse relationship derived from Table 3.

	From Shao et al.[16] $k_1 = 4900$	From Table 3 $k_2 = 1600$
C_{dust} (mg/m^3)	$V = k_1/C_{dust}^{1.19}$(m)	$V = k_2/C_{dust}$(m)
2	2148	800
20	139	80
200	9	8
2000	0.6	0.8

engines. During discussions between the BA009 pilot, Captain Eric Moody, and the authors, Captain Moody confirmed these observations. He added that he distinctly remembers seeing, from the cockpit, a very bright light coming from the engine core inlet, behind the fan blades (also see Boeing[1]), which could be seen rotating due to a strobe effect. The ability to make out features on the engine, such as fan blades and the core inlet, would not be consistent with a visibility of a few feet; the engines and wings would not be visible from the cockpit or the rear of the aircraft. Observation of details like these is more consistent with the visibility at ash concentrations of around 200 mg/m^3 or less. No visibility evidence from the KLM867 encounter appears to be available, except a comment from the flight crew made during the encounter that it had gone quite dark.

Considerations from the presented BA009 and KLM867 encounter re-evaluations

If the observations and rationale described above are accepted, an ash concentration of 2000 mg/m^3 for the BA009 and KLM867 encounters would appear unlikely. The volcanological data suggests that an ash concentration of around 200 mg/m^3 for the two encounters is substantially more likely, with such a figure being towards the lower limit of plausibility based on the engineering data; stretching the engineering analysis to obtain ash concentrations below 200 mg/m^3, to say 100 mg/m^3, is possible but lower than this would be difficult to justify. The visibility evidence from the BA009 event also supports the lower ash concentration. Therefore, it feels prudent to set the lowest justifiable concentration for the BA009 encounter at 100 mg/m^3, with the slightly higher value of 200 mg/m^3 probably being more appropriate for the KLM867 encounter. Although unlikely, it still feels appropriate to leave the upper justifiable concentration for both encounters at 2000 mg/m^3. Consequently, an adjustment to the position of the BA009 and KLM867 events on the 2010 ‘Safe-to-Fly’ chart is proposed to reflect the revised analysis – see Figure 5.

There is one consideration worthy of comment that would make the visibility evidence, the satellite measurement data and the ash cloud modelling work potentially more consistent with a concentration towards the higher end of the 200–2000 mg/m^3 range and that is the particle size distribution of the ash each aircraft encountered. Satellite infra-red measurement techniques are most effective at detecting ash particles in the 2–30 µm size range. An example where a satellite measurement might only be detecting 10% of the ash present would be if something like 70% of the mass of ash existed as particles with sizes greater than 100 µm. Such a size distribution would also increase the visibility for a given concentration compared with a distribution that had the majority of the ash mass existing in particles smaller than 100 µm. A counteracting effect with respect to engine damage though was indicated by a study within the NEWAC project[9] that looked at the centrifuging effect engine fans have on ash particles. This study suggested that, while effectively 100% of particles 10 µm or less in size, in the core streamtube, will pass through the fan and into the core, only something like 30% of particles greater than 100 µm will find their way into the core; the remaining 70% of particles at 100 µm or greater get centrifuged down the bypass duct where they do negligible damage (noting that the exact proportion of ash particles that get centrifuged down the bypass duct will depend on the fan design details and the engine power setting).

Consequently, if the only way the ash concentrations the BA009 and KLM867 aircraft encountered could have been as high as 2000 mg/m^3 is due to a very high proportion of the ash particles being greater than 100 µm, the bulk of the engine core damage would have been caused by the small proportion of ash mass present as particles less than 100 µm in size. Such a situation would need to be taken into consideration when extrapolating the consequences of the BA009 and KLM867 events to the likely impacts on aircraft engines at ash concentrations in the 2–20 mg/m^3 range; these usually occur a greater distances from the volcano vent than the 150 km that the BA009 and KLM867 encounters occurred and where ash particle size distributions contain much lower proportions of particles greater than 100 µm in size.

It was stated in the introduction of this paper that the original 2010 version of the ‘Safe-to-Fly’ chart was used to make judgements on the predicted ash concentration below which flight would be safe. The possibility that the two key historical aircraft encounters used in the ‘Safe-to-Fly’ chart occurred at 100–200 mg/m^3 rather than the originally assumed 2000 mg/m^3 suggests an assessment of what this means for flight operations in actual ash concentrations of 2 mg/m^3 is justified. To facilitate this and noting the shortcomings of the ‘Safe-to-Fly’ chart indicated above, that it is essentially a one-

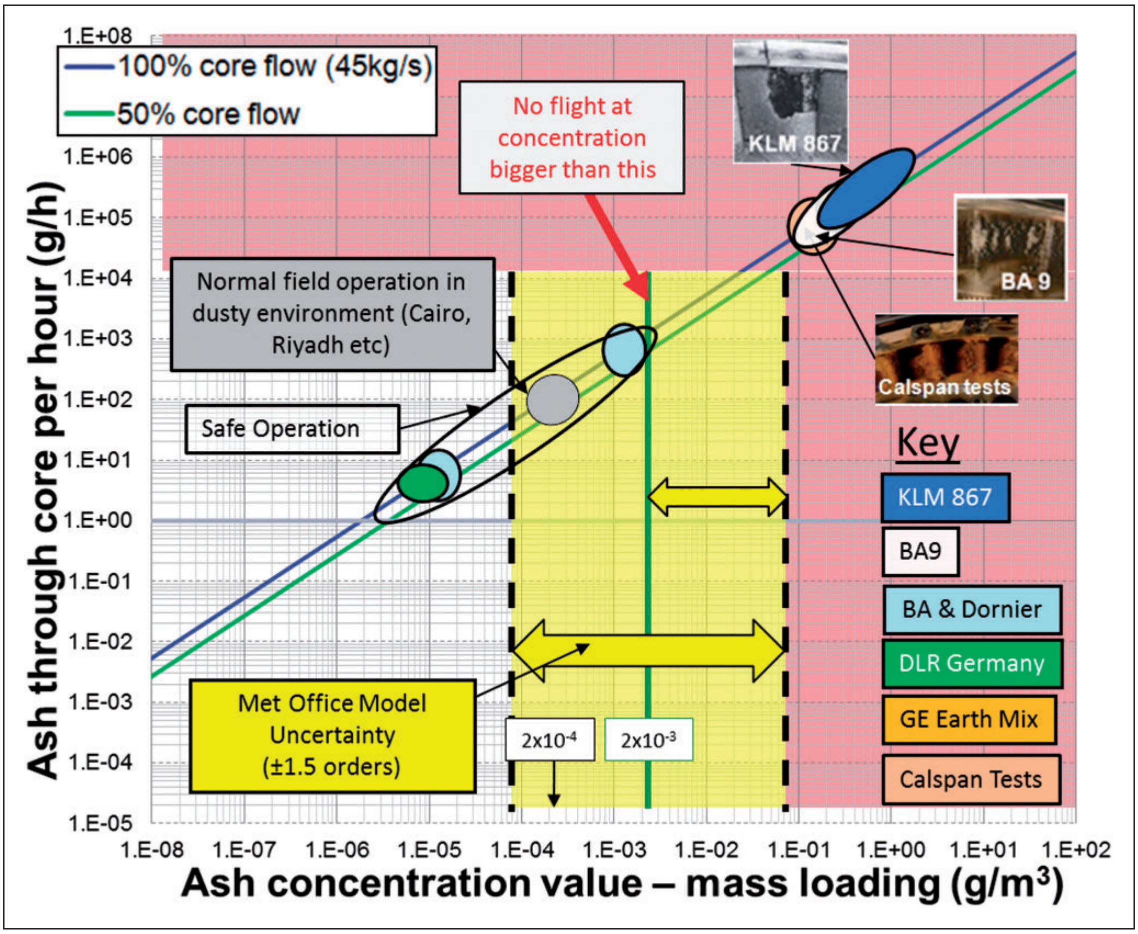

Figure 5. Revised 'safe-to-fly' chart.

dimensional plot, a new chart is proposed: a duration of exposure against ash concentration chart (Figures 6–8).

Duration of exposure against ash concentration chart

One of the limitations of the original 'Safe-to-Fly' chart is that although it indicates a range of ash concentrations in which flight is safe (i.e. a suggested value of up to 2 mg/m^3) and a range where flight is definitely unsafe (i.e. a suggested value of greater than ~80 mg/m^3), it gives no indication of the safety status between these two ranges (i.e. between 2 mg/m^3 and 80 mg/m^3). The implication would be that within this intermediary range the flight might be safe or might not be safe, and if it is potentially unsafe it gives no indication what criteria or circumstances would lead to an unsafe situation. It is likely that there are a large number of factors that will make flight unsafe in the intermediary range of concentrations (e.g. ash type, engine age, engine design and operating condition). Of these factors, one of the most significant is probably the duration of the volcanic ash exposure. Hence, it makes sense to produce a chart that plots ash concentration against duration of exposure and it was the UK Ministry of Defence (MoD) who requested that the authors produce such a chart as part of a work package the UK MoD were funding in 2012. The drawback of such a chart is that it is still very difficult to represent all the factors that will influence flight safety; despite this, such a chart has proved very instructive in illustrating the main considerations for flights between a totally benign ash concentration and one that would rapidly lead to an unsafe condition.

Figures 6–8 illustrate the main features of the proposed 'Duration of Exposure v Ash Concentration' chart. Because of the chart limitations already mentioned above and because there is very little reliable quantitative data linking ash concentration and exposure duration to engine impact, with the added complication that what data points exist almost certainly occurred over a range of ash concentrations, the chart presented is effectively just a sketch; in its current form, it should not be used as an aid to flight operations. The chart's purpose is to illustrate what is known, what is not known and what the main considerations would be if flight between a totally benign ash concentration and one that would rapidly lead to an unsafe condition was being considered or occurred accidentally.

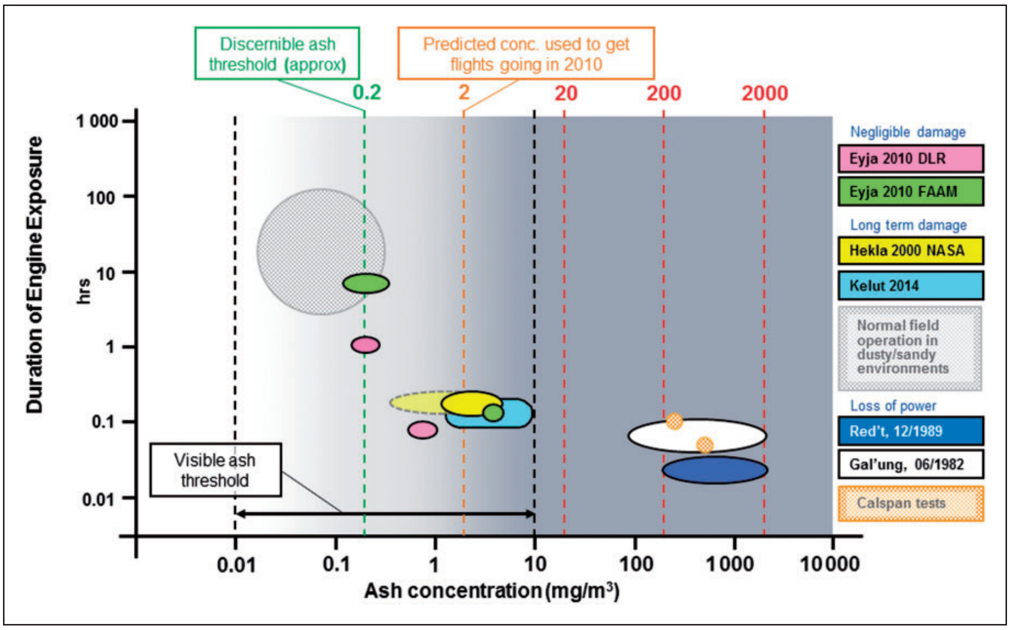

Figure 6. Duration of exposure against ash concentration chart.

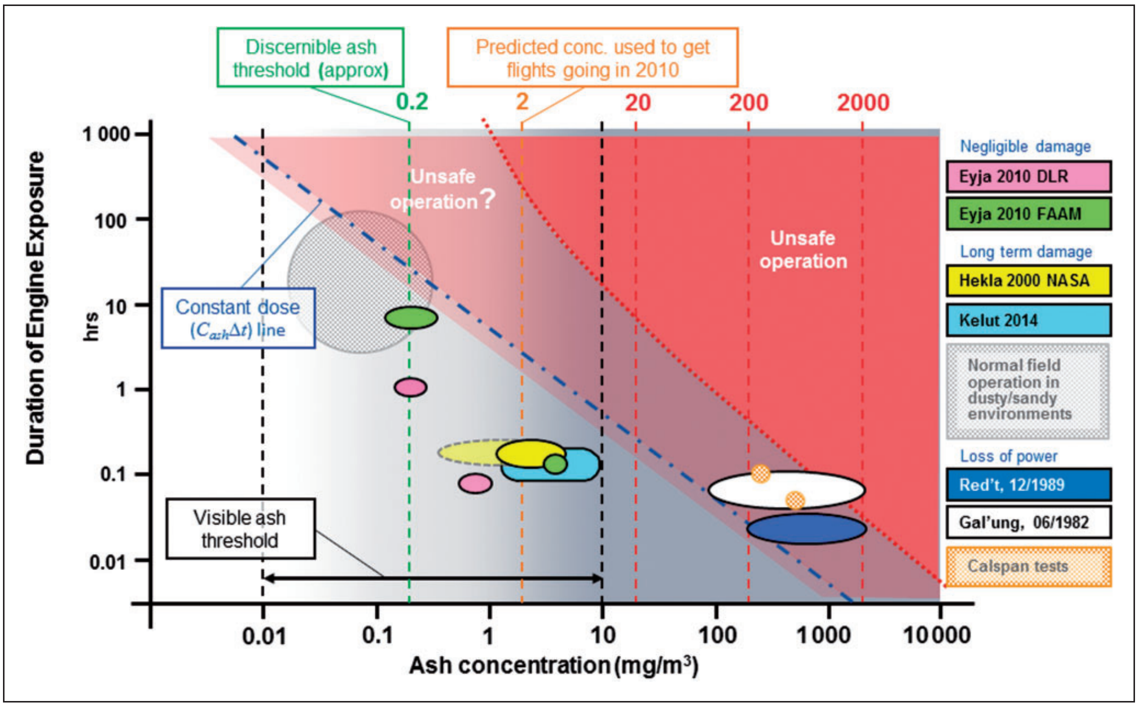

Figure 7. Duration of exposure against ash concentration chart with unsafe operation regions added.

The key features to note in Figure 6 are:

- The ash concentrations to which aircraft have been exposed covers around six orders of magnitude and the durations of exposure that are of interest range from minutes to potentially 10 s of hours, for multiple exposures, consequently a log-log scale is used.
- For many years, ash visibility has been one of the criteria used for judging whether it is safe to enter an ash cloud, hence the often referenced phrase ‘avoid visible ash’. There has been much debate and confusion about what is actually meant by ‘visible ash’ and what ash concentrations and ash cloud size would lead to ash being detectable by a human eye or indirectly visible by some other means (e.g. existence of St Elmo’s fire on a cockpit windshield, smell, observation of a measurement instrument – noting that the Oxford English Dictionary gives the common use definition of

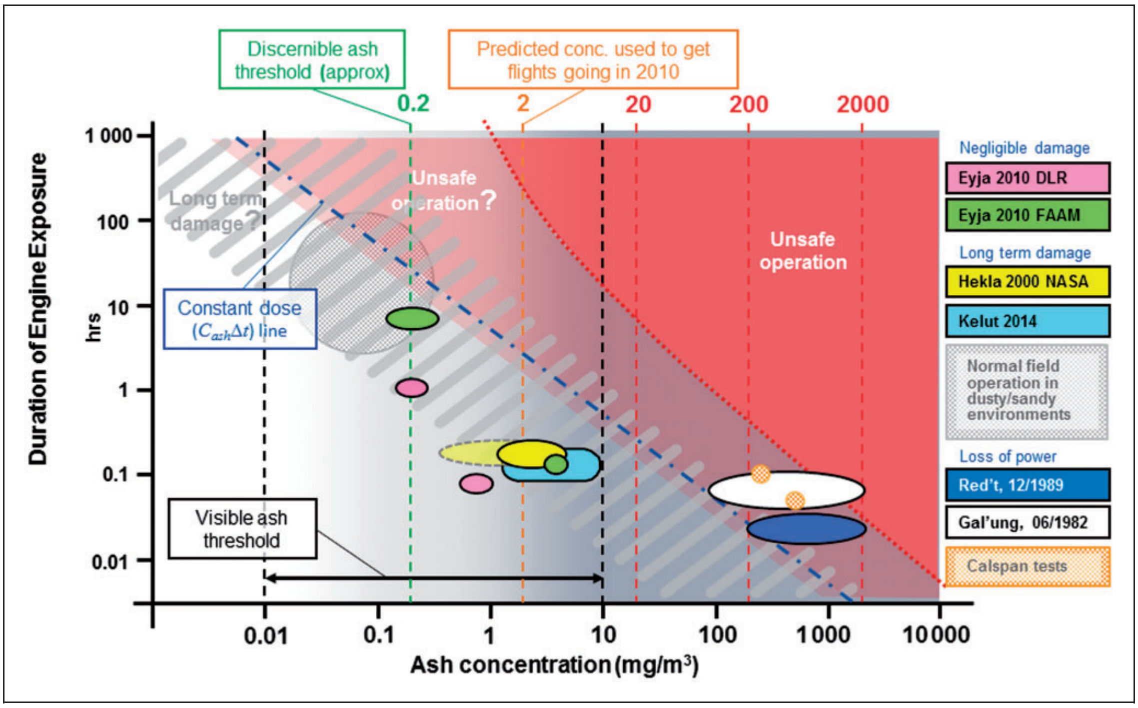

Figure 8. Duration of exposure against ash concentration chart with long term damage region added.

'visible' as 'able to be seen, perceived or noticed easily'). For the aviation context, the International Civil Aviation Organisation (ICAO) has provided a definition of 'visible ash';[21] however it was felt useful to illustrate within the chart the range over which ash starts to become visible to the human eye i.e. ∼0.01–10 mg/m^3.[22] This is done using a white to grey background shading from 0.01 mg/m^3 to 10 mg/m^3; ash should always be visible to the human eye in good light above 10 mg/m^3.

- The approximate lower limit concentration that current satellite infra-red instruments can detect, 0.2 mg/m^3 (essentially based on a lowest detectable total column loading of 0.2 g/m^2 distributed over a representative ash cloud of 1 km vertical thickness[23]) and the predicted ash concentration up to which flight was allowed in 2010, 2 mg/m^3, are shown as vertical lines. Vertical lines are also included at 20, 200 and 2000 mg/m^3.
- Note that it is the usual convention when discussing aircraft volcanic ash encounters not to link an airline name to an encounter; events are identified by the volcano that produced the ash cloud and the date of the encounter. If this is insufficient to uniquely identify an encounter, additional information has been included. Hence, the choice of labels for the event bubbles.
- The aircraft encounter event bubbles are positioned using the best data available on the exposure duration and ash concentration associated with these events. The size of the bubbles relates to the uncertainty in the data; the larger the bubble, the greater the uncertainty.
  - The concentration and duration of exposure for the 'Eyja 2010 FAAM' encounters were taken from Johnson et al.[24] and involved a BAe 146 aircraft fitted with ash concentration measuring instruments. Two bubbles are shown to illustrate the accumulated effect of a group of separate exposures at similar concentrations (upper left bubble) and a single short duration exposure at a relatively high concentration (lower right bubble). No short-term or long-term effects on the engines were reported.
  - The 'Eyja 2010 DLR' data were taken from Schumann et al.,[25] and involving a Falcon 20 E aircraft fitted with ash concentration measuring instruments. Again two bubbles are shown to separate the effects of a short-term exposure and accumulated longer-term exposures at lower concentrations. No short- or long-term effects on the engines were reported.
  - The concentration and duration of exposure for the 'Hekla 2000 NASA' event were primarily taken from Witham et al.[5] (solid yellow bubble), but an analysis conducted by Prata (A J Prata, 2014, personal communication) suggests the encounter may have occurred at a substantially lower ash concentration (broken yellow bubble). The consequences of this event were long-term damage to the engines such that they had to be prematurely removed from the aircraft shortly after the exposure.[26]
  - The most recent point on the chart ('Kelut, 2014') was an encounter that occurred during the Kelut eruption of February 2014, where, after a safe landing, the engines of the A320

aircraft involved were removed and underwent substantial repair. The concentration and duration of the encounter have been based on two independent analyses of the event, one by Kristiansen et al.[27] and another by Pavolonis et al.[28] (of the National Oceanic and Atmosphere Administration (NOAA)). The results from Pavolonis were given in a personal communication, the method of the analysis being that reported in Pavolonis et al.[28] Both analyses produced essentially the same results.

  - ○ The concentrations for the BA009 (i.e 'Gal'ung 06/1982') and KLM867 (i.e. 'Red't 12/1989') encounters are taken from the current revised analysis of these events. The duration of the events has been taken from an internal Rolls-Royce report of the BA009 event and from data on the KLM867 event in Przedpelski and Casadevall.[3] The consequences of these exposures are well documented (see above).

- The large grey bubble labelled 'Normal field operation in dusty/sandy environments' represents typical operation of engines between major overhaul in sandy dusty environments, such as the Middle East and Persian Gulf (data taken from Rolls-Royce's service records). It is included to provide some insight into the effects of many repeated exposures to low concentrations. It should be noted that the data only really apply to desert sand and dust, a substantially less damaging material than volcanic ash.
- Two of the Calspan points are included for reference, the points being the two F100 engine tests inferred from Dunn[13] – see above. Again it should be noted that the material ingested during these tests is not strictly volcanic ash

Figure 7 is Figure 6 with three regions superimposed showing different safety regimes. The dark red region covering the top right corner, labelled 'Unsafe operation', covers the region of the chart where there is little doubt flight would be unsafe. Its lower extent is bounded by a line extending from the upper ash concentration deemed plausible for the BA009 and KLM867 events (see above) towards longer duration exposures at lower concentrations. The non-linear curving up of this lower boundary line reflects the possibility that some of the damage mechanisms may attenuate at lower concentration, something that is credible but currently only speculation.

The pink region labelled 'Unsafe operation?' covers the region of the chart where there is an increasing uncertainty over what represents unsafe operation. Its lower boundary is defined by a constant dose line – the product of exposure duration and ash concentration – calculated from the lowest justifiable ash concentrations for the BA009 and KLM867 events presented above, i.e. ash concentrations of 100–200 mg/m^3. Using a constant dose line to bound this region is reasonable if it is assumed that engine damage is simply a function of the mass of ash ingested. The additional lighter pink region below the constant dose line covers the possibility that more modern engines to those associated with all the event bubbles have greater susceptibility to ash; all the engines associated with the plotted events were designed before the mid-1990 s. It also covers the possibility that the BA009 and KLM867 events did not take place in the most damaging ash type.

Figure 8 is Figure 7 with an additional region added (grey cross hatched region), a region covering exposures that would not lead to unsafe operation but would lead to longer term damage, damage that would result in early engine removal for repair or in the worst case could ultimately lead to a single engine in-flight shutdown due to component failure many flights after the exposure.

It is important to comment here that the exact boundaries of the unsafe operation and long-term damage regions of Figure 8 are currently unclear, hence the question marks associated with their labels. Their position and extent in Figure 8 are based on the limited data currently available. In addition, it is stressed that for a given engine type, engine condition (i.e. use since previous overhaul), power setting and ash type, the position and extent of the regions will change, which is why such a generic chart is essentially only a sketch of the available data. Having said this, the chart does illustrate the main considerations covering operation over the 0.01–100 mg/m^3 concentration range, i.e. duration of exposure, safety and long-term, primarily economic, damage.

Conclusions

An extensive review of relevant and available engineering data has been undertaken in relation to the average ash concentrations ingested by the engines involved in the 1982 BA009 and the 1989 KLM867 volcanic ash encounters. Although there is substantial uncertainty in the engineering data, the data that are available suggest that these encounters could quite plausibly have occurred in ash concentrations of around 200 mg/m^3. Such a conclusion has been verified, to a degree, against volcanological and ash cloud visibility data; the bulk of this type of data also suggests that these encounters are more likely to have occurred in average ash concentrations closer to 200 mg/m^3 than 2000 mg/m^3. However, the available evidence does not preclude the possibility that both encounters occurred in concentrations of around 2000 mg/m^3; it just suggests such a concentration is unlikely.

The possibility that the BA009 and KLM867 encounters took place in ash concentrations an order of magnitude less than assumed in 2010 may have implications for judgements made in 2010 and probably justifies further analysis. To help understand the implications a new chart is proposed that plots known engine ash encounters on a graph of exposure duration versus encounter average ash concentration. Although useful for illustrating the important considerations associated with flight in volcanic ash, the level of quantitative uncertainty remains high. Reducing the uncertainty would require further engineering and volcanological studies, such as, respectively, engine and engine sub-system volcanic ash testing and assessments of variations in ash concentrations with distance from volcanoes using volcanic ash cloud measurements and modelling.

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Appendix

Notation

$\mathrm{C}_{\mathrm{ash}}$	ash concentration (mg/m^3)
C_{dust}	sand and dust concentration (mg/m^3)
k_1, k_2	constants of proportionality in visibility expressions
m_{ash}	mass of ash deposited (kg)
m_{ero}	mass of rotor eroded (kg)
$\dot{m}_{air}$	engine core mass flow (kg/s)
Δt	duration of exposure (s)
V	visibility (m)
β	rotor blade ash incidence ratio (%)
ε	rotor blade erosion rate (g/kg)
ρ_{air}	density of ambient air (kg/m^3)
ζ_{NGV}	nozzle guide vane accumulation factor (%)