Maximising Airspace Use During Volcanic Eruptions: Matching Engine Durability against Ash Cloud Occurrence

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ABSTRACT

Maximising the usable airspace during volcanic eruptions is important for both civil and military aviation. A key strategy for achieving this would be to establish more accurately the susceptibility of gas turbine engines to volcanic ash damage, from both a safety implication and economic damage perspective; such knowledge could then be used to plan operations that keep exposure to ash within acceptable limits.

This paper explores the most recent understanding of aircraft gas turbine engine susceptibility to volcanic ash, based on historical and more recent in-service events, engine level testing and fundamental research at a laboratory level. An updated and enhanced duration of exposure versus ash concentration (DEvAC) chart is presented and a phenomenological mathematical model of core compressor surge margin loss is proposed. A means of defining an engine's ash susceptibility based on ash dose is also proposed. How such an engine susceptibility could be used operationally is discussed using a hypothetical ash cloud scenario.

1.0 INTRODUCTION

It has been known for some considerable time that volcanic ash can seriously damage gas turbine engines; yet there is evidence engines can be exposed to small quantities of volcanic ash and suffer negligible damage. The level of impact volcanic ash has on gas turbine engines is a complex function of the ash's nature – its chemistry and physical characteristics – and the engine's design, general condition, flight operating point and thrust setting. In addition to these factors it is also reasonable to expect that the length of time an engine is exposed to a particular ash concentration has a strong influence over whether the impact is relatively benign or quite damaging.

Since gas turbine powered aviation began there have been many, and regular, volcanic ash related flight disruption events. The extent of the disruption has been driven to a large degree by an ash total avoidance strategy for maintaining flight safety margins. The financial losses and general frustration such flight disruption can cause civilian operators, and their customers, has led many stakeholders to question whether a total avoidance strategy is entirely acceptable, particularly as there is evidence to suggest it is not absolutely necessary. For military operators the impacts of not flying are more to do with a loss of operational flexibility; from an inability to undertake combat missions, conduct short and long range medical evacuations, keep airborne supply routes open and not least provide essential humanitarian aid.

Clearly the only alternative to a total avoidance strategy is to allow flight operations in airspace contaminated with some level of volcanic ash. However, before operation in volcanic ash contaminated airspace can be undertaken a better understanding of engine volcanic ash susceptibility is needed. Specifically there is a requirement to establish the level of ash contamination which might lead to safety concerns, but there is also a need to give an indication of the contamination levels which could result in unacceptable economic damage or an unacceptable maintenance burden.

To be able to establish a volcanic ash susceptibility it is reasonable to expect, as a pre-requisite, that a detailed quantitative knowledge be available of the relationship between the level of damage and the factors that influence the damage; such knowledge could be used to mathematically model engine behaviour and the rate at which they deteriorate from exposure to different volcanic ash conditions. Although a sizable amount of theoretical and experimental work has been carried out in recent years – looking at the effects and relative importance of the factors that influence damage – there are still substantial gaps in the knowledge. These gaps mean that any calculations carry considerable uncertainty, which in turn will inevitably lead to conservative conclusions; a declared susceptibility would have to err on the side of caution. However, declaring a conservative susceptibility which allows some operational flexibility is preferable to a total avoidance strategy.

The purpose of this paper is to give an outline of an approach which has been used by Rolls-Royce to define a gas turbine engine susceptibility to volcanic ash. The defined susceptibility offers operators the option of flying for a limited and controlled period of time in airspace contaminated with low levels of volcanic ash without significantly reducing flight safety margins. A description is included of a volcanic eruption scenario to illustrate where the engine susceptibility can be used practically for flight operations.

2.0 ENGINE SUSCEPTIBILITY

The primary mechanisms by which volcanic ash damages gas turbine engines are well known. Consequently, in principle, complex mathematical models based around computational fluid dynamics (CFD), combined with finite element analysis (FEA) to represent mechanical interactions, could be constructed which would allow the analysis of the main damage effects. Unfortunately, however, there is still currently too much uncertainty over many of the detailed phenomena involved in the damage mechanisms to allow such models to be calibrated and validated; any results they produce would be unreliable. They would also be very expensive to run in terms of time and required computing power.

There are two alternative approaches to using large complex computational models. The first involves studying whole engine data to look for trends in behaviour; that is, collect data from suitable engine volcanic ash exposure events or tests and then correlate the data against likely safety and cost of ownership implications. If such holistic data covers a sufficiently varied set of volcanic ash and engine conditions, an acceptable ‘not worse than’ susceptibility could be inferred. The second approach involves using simple phenomenological mathematical models that are based on empirically derived correlations. Such models are easy to construct, calibrate and validate. They are also very fast to run.

2.1 Whole Engine Data

A good starting point to understand gas turbine engine susceptibility to volcanic ash is to study previous ash exposure events and to look for trends in the parameters affecting damage. The potential number of such events from in-service encounters might appear large. A study by the US Geological Survey (USGS)[1] published in 2010 identified 126 encounters between April 1975 and August 2008. More recent work by DLR [2] identified 113 aircraft exposure events covering six volcanic eruptions between April 2010 and December 2014. However, there are three comments worth making in relation to these data sets.

First, both data sets have only catalogued reported exposure events; there is strong evidence that there are substantially more aircraft volcanic ash encounters than publicly reported or identified. It is difficult to establish the level of under reporting of aircraft volcanic ash encounters, but 50% does not feel excessive, and the level is potentially greater.

The second comment to make about the volcanic ash encounter data sets is that although the consequences of the exposures are reasonably well catalogued there is a limited amount of data associated with most of the events which would allow all the parameters influencing damage to be characterised. However, there is enough information available to surmise that the two most important parameters affecting damage are the concentration of the ash and the length of time the aircraft and its engines were in the ash cloud. Consequently it is reasonable to plot the exposure events on a graph of mean ash concentration against the duration of the exposure. To this end, in 2012 the lead author proposed such a chart – the duration of exposure versus ash concentration, or DEvAC chart. The structure of the chart and the data it contained up to the middle of 2014 was published by Clarkson et al., 2016 [3]. Although the primary purpose of the DEvAC chart was to illustrate the influence volcanic ash concentration and duration of exposure have on the level of damage and its consequences, it has also proved useful in giving an indication of the degree of influence other factors have on the level of damage.

Thirdly, with respect to positioning events on the DEvAC chart, unfortunately out of the 239 or so known in-service encounters there are very few where sufficient information exists to allow even an estimate to be made of both the ash concentration and the exposure duration. More positively, for the encounters where these parameters can be established there is usually sufficient information available to make a good assessment of the level of engine damage.

2.2 Damage Levels

Clearly both the ash concentration and the duration of an exposure can be described numerically, but it is more difficult to assign numeric values to the level of damage. Consequently four qualitative categories of engine damage have been adopted based on observations from in-service events and feedback from industry stakeholders. The four categories are; (i) Negligible damage, (ii) Long term damage, (iii) Exigent damage and (iv) Safety implications.

Negligible damage would cover events where there was clear evidence that an engine had been exposed to ash but it had effectively no detrimental impact on the engine.

Where the damage to the engines is purely economic – i.e. there was no significant deterioration in flight safety margins between the start of the encounter and completion of the mission – the level of economic impact has been divided into two separate categories; the Long term damage and Exigent damage categories.

The long term economic damage category represents low level damage which has resulted in detectable abnormal deterioration in the engine performance or reduction in the service life of one or more components. However, such a level of damage would not require immediate action to be taken; the engine could be left installed in the aircraft for many more flights and the timing of its repair managed to minimise cost or disruption. The economic impact of such damage would be an increase in subsequent fuel burn relative to what might otherwise have been expected or sufficient reduction in component life that the engine would ultimately need to be brought in earlier than anticipated for a major overhaul.

The more problematic category of economic damage, termed Exigent damage, is engine damage that needs immediate attention (e.g. extensive cleaning or in aircraft repair) and potentially immediate removal of the engine from the aircraft. Such a level of damage would normally mean unscheduled and prolonged loss of aircraft availability and potentially extensive engine repairs, both of which would be very undesirable to an operator from an operational availability perspective or on economic grounds.

The forth and most serious damage implication is a significant deterioration in flight safety margins during an encounter or after the encounter but before the aircraft lands. Typically this would include actual or likely loss of controllable engine thrust, either temporarily or permanently.

To allow the impact of an exposure event to be easily identified on the DEvAC chart each event point is plotted with a coloured circle or ellipse (see below for plotting convention). The colours used are listed in Table 1. Note that for some exposure events a lack of detailed information means that one of two possible damage categories could be applied. For these cases the circle or ellipse representing the event on the chart has been coloured with a hatched pattern using the colours from the two possible damage categories. Also note that the adoption of a circle and ellipse colour code for indicating the damage category is a departure from the colouring convention used in the original 2014 DEvAC chart (see Clarkson et al., 2016 [3]); the original chart used different colours for each individual event to allow it to be identified.

Table 1: DEvAC chart event colour codes used to denote engine damage category.

Damage Category	Colour
Negligible damage	Green
Long term damage	Yellow
Exigent damage	Orange
Safety implications	Red

2.3 DEvAC Chart Plot

Figure 1 shows the general layout of the DEvAC chart. The fundamental features of the chart have been retained from Clarkson et al., 2016 [3]; the log-log scale, the depiction of the concentrations over which ash starts to become visible in good light, the ash concentration around which multispectral satellite imagery starts to discern ash (0.2 mg/m^3) and the vertical lines at 2, 20, 200 and 2000 mg/m^3. Also retained is the convention for differentiating between circles or ellipses for volcanic ash exposures and the sand or dust exposures; a solid colour for a volcanic ash exposure, a chequered pattern for a sand or dust exposure.

To help relate one ash exposure event to another a selection of constant dose lines have also been added to the chart. Again it is worth noting that in this context the ash dose is defined as the product of the exposure duration and the ash concentration. Such a dose is proportional to the mass of ash ingested into an engine's core (a full description of the relationship between the ash dose used here and the core ingestion rate of an engine is included in Clarkson, 2016 [4]). Lines of constant dose run diagonally from the chart's top left towards the bottom right, and are shown as dark blue dotted broken lines.

The 2014 version of the DEvAC chart only included 11 events. By the end of 2016 a further 13 events had been identified, four in-service events and nine from test bed engine tests. Also, although six of the 13 new events are sand and dust exposures all six have been included because, either the nature of the sand and dust ingested has some characteristics in common with volcanic ash (i.e. the dust contained at least 15% glass or the dust composition was a mineral blend which melts within the temperature range volcanic ashes are known to become effectively molten) or the exposure consequence was comparable to that resulting from a similar volcanic ash dose.

An additional observation which needs to be made is that for a large proportion of the datum points – predominantly the in-service events – the ash concentration being ingested would have varied to at least some degree throughout the encounter. In these situations the point has been plotted using the time averaged ash concentration for the encounter. Acceptable criteria for establishing the average concentration were that a reliably accurate measurement of the concentration was taken or that two independent, non-contradictory, indirect assessments of the concentration are available.

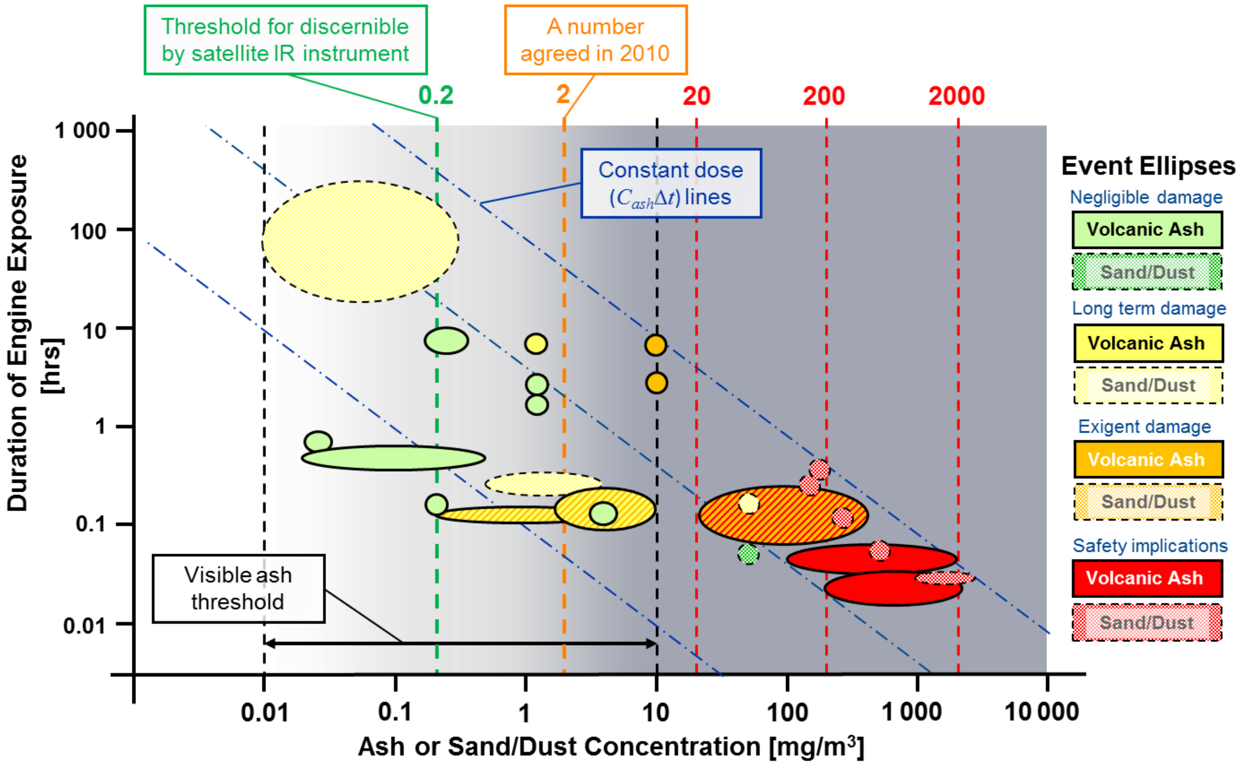

Figure 1: General layout of the DEvAC chart.

A further point to note is that current operational procedures mean that in-service exposures tend to occur for no more than a few tens of minutes. Consequently cumulative exposure to ash for more than 30 to 60 minutes is very likely to require multiple exposure events; deliberate continuous exposure to ash for more than 60 minutes is possible but would probably require either a deliberate intent to remain in an ash cloud, exposure to a very extensive ash cloud or a test bed experiment. Therefore some encounter events on the chart are constituted by combining a number of separate exposures to a single engine. Again, this is felt to be justified because it is likely to be representative of at least some in-service reality.

The uncertainty in the average concentration and duration of exposure of an event on the chart is reflected in the size of the ellipse axes or circle radius; noting that a minimum circle radius has been used to make events with a precisely known concentration and duration visible.

A full description of how the exposure consequences, concentrations and the durations have been arrived at for each event illustrated in Figure 1 is recorded in an internal Rolls-Royce report (Clarkson, 2016 [4]). The report also includes additional information on factors such as the ash, sand or dust composition, the flight condition (e.g. cruise, climb, descent) and the level of engine technology. It is worth noting that the 15 volcanic ash and nine sand/dust exposure events plotted on the DEvAC chart contain representatives from a wide range of engine technology levels, from military fast jet engines of the early 1970s to high by-pass ratio civil turbofans of the 1970s, 80s, 90s and 21st century. In addition the dataset includes engines that are only a few hours old to those very close to needing a major overhaul. The 15 volcanic ash exposure events include examples from across the full spectrum of ash compositional types, from high silica content rhyolite to low silica content basalt, as well as a high potassium and sodium phono-tephrite. The majority of the ash exposures are at a high altitude cruise, with one at a reasonably high altitude climb, noting that for many modern engine types cruise and climb are the critical flight points for turbine ash accretion.

2.4 Chart Damage Impact regions

The relative positions of the event ellipses and circles on the DEvAC chart are instructive in that they give an indication of the exposure doses that might lead to the four damage impact categories. The chart would be even more instructive if regions were defined on the chart where the four damage categories are most likely to occur. The possibility of arriving at these regions by conducting a statistical analysis of the chart dataset is being explored. For example, an attempt has been made to produce an ordinal regression model combined with a Markov Chain Monte Carlo analysis to look at the probability of an exposure impact for a given ash dose. Initial indications are that the dataset is too small to make the output of such an analysis definitive; the uncertainties in an impact probability would be higher than generally acceptable for aviation decision making. However, it is believed that regions of the chart where a safety implication might be expected can be estimated by making some rational engineering assumptions. In a similar way a conservative estimate might be attempted of where on the chart purely economic impacts, both long term and exigent damage, might be expected.

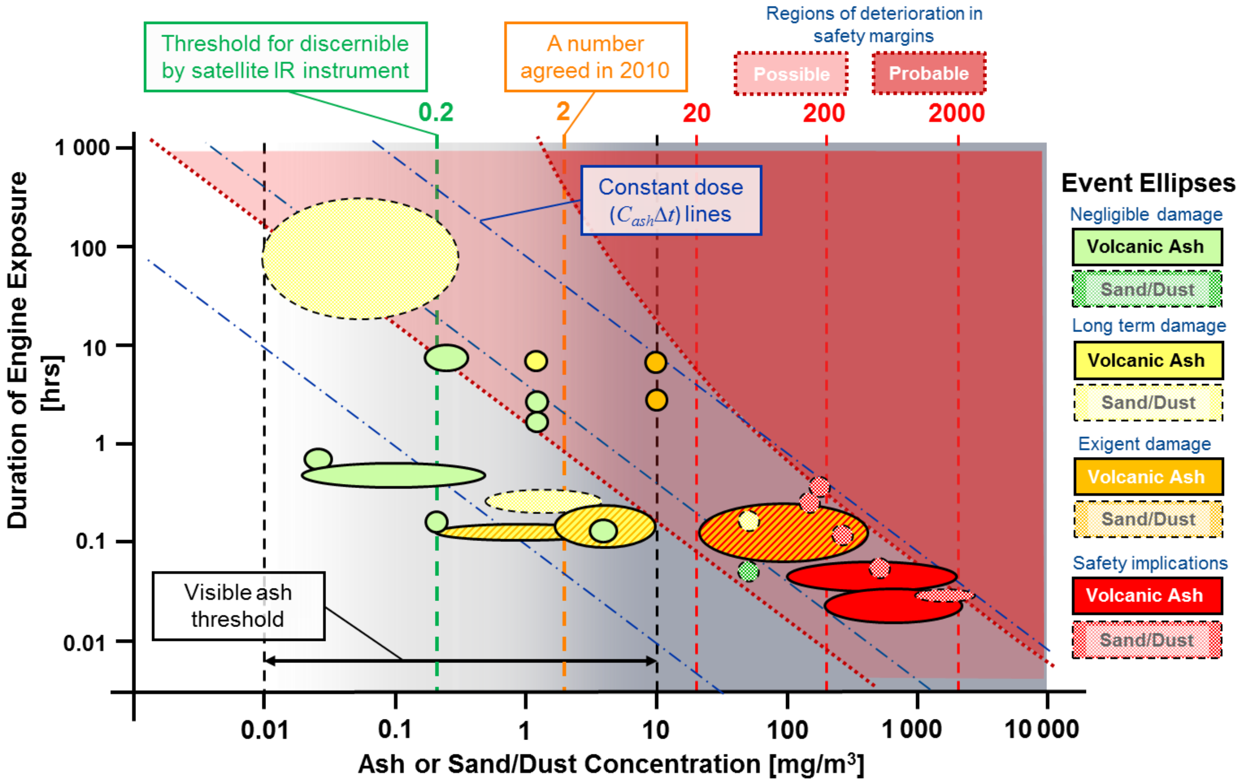

Figure 2: Safety implication regions on the DEvAC Chart.

The original DEvAC chart described in Clarkson et al., 2016 [3] split the regions where safety implications might be expected into three sub-regions. However, with the revised version of the chart described here the safety implication region is only split into two sub-regions; a ‘Probable’ region (coloured red) and a ‘Possible’ region (coloured pink) – see Figure 2.

The red ‘Probable’ region indicates doses that are most likely to result in a significant deterioration in safety margins. The region occupies the top right of the chart. Its lower extent is bounded by a line extending from the upper ash concentrations deemed plausible for the exposures where Safety implications resulted, running towards longer duration exposures at lower concentrations. The non-linear curving up of this lower boundary line, relative to a constant dose line, reflects the possibility that some of the engine damage mechanisms may attenuate at lower ash concentrations.

The pink ‘Possible’ region covers the portion of the chart where there is reduced likelihood that the ash dose would lead to a Safety implication. The region’s upper boundary line is the lower boundary line for the ‘Probable’ safety implication region; its lower boundary is defined by a constant dose line running a little way below the lowest justifiable dose for the volcanic ash exposures which resulted in safety implications.

Using a constant dose line as the lower boundary of the ‘Possible’ region is reasonable if it is assumed that the degree of engine damage is simply a function of the mass of ash ingested, which is closely related to the ash dose. Setting the boundary slightly below the lowest plausible dose for the events on the chart that experienced safety implications is justified on the grounds that these events occurred with older generation engines, the ash involved may not have been the most damaging and the engine condition and operating point may not have represented the most vulnerable combination. If the lower boundary of the ‘Possible’ region is accepted as the lowest possible dose that could lead to a safety implication, operations that do not exceed such a dose should not experience unacceptable reductions in engine related flight safety margins. The lower boundary of the ‘Possible’ region passes through the 2 mg/m^3 concentration at an exposure duration of around 50 minutes, i.e. keeping an engine’s ash expose dose to less than 6 g s/m^3 (i.e. 0.002 g/m^3 x 3000 seconds) should not result in safety implications. However, engines that are exposed to ash doses approaching 6 g s/m^3 may still experience economic damage.

It is worth pointing out that, in addition to all eight events with confirmed or possible safety implication outcomes, the ‘Possible’ safety implication region contains nine events that did not have safety implication outcomes; also, all nine of these non-safety implication events took place in ash or sand/dust concentrations which were substantially less than 100 mg/m^3.

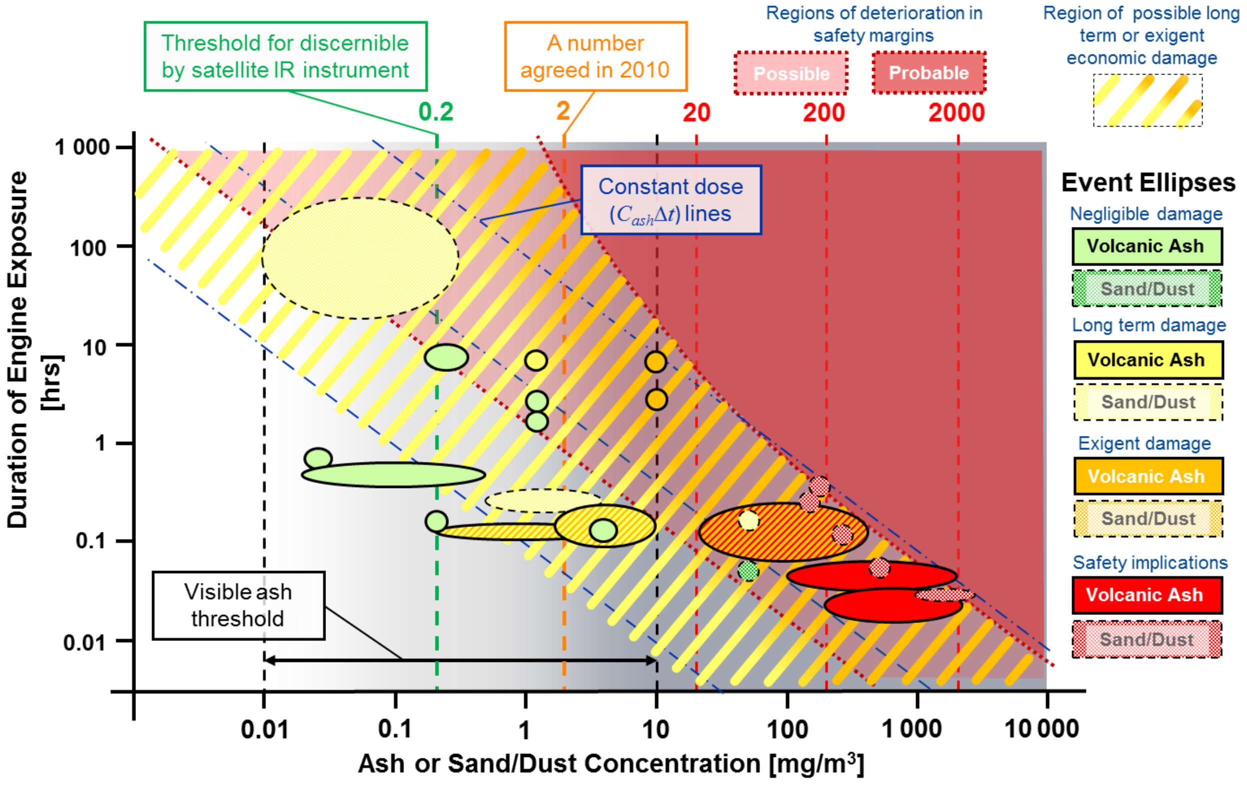

Figure 3: Exigent and long term damage regions on the DEvAC Chart.

The two economic damage implications, Exigent damage and Long term damage, are represented by a single region on the chart – see Figure 3. The reason for using a single region for both economic damage categories is that the exact demarcation point between the two classifications is very uncertain and with two of the events it isn't clear whether the damage was exigent or long term. An added difficulty in positioning this region on the chart is that a large portion of it lies over the pink 'Possible' safety implication region. To overcome this difficulty a diagonal hatched pattern is used. The colour used for the diagonal hatching is a gradual change from orange for Exigent damage to yellow for Long term damage. The upper right boundary for the region, where exigent damage is most likely to occur, is the lower boundary for the red 'Probable' safety implication region. The lower left boundary is formed from a slightly curved line, relative to a constant dose line, to represent the self-repairing nature that normal engine operation in clean air has on some of the damage mechanisms (e.g. removal of turbine deposits).

The economic damage region encloses virtually all the event ellipses that have been classified as economic damage; the one exception is an event which involves uncertainty over the level of the damage and the ash concentration the engines were exposed to – the Hekla 2000 event.

2.5 Relationship between Damage and Ash Dose

A number of the events plotted in Figures 1-3 confirm that it is not just the ash concentration which dictates the level of damage; how long an engine is exposed to the ash concentration is important. The two circles representing sand and dust exposures at 50 mg/m^3 are two tests of the same engine run to the same condition but for different durations; clearly the level of damage increases the longer the exposure duration. The same observation can be made for the three volcanic ash circles representing exposures at around 1 mg/m^3; these are points from the 2015 VIPR-III ash tests. The two volcanic ash circles at 10 mg/m^3 are also VIPR-III points, the relative level of damage between them will be returned to below.

Further, inspection of Figure 2 suggests that the dose which would lead to unacceptable safety implications at say 200 mg/m^3 is less than would be required at 10 mg/m^3, that is to say there appears to be a nonlinear relationship between dose and concentration for a given level of damage. If such a relationship is real it would suggest that for flight operations conducted in ash concentrations of less than 10 mg/m^3 the lowest ash dose that would lead to safety implications – the critical ash dose – is potentially substantially greater than the 6 g s/m^3 discussed above.

Before an acceptable dose greater than 6 g s/m^3 can be accepted at ash concentration below 10 mg/m^3 a robust and verified explanation for the nonlinear relationship needs to be established. Further, a way of establishing such an acceptable dose needs to be available. A route to both requirements would be a reliable mathematical model of engine damage that can calculate ash doses which lead to safety implications. As indicated above, complex models based around CFD and FEA are currently impractical. An alternative approach would be a simple phenomenological model that captures the key effects which lead to a loss of controllable engine thrust.

2.6 Assessment of Vulnerable Engine Systems

Before a simple phenomenological model can be arrived at the key engine damage effects need to be identified. To this end a qualitative assessment of potentially vulnerable engine systems was carried out to identify which would result in a loss of controllable thrust from exposure to the lowest ash dose. The supplementary data collected during the assessment of the exposure events plotted on the DEvAC chart (catalogued in Clarkson, 2016 [4]) indicate that the critical engine system is the core compressors' stability margins; i.e. as the exposure dose increases the compressors run out of surge margin before any other engine system suffers a critical failure. More specifically, the core compressor surge margin is lost due to compressor erosion and the build-up of ash deposits at the controlling flow area in the core turbines – the high pressure turbine nozzle guide vane (HP NGV) throat.

It is conceivable that a specific vulnerability to a lower ash dose has inadvertently been designed into another engine system, but qualitative and if appropriate simple quantitative assessment of these systems should identify if this is the case. For the vast majority of gas turbine engine designs core compressor operability will be the critical system.

3.0 A SIMPLE PHENOMENOLOGICAL MODEL OF COMPRESSOR SURGE MARGIN LOSS

Figure 4 presents a schematic diagram of how core compressor surge margin is lost; (i) through a shift in the compressor stability line resulting from opening up of compressor running clearances and a loss of compressor aerodynamic efficiency, and (ii) a shift in the compressor working line resulting from a reduction in the HP turbine NGV throat area. Analysis using erosion rates derived from laboratory experiments and evidence from engines exposed to sand, dust and volcanic ash indicates that compressor erosion is only a second order contributor to the net change in surge margin; accumulation of ash deposit on the HP NGVs causing a reduction in throat area, and thus flow capacity, is a much stronger effect, particularly at moderate and high ash concentrations.

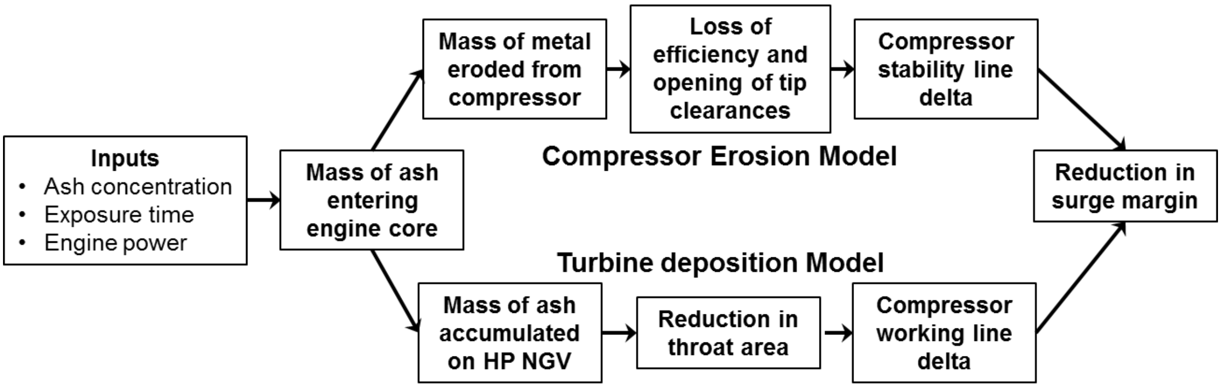

Figure 4: Schematic of a compressor surge model from ash contamination.

Consequently, to explain the nonlinear behaviour between ash concentration and critical ash dose (discussed above) a greater proportion of the ash entering an engine core must build up on the HP NGVs at high ash concentrations than builds up at low concentrations. Various mechanisms were considered as candidates for this phenomenon (e.g. aggregation of particles in the engine combustor at high concentrations, leading to an increased proportion of larger particles which are more likely to strike the HP NGVs), but with the exception of one phenomena, they all had substantial shortcomings. The exception related to gradual shedding of deposit on the HP NGVs.

In detail, the proportion of ash that gets deposited on the NGV surfaces is actually constant irrespective of ash concentration, but there is a slow deposit shedding mechanism which has negligible impact on the rate deposit builds up at high concentrations but significant influence at low concentrations. The substantially longer times it takes to accumulate a given amount of deposit at low concentrations means a slow shedding mechanism has time to have an impact.

There is evidence to support the existence of the slow shedding phenomena from Rolls-Royce RB211 engines that were exposed to high ash concentrations in the 1980s and in directly from the recent VIPR-III testing. The key characteristic of the RB211 engine exposures is not just that they were exposed to high ash concentrations, but when they left the ash clouds, and entered clean air, some of the engines were either still running or they were restarted as they left the ash cloud. Either from inspection evidence from a sister engine which was not restarted on the same aircraft, or by inference from engine performance data and a knowledge of the likely ash dose, the amount of deposit on the NGVs as the RB211 engines left the ash cloud can be established reasonably well. Looking at the mass of ash left on the NGVs after different lengths of time running at high power in clean air it can be seen that ash gradually sheds from the NGVs: Fortunately with the RB211 engine exposures under consideration, not only can the amount of deposit on the NGVs be established on leaving the ash cloud, the amount shed can be estimated after approximately 30 minutes, 4 hours and 16 hours operating at high power in clean air. This allows the characteristics of the shedding behaviour to be established.

It is worth noting in passing that the often quoted reason why engines which shutdown during ash encounters can be restarted – because the ash deposit falls off the NGVs as the engine cools – is very questionable. The theory is that once the ash has fallen off the NGVs the engines can be restarted again. Inspection of photographs from numerous engines which were exposed to considerable ash doses and shut down without being restarted, including one that was windmilled in cold air for around 30 minutes, shows that very little ash, if any, has fallen off. What is more, the deposit falling off the NGVs is not needed to explain why the engines could be restarted. The most likely reason the engines could be restarted is that although the ash deposit continues to restrict gas flow through the NGV passages, as the aircrafts descended into denser air enough gas mass flow could be passed through the combustor to stabilise the flame, allowing the engines to pull away to a stable idle and higher powers. It is unlikely to be coincidental that the engines on the Boeing 747 aircraft from the 1982 Galunggung and 1989 Redoubt encounters were restarted at around 10,000 to 15,000 ft below their normal windmill relight altitude. Some of the ash deposit may fall off during the subsequent run up to power, but again there is evidence from the RB211 events discussed above, and other events, that this is a minor effect.

3.1 Turbine Accretion Modelling

From the considerations discussed above it is possible to derive a simple model for the rate at which ash deposit builds up on the HP turbine NGVs. Figure 5 illustrates the two phenomena that constitute the model; deposit accretion and deposit shedding. Table 2 lists the parameters that make up the model and the notation used to represent them.

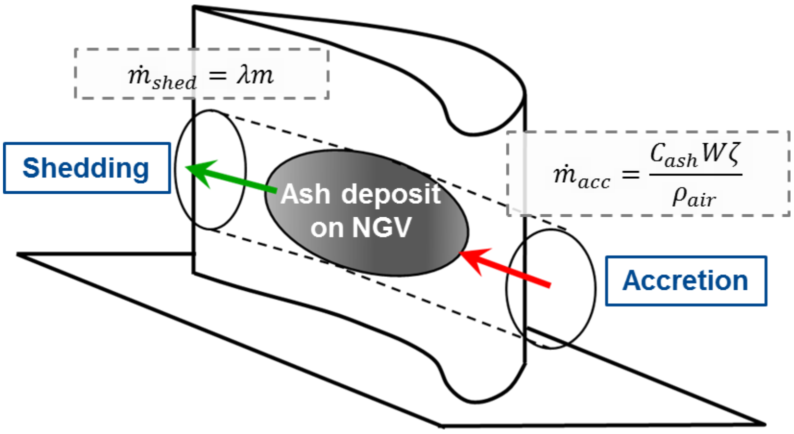

Figure 5: Mathematical model of turbine NGV ash deposit build up

The accretion effect is simply represented by defining an accumulation factor (ζ), which is the proportion of ash entering the engine core which will hit and stick on the NGV surfaces. Applying the accumulation factor to the mass of ash entering the core – given by the product of the atmospheric ash concentration and the mass flow of air into the core, divided by the ambient air density (see Figure 5) – gives an ash accretion rate. The shedding effect assumes the rate of deposit shedding is proportional to the mass of ash deposited, with the constant of proportionality being designated as the shedding rate parameter (λ). The difference between the accretion rate and the rate of deposit shedding will give the rate of change in deposit mass. Expressed mathematically:

$$\frac{dm}{dt} = \dot{m}_{acc} - \dot{m}_{shed}$$

$$\frac{dm}{dt} = \frac{C_{ash} W \zeta}{\rho_{air}} - \lambda m$$

Solving the above equation to give the mass of deposit at any time gives:

$$m(t) = m_0 e^{-\lambda t} + \frac{C_{ash} W \zeta}{\rho_{air} \lambda}\left(1 - e^{-\lambda t}\right) \qquad \text{– Equation (1)}$$

Note that at time zero the initial mass of deposit on the NGV may be a number greater than zero if the particular ash encounter under consideration is a follow on encounter to a previous exposure, i.e. there was already an ash deposit on the NGVs.

Table 2: Notation used in the turbine accretion model.

Symbol	Parameter	S.I. Units
C_{ash}	Atmospheric ash concentration	mg/m^3
m	Mass of ash deposit on NGV	kg
m_0	Initial mas of deposit on NGV	kg
$m(t)$	Mass of ash deposit on NGV at time *t*	kg
$\dot{m}_{acc}$	NGV deposit accretion rate	kg/s
$\dot{m}_{shed}$	NGV deposit shedding rate	kg/s
t	Time	s
W	Air mass flow rate through engine core	kg/s
ρ_{air}	Ambient air density	kg/m^3
λ	Shedding rate parameter	1/s
ζ	Accumulation factor	%

The accumulation factor (ζ) and shedding rate (λ) parameters in Equation (1) are assumed to be constant for a given ash type, engine design and engine operating point (power and flight condition). Both parameters can be derived empirically from engine evidence, e.g. the RB211 ash encounter events described above, or tests such as the Calspan studies conducted by Mike Dunn and colleagues [5]. The accumulation factor can also be refined using evidence from recently undertaken laboratory level work (e.g. Song et al, 2016 [6], Giel et al, 2016 [7] and Taltavull et al, 2015 [8]).

Once suitable values for the accumulation factor and shedding rate have been established the model described by Equation (1) can be used to calculate a critical ash dose by applying it to the most vulnerable engine operating point. The most vulnerable operating point will usually be a point where the turbine entry temperature is high – to promote a high accumulation rate – and the core mass flow to ambient air density ratio is high, typically a top of climb or cruise point.

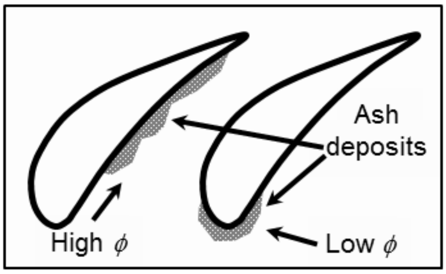

Figure 6: The deposit distribution factor ϕ

Establishing the mass of ash deposited on the NGV surfaces is only the initial part of the calculation; the density of the deposit and where the deposit accumulates on the NGV needs to be established, so that its effect on NGV throat area and flow capacity can be established (see Figure 4). It is prudent to adopt conservative assumptions for these calculations. The authors also adopted a parameter termed the deposit distribution factor, ϕ, which relates the total volume of deposit on the NGV to its effect on flow capacity, as a result of where the deposit builds up. Figure 6 illustrates this concept. An engine type where the peak gas temperature associated with the combustor exit temperature profile is pointing at the NGV leading edge would have a low ϕ, whereas a high ϕ would result where the peak temperature passed down the NGV passage. Assuming a high ϕ value is clearly a conservative assumption for some engine types.

The final element of the critical ash dose calculation is to relate a reduction in HP NGV flow capacity to a shift in the core compressor working lines, a relationship usually well understood from engine operability analysis.

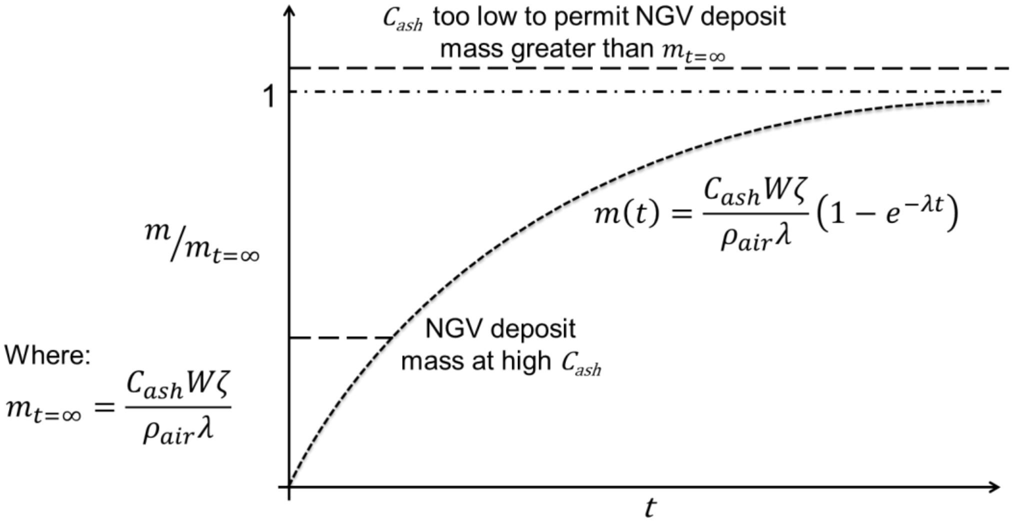

Figure 7: Asymptotic nature of the ash deposition model

Before moving on to discussing how the model above has been applied it is worth making some observations about it. The form of Equation (1) suggests that the mass of deposit on the NGVs could eventually reach an asymptote, the asymptotic mass being dependent on the atmospheric ash concentration, engine core mass flow, ambient air density and the ratio of ζ/λ – see y-axis of Figure 7. Whether an engine ash encounter leads in the asymptote being reached will depend on whether a mass of deposit less than the asymptote is sufficient to shut down the engine. For an encounter with a high ash concentration the theoretical deposit asymptotic mass would be so high the engine would surge and stop well before such a mass could be deposited. For an encounter with a lower concentration the asymptotic mass may be reached before the engine surges and stops.

3.2 Applying the Surge Margin Loss Model to the DEvAC Chart

The above turbine accretion model can be extended to include a simple representation of compressor erosion and applied to some of the data points on the DEvAC chart. Going further, this combined surge margin loss (SML) model can be used to assess the likely trend in the critical ash dose across a range of ash concentrations. The best way to represent such analyses is to redraw the regions of the DEvAC chart which represent 'Possible' and 'Probable' safety implications, as illustrated in Figure 8. The lower boundary of the pink 'Possible' region is based on a worst case (i.e. worst ash type, engine condition, engine operating point, etc.) analysis of a modern gas turbine turbofan engine. The upper boundary of the 'Possible' region is based on the most optimistic set of assumptions that can be made for Event A in Figure 8; clearly this upper boundary for the 'Possible' region forms the lower boundary for the 'Probable' region. Figure 8 also includes a broken red line that shows the critical ash dose for the lowest plausible set of assumptions relating to Event A, applied over a range of concentrations.

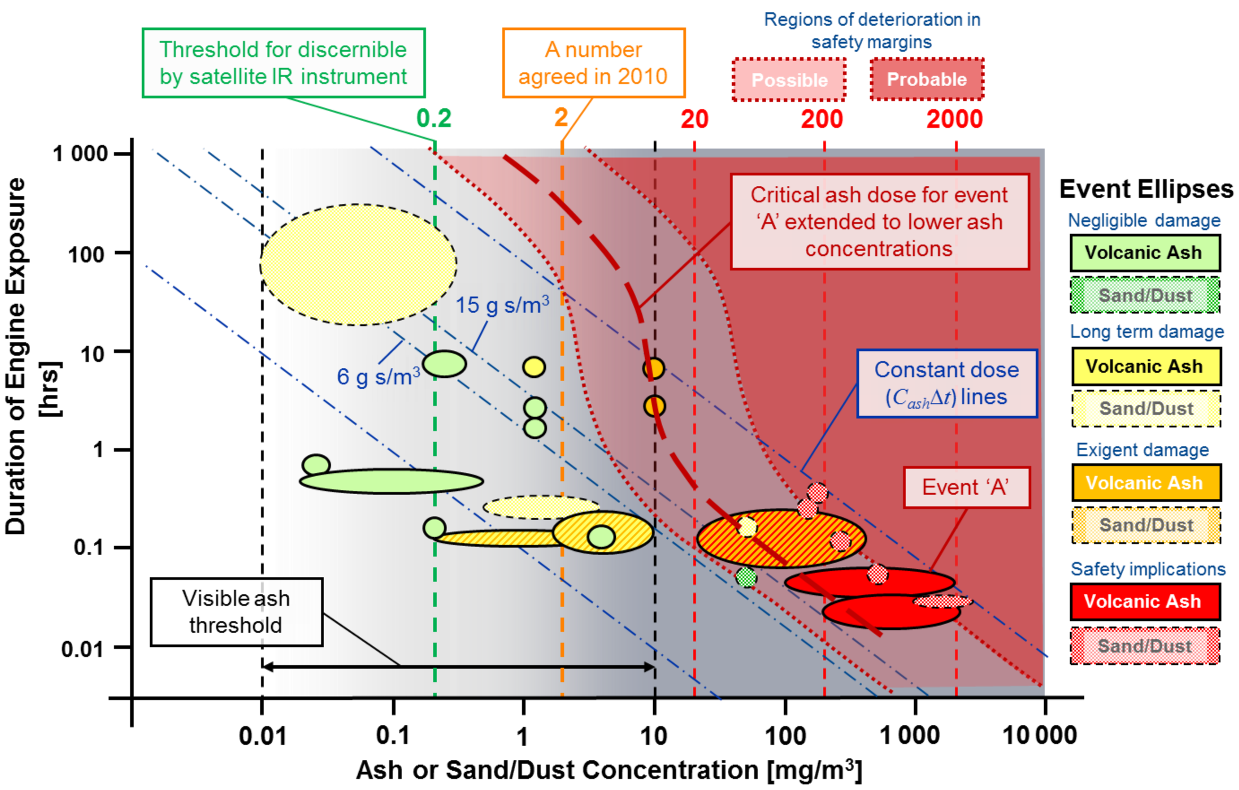

Figure 8: Compressor surge margin loss (SML) model applied to the DEvAC Chart

One of the key features of how the SML model defines the regions indicating safety implications in Figure 8 is that it reproduces the nonlinear relationship between dose and concentration for a given level of damage discussed above. Also, all the events on the DEvAC chart that resulted in either safety implication or exigent damage fall within the regions defining significant deterioration of flight safety margins. Potentially more important is that only two events that led to negligible or long term economic damage fall within the pink 'Possible' region of Figure 8. As these two events involved a reconditioned fast jet engine from the 1970s and the ingestion of a sand and dust blend with relatively low glass content, it is probable that the engine could tolerate a higher particulate dose than a more deteriorated turbofan operating in a high glass volcanic ash.

Returning to the two volcanic ash circles at 10 mg/m^3, the two higher concentration VIPR-III test points; their position on the DEvAC is where the turbine accretion model predicts the deposit asymptotic mass could be reached. Boroscope images of the engine's HP NGV included in a VIPR-III presentation (Zelesky, 2015 [9]) would suggest that the deposit asymptotic mass has either been or is very close to being reached.

It should also be noted that the impact of compressor erosion only becomes significant at ash concentrations below the concentration at which the asymptotic NGV deposit mass would be reached – illustrated by the reduced gradient of the 'Possible' and 'Probable' safety implications regions at exposure durations greater than 100 hours.

A detailed description of how the deterioration in safety margin regions of Figure 8 were defined, including how the parameters in the SML model where arrived at, is not included here because it involves substantial Rolls-Royce proprietary data and intellectual property; it would also require a lengthy discussion which is beyond the scope of the current paper. The key conclusion from the information in Figure 8 is that not only do the engine exposure events on the DEvAC chart suggest the critical ash dose follows a nonlinear relationship with ash concentration, but a robust phenomenological model of engine surge margin loss supports the relationship. Consequently the critical ash dose of 6 g s/m^3 discussed above and derived from Figure 2 would appear supportable and from Figure 8 a higher critical ash dose could be justified at ash concentrations below 5 mg/m^3.

4.0 ASH SUSCEPTIBILITY - OPERATIONAL APPLICATION

Calculations undertaken for a notional modern turbofan engine with the SML model, along with the data displayed on Figure 8 suggest that at an ash concentration of 5 mg/m^3 the critical ash dose – the ash dose below which engines will experience insignificant reductions in flight safety margins – is around 15 g s/m^3. The 15 g s/m^3 constant dose line is shown on Figure 8. In effect such a critical ash dose defines an engine type's susceptibility to volcanic ash. However, having established such a number it is only of value if operators can use it operationally. Discussed below is a proposal for how such a critical ash dose could be used operationally.

Before going further a more specific declaration of an engine type's ash susceptibility needs to be defined to cover the ash concentration range over which the critical ash dose applies. In the Figure 8 example 15 g s/m^3 clearly should not be applied at concentration above 5 mg/m^3, but it would also be reasonable to conclude that at concentrations less than 5 mg/m^3 the critical ash dose is higher than 15 g s/m^3. To allow a useful operational procedure to be developed it is easier to define a constant value critical ash dose between the higher concentration where the critical ash dose starts to significantly decrease and the lower concentration where engines can effectively tolerate an infinite dose. Figure 9 illustrates the concept. The dark blue broken line defines a 15 g s/m^3 critical ash dose between the concentrations of 0.2 and 5 mg/m^3. Engines can be operated in the pale blue region to the left of the dark blue broken line, but once that line is reached engines need to be inspected and decisions made over whether they can continue to be operated in ash concentrations greater than 0.2 mg/m^3 or whether some remedial cleaning or repair is needed.

Two further comments are needed in relation to Figure 9:

(i) As indicated above, an engine's exposure to ash concentrations below 0.2 mg/m^3 can be neglected. Not only would exposure to such ash be very difficult to establish, there is considerable evidence that extremely large exposure times would be needed for significant damage to occur.

(ii) Although engines can tolerate exposure to ash concentrations greater than 5 mg/m^3 for reasonable lengths of time, it is advisable to set 5 mg/m^3 as the upper concentration limit beyond which the critical ash dose concept can be used; the 5 mg/m^3 concentration, in this example, effectively acts as a no fly boundary.

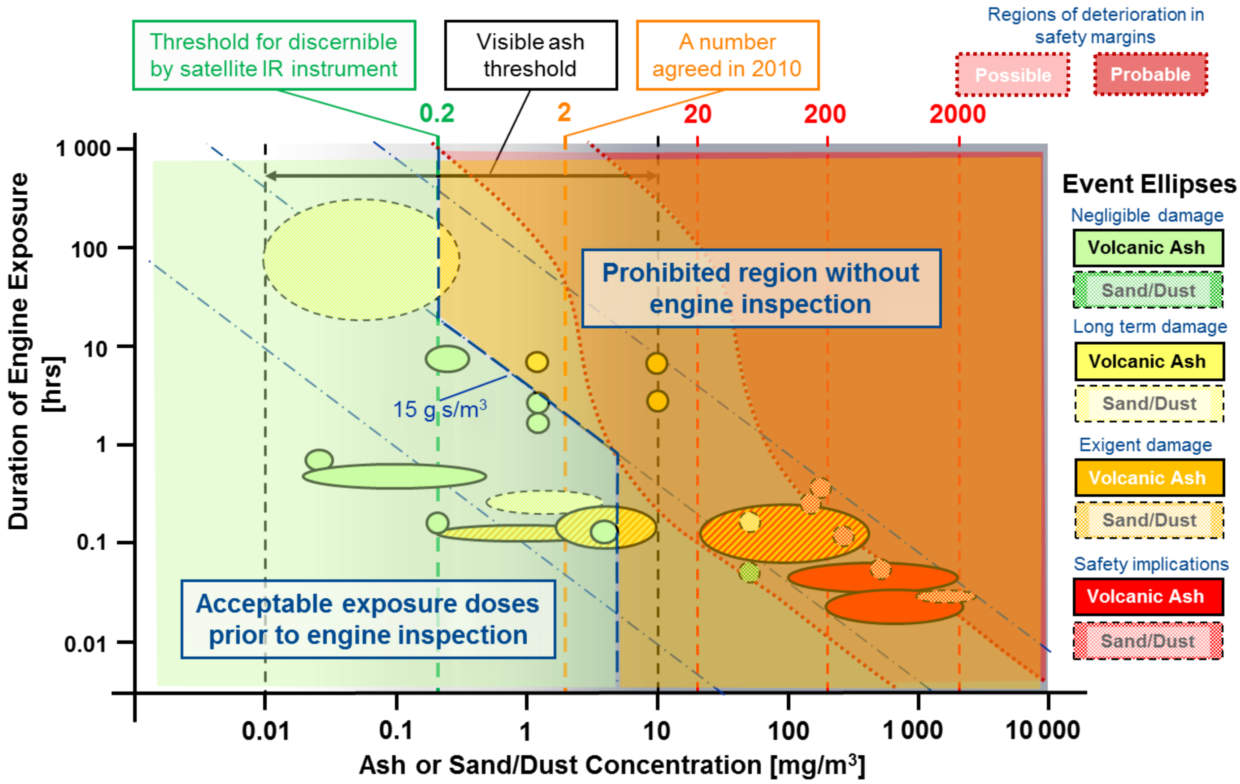

Figure 9: DEvAC chart showing a potential definition of engine susceptibility to volcanic ash.

The two considerations above mean that an engine's ash exposure dose only needs to be monitored and numerically accounted when it is operated in ash concentrations above 0.2 mg/m^3. The dose should not need to be assessed for the notional engine under consideration at concentrations above 5 mg/m^3 because this acts as a no-fly boundary.

It is also very import that operators realise that an engine's ash dose needs to be accounted for across multiple flights; the dose accounting should not be set back to zero at the completion of a flight unless suitable engine inspections are carried out.

4.1 Illustrative Operational Example

The easiest way to explain how the engine ash susceptibility set out above can be used operationally is via an example. Figure 10 presents an entirely hypothetical situation of an ash producing eruption on a volcanic island arc; clearly the geography, city names and ash concentration contours are invented, which is deliberate to illustrate the general, non-European specific, applicability of the approach. The ash cloud to the south west of City C is from an earlier eruptive phase whereas the ash cloud to its east is from a relatively fresh ejection of ash. The contours cover the forecast position of the ash for t+6 hours.

Figure 10 shows three possible flight plans through the ash cloud between City A and City B. Also shown is how an assessment can be made of an engine's potential ash exposure dose along each route in the absence of direct on-board measurements. The key assumption which allows the assessment is that the entire airspace between the 0.2 mg/m^3 and 1 mg/m^3 contours is contaminated with ash at an actual concentration of 1 mg/m^3

and that between the 1 mg/m^3 and 5 mg/m^3 contours the actual concentration is 5 mg/m^3 everywhere. This is clearly very conservative (see below) but it does permit an assessment of exposure dose to be made.

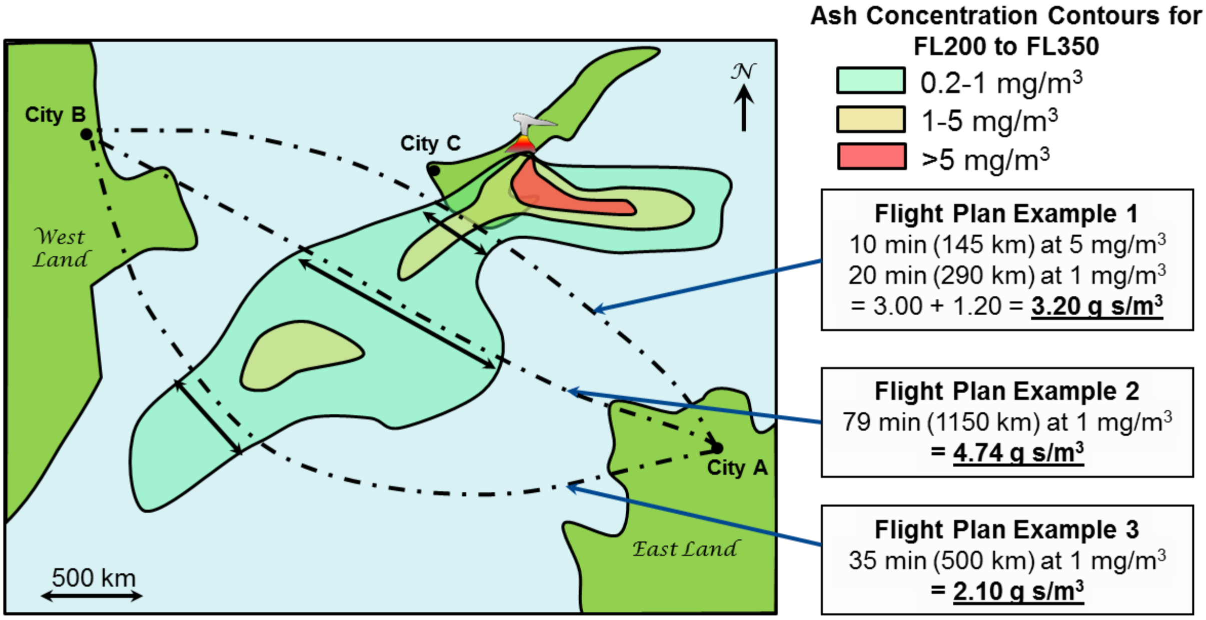

Figure 10: Fabricated example of an ash producing eruption, with ash concentration contours covering the next 6 hours.

From Figure 10 Flight plan 3 would probably involve the lowest ash dose exposure but would also involve the longest route, and thus use the most fuel. Flight plan 2 is the most direct route, thus using the least fuel, but would probably incur the greatest ash dose exposure. Flight plan 1 has an intermediate route length and probably also incurs an intermediate ash dose exposure. However, Flight plan 1 goes through some airspace forecast to contain a higher concentration of ash than the other two routes, and passes much closer to the source volcano. Both of these could be seen as representing increased risk of inadvertently encountering ash concentrations greater than 5 mg/m^3. However, such considerations are offset to a degree by the proximity of City C to the flight path. Should an emergency occur the flight crew would be able to divert to City C relatively quickly. It would take substantially longer to divert from Flight plan 2 to City C, or back to City A. For Flight plan 3 getting to an alternative airport should an emergency occur requires a much longer flight time.

With reference to the current situation in Europe, where the concentration contours produced by the London and Toulouse VAACs are 0.2, 2 or 4 mg/m^3; these contours are not necessarily lines that define where the ash concentration is 0.2, 2 or 4 mg/m^3. The contours are defined such that the peak ash concentration in the airspace volume between the 0.2 to 2 mg/m^3 contours should be no greater than 2 mg/m^3; similarly the peak concentration in the region between the 2 and 4 mg/m^3 contours should be no greater than 4 mg/m^3. The computer models that form the basis of the concentration forecasts are not perfect, so it is possible the peak ash concentrations may be higher than the nominal peak for that region, but if they are they are highly unlikely to be substantially larger than the nominal peak and will be confined to very small airspace volumes.

Another important point worth making about the London and Toulouse VAAC concentration charts is that not only should the peak concentration between two contours be no greater than the value of the upper contour, the bulk of the airspace volume the two contours define will contain ash concentrations significantly lower than the lower contour value; it is also likely much of the airspace will contain no volcanic ash. Consequently the assumption that the actual ash concentration between the 0.2 and 2 mg/m^3 contours is 2 mg/m^3 everywhere is very conservative with respect to calculating exposure dose, even allowing for the possibility that locally ash concentrations could be greater than 2 mg/m^3.

Returning to the hypothetical world of Figure 10, the same arguments above would apply, but translated to 1 and 5 mg/m^3. It can probably also be seen why 1 and 5 mg/m^3 have been chosen for Figure 10; having to assume the ash concentration is 1 mg/m^3 everywhere in the volume of airspace most operators would make flight plans for is potentially less restrictive than having to assume the concentration is 2 mg/m^3 everywhere. To illustrate this point Figure 11 shows a set of concentration contours at 0.2, 2 and 4 mg/m^3 for the same eruption scenario with the equivalent dose calculations for the same three flight plans. Clearly for all the flight plans the contour selection in Figure 10 is more appealing. Also, contours at 1 and 5 mg/m^3 make utilising the airspace between these contours substantially more practical than using the airspace between contours at 2 and 4 mg/m^3, which in most situations will be very narrow.

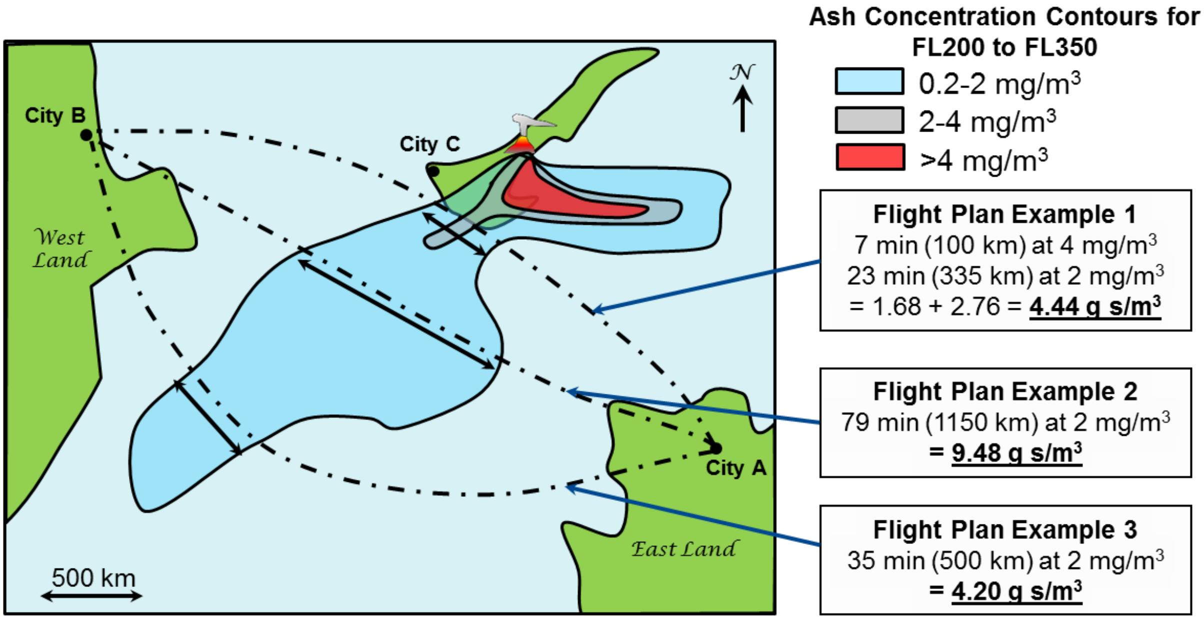

Figure 11: Same ash cloud scenario presented in Figure 10, but with ash contours at 0.2, 2 and 4 mg/m^3.

A final point worth noting is that even if an instrument capable of measuring ash dose is available on an aircraft traversing an ash cloud, the above approach will still be needed for flight planning purposes. To minimise the likelihood of an engine reaching its critical ash dose midway through the ash cloud, suitable flight plans would need to be put in place. The approach outlined above facilitates this, even if the dose an engine has been exposed to is assessed separately using the on-board instruments.

4.2 Avoiding Visible or Discernible Ash

It should be recognised that before an approach such as the one outlined above can achieve its full utility, there has to be an acknowledgement that not all visible or discernible ash needs to be avoided. There is clear evidence engines can be exposed to some visible or discernible ash without a significant reduction in flight safety margins. A paper submitted to the ICAO International Volcanic Ash Task Force [10] showed that ash can be visible at concentrations as low as 0.01 mg/m^3. Prata and Prata, 2012 [11] have shown that multispectral satellite imagery can discern ash at concentrations as low as 0.2 mg/m^3. Consequently a volume of airspace forecast to contain ash concentrations of up to 2 mg/m^3 is likely to contain a fair amount of visible and discernible ash. However, as discussed above, it is unlikely any substantial volumes of this visible or discernible ash will have a mean ash concentration greater than 2 mg/m^3. Knowing that an engine is tolerant of such ash for substantially more than an hour should negate the need to totally avoid it.

The argument has been made for avoiding all visible or discernible ash, essentially because it is very difficult using current on-board technology to establish even the approximate concentration of such ash; it may be a relatively benign concentration of 0.2 mg/m^3 or a more problematic 10 mg/m^3. Whilst true, there are two mitigations to this problem.

First, there is increasing confidence that forecasts of ash concentrations are sufficiently good that they can be trusted; if visible ash is seen on one of the flight plans presented in Figures 10 and 11 it can be assumed to be at a sufficiently low concentration that flying through it would not represent a substantial ash dose.

The second mitigation specifically relates to ash discernible from the flight deck or cabin. Figure 12 illustrates the authors' current best understanding of the concentrations at which ash becomes discernible from on-board an aircraft; the information is based on evidence collected from ash cloud encounters and relevant engine tests compared with the best estimate of the ash concentration at which the encounter or test took place. There is inevitably some uncertainty associated with the information in Figure 12, but the authors' believe it is reliable enough to be a useful guide. The assessments represented in Figure 12 suggests that ash only starts to become discernible via impacts on the aircraft at concentrations greater than allowed by the engine susceptibility defined in Section 4.0 above. Consequently, if ash does start to become discernible from within the flight deck or cabin an expeditious exit from the ash cloud would be recommended.

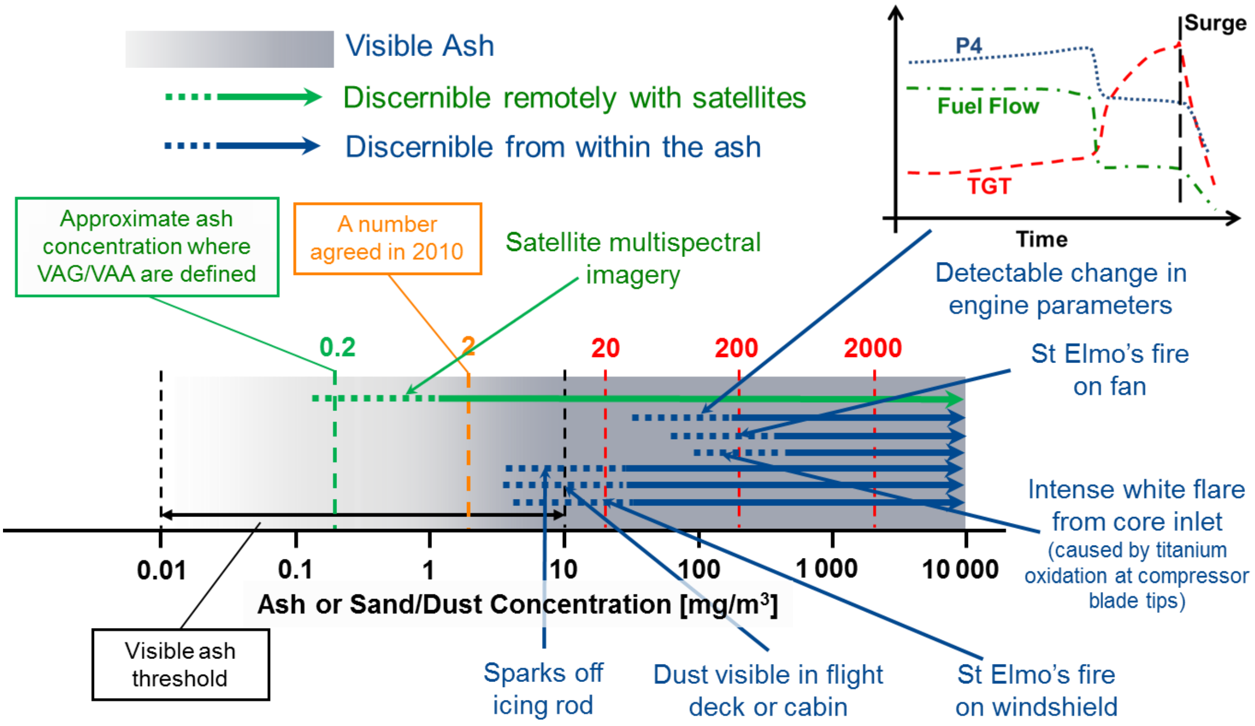

Figure 12: Visible and discernible ash plotted against ash concentration.

With respect to short term tactical avoidance of ash whilst flying, ash discernible by satellites has a significant limitation; currently it would take more than an hour to process the satellite data and relay a message to flight crew.

5.0 CONCLUSIONS

The identification of additional volcanic ash and suitable sand and dust engine exposure events has allowed a significant enhancement to the 2014 DEvAC chart. Also, substantial re-analysis of available data, augmented by recently published laboratory level work has allowed a phenomenological model of compressor surge margin deterioration to be developed. Calculations conducted with the model reproduce the trends seen on the enhanced DEvAC chart. Consequently it is believed that sufficient understanding of engine operability deterioration in volcanic ash is now available to allow the establishment of an engine's susceptibility to volcanic ash. The most appropriate way of defining the susceptibility is through a critical ash dose that the engine should not exceed, applicable between upper and lower ash concentration thresholds.

The establishment of an engine volcanic ash susceptibility based on ash dose also facilitates a practical approach for managing flight operations in airspace contaminated with low and moderate levels of volcanic ash without the absolute necessity to avoid all visible and discernible ash.

6.0 ACKNOWLEDGEMENTS

The work reported here could not have happened without the support and guidance of numerous people, both within and outside of Rolls-Royce, who offered advice, critical insight and technical material. Particular thanks go to staff at the universities of Bristol, Oxford, Cambridge, Manchester and Ludwig Maximilians University, staff at the UK Ministry of Defence and the UK Met Office. Finally we would like to acknowledge the contribution made by the late Beth Majewicz (née Erlund) to our work on volcanic ash.

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