Volcanic Ash and Aviation – Rolls-Royce Position, May 2017

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Introduction

The disruption to aviation that resulted from the 2010 eruption of the Eyjafjallajokull volcano led to the introduction of procedures, through the International Civil Aviation Organisation (ICAO), that formalised the possibility of flight operations in volcanic ash (VA) contaminated airspace. These procedures marked a move away from the conservative, if understandable 'AVOID AVOID AVOID' approach previously advocated by ICAO. The change in approach was also accompanied by the widespread adoption of concepts such as visible and discernible ash and linking engine VA susceptibility to ash concentrations, both actual and predicted. Unfortunately the urgency of the 2010 situation meant that these concepts were deployed before an in depth understanding of what they actually represent had been arrived at, or what the implications would be of attempting to use them operationally.

Since 2010 work has continued on the development and refinement of the concepts adopted during and immediately after the Eyjafjallajokull eruption, to such an extent that it has now become necessary to update and clarify the Rolls-Royce VA guidance. The purpose of this note is to summarise the main scientific and operational developments since 2010. It also briefly describes how and why Rolls-Royce is updating the recommendations and guidance for operating its engines in airspace contaminated with VA; supporting information is offered which could be used to implement the Rolls-Royce guidance.

Abbreviations

AFM	Aircraft Flight Manual	NAT	North Atlantic
AMM	Aircraft Maintenance Manual	NATO	North Atlantic Treaty Organisation
DEvAC	Duration of Exposure versus Ash Concentration	SIB	Safety Information Bulletin
EASA	European Aviation Safety Agency	SMS	Safety Management System
EOI	Engine Operating Instruction	SRA	Safety Risk Assessment
EUR	European	USAF	United States Air Force
FAA	Federal Aviation Administration	VA	Volcanic Ash
FCOM	Flight Crew Operating Manual	VAA	Volcanic Ash Advisory
IATA	International Air Transport Association	VAAC	Volcanic Ash Advisory Centre
ICAO	International Civil Aviation Organisation	VAG	Volcanic Ash Graphic
ICCAIA	International Coordinating Council of the Aerospace Industries Association	VIPR-III	Vehicle Integrated Propulsion Research test 3
IFALPA	International Federation of Airline Pilots' Associations	VONA	Volcano Observatory Notice for Aviation
IVATF	International Volcanic Ash Task Force	WMO	World Meteorological Organisation
NASA	National Aeronautics and Space Administration	WWC	Worldwide Communication

Key Developments Since 2010

Ash Cloud Forecasting

Post 2010, under the guidance of ICAO and the WMO, substantial effort has been directed by the atmospheric and volcanological science communities at improving volcanic ash cloud identification and forecasting. These efforts have been very actively supported by all aviation stakeholders, through IATA, IFALPA, ICCAIA and state regulatory authorities. Consequently the nine VAACs now have significantly more sophisticated tools and procedures for mapping and forecasting the location of ash clouds than were available in 2010. In addition to the nine VAACs, operators can also use ash cloud forecast products from independent providers, some of whom are now offering VA concentration charts for any global location.

Engine Susceptibility to Volcanic Ash

In parallel to the ash cloud identification and forecasting activities various research institutions and engine manufactures have been engaged in improving the quantitative understanding of how much ash it takes to significantly damage aircraft gas turbine engines. In particular the focus has been on differentiating between damage that has an airworthiness implication, an immediate cost of ownership implication (e.g. abrupt engine removal and repair) or a longer term economic impact implication (e.g. performance deterioration or earlier than intended overhaul). To support this effort attention has been directed at understanding in more detail recent and historic service experience, conducting laboratory level fundamental science research and engine testing. Rolls-Royce has been very much at the forefront of these activities; notable examples are the VERTIGO[1] and PROVIDA[2] fundamental science studies undertaken in European universities, various studies sponsored by the UK Military and NATO plus the NASA/USAF led VIPR-III VA engine test completed in August 2015.

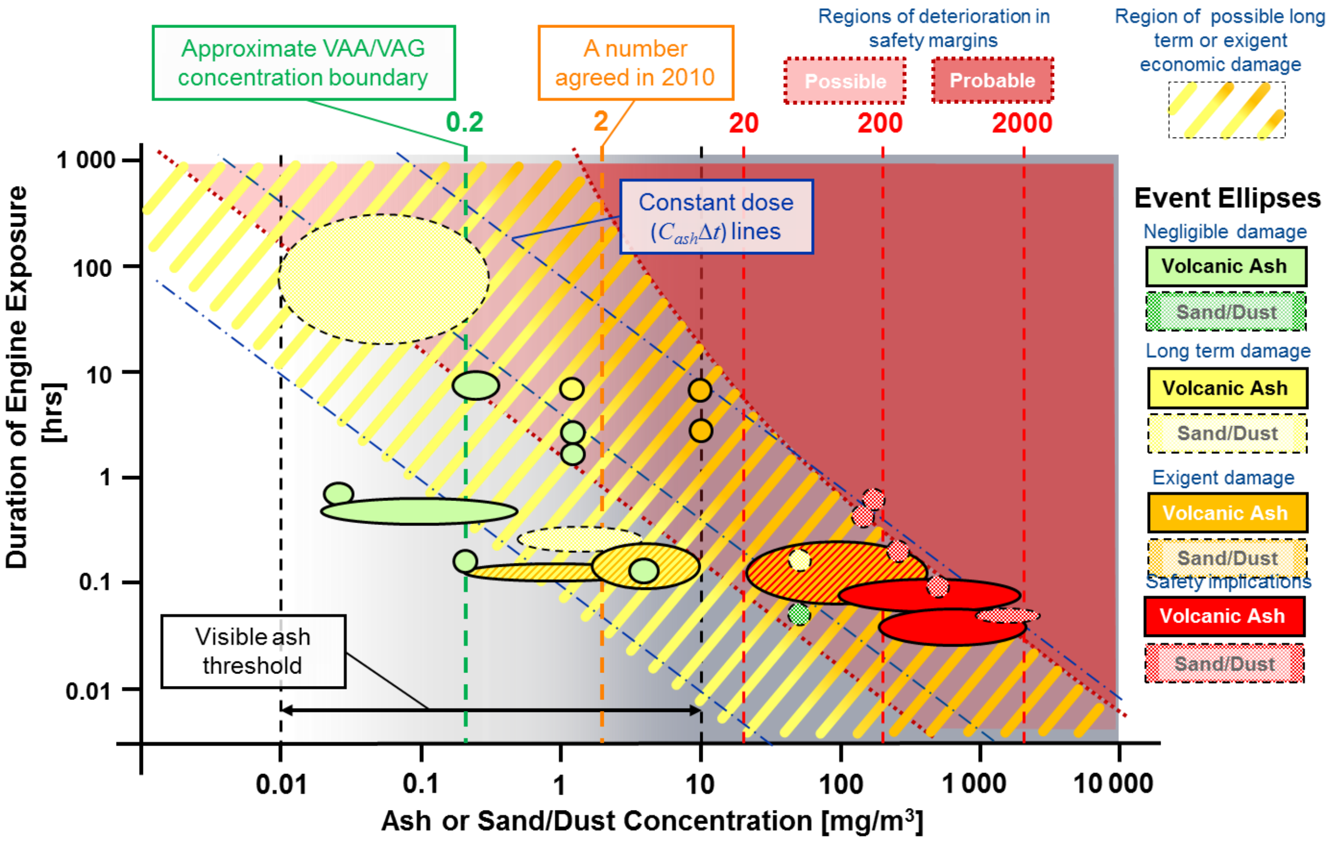

Figure 1 – Most recent Rolls-Royce DEvAC Chart. Each ellipse or circle represents an engine exposure event. (The pink background regions are tentative suggestions for where combinations of ash concentration and exposure duration could lead to significant flight safety implications. The yellow/orange hatched region is a tentative suggestion of where purely economic impacts might be expected. A full description of the Chart, including a list of the exposure events the ellipses represent, is available from Rolls-Royce on request.)

A synthesis of the compiled data, and the understanding this is giving, has been brought together in the widely used Rolls-Royce Duration of Exposure versus Ash Concentration (DEvAC) chart[3] (see Figure 1). A key conclusion of all the work is that engine susceptibility to VA is not purely a function of the ash concentration encountered; the duration of the encounter is important, e.g. a certain concentration may be relatively benign for a short duration exposure but quite damaging for long duration or multiple short duration exposures over a number of flights. Effectively it is the VA dose – the duration of the exposure multiplied by the mean ash concentration during the exposure – which is important.

[1] VERTIGO is an EC funded ITN research project; see www.vertigo-itn.eu

[2] PROVIDA is a loose consortium of universities, research institutions and companies studying the effects of VA on gas turbine engines; see www.ccg.msm.cam.ac.uk/initiatives/provida

[3] The latest version of the DEvAC chart is described in a NATO STO paper: Clarkson, R, Simpson, H - Maximising Airspace Use During Volcanic Eruptions: Matching Engine Durability against Ash Cloud Occurrence – NATO STO-MP-AVT-272, March 2017

Ash Detection and Ash Concentration

Another significant scientific development which has occurred since 2010 relates to the concentrations of ash where the ash becomes visible. In 2010 it was assumed that a concentration of 2 mg/m^3 was about the concentration where ash would become visible to a human eye. A 2011 paper by the IVATF science subgroup[4] concluded that in good light ash starts to become visible at concentrations somewhere between approximately 0.01 mg/m^3 and 10 mg/m^3; ash at 10 mg/m^3 should always be visible in good light. Furthermore ICAO has explicitly stated that visible ash and a concentration of 2 mg/m^3 should not be treated as synonymous. The increasingly darker grey background shading in Figure 1 and Figure 2 illustrates the concentration range over which VA becomes visible.

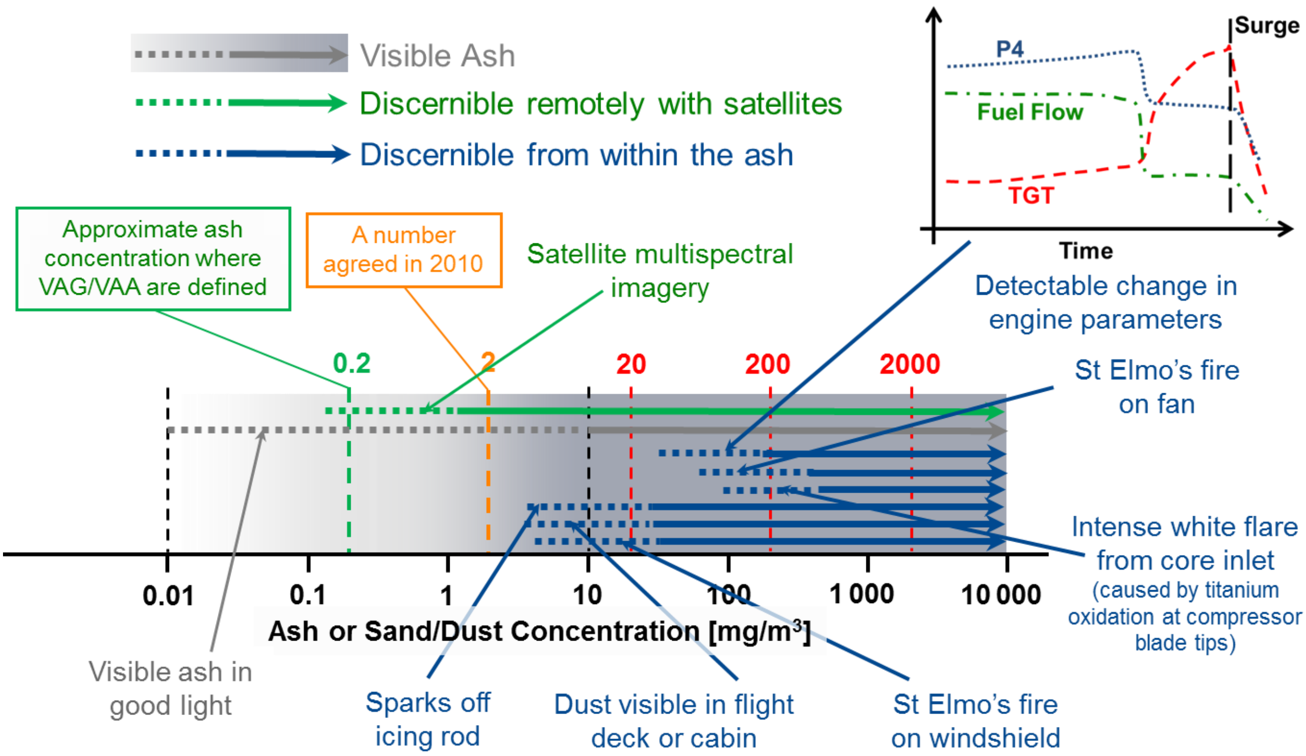

Figure 2 – Visible and discernible ash plotted against ash concentration.

The usefulness of visible ash as a concept for guaranteeing avoidance of ash, yet maximising the use of uncontaminated airspace, was also reviewed by the IVATF. Acknowledging that in 2010 visible ash meant different things to different people, if the term was taken to mean ash that is visible to the human eye it has two significant limitations. The option of simply relying on what flight crews can see out of the flight deck window to avoid VA is very unreliable. This is partly based on the 3 orders of magnitude concentration range over which it starts to be seen in good light; but also backed up by evidence from previous ash encounters where the ash was not seen because it was obscured by water cloud, ice cloud or it was night time and thus too dark.

Developing flight plans designed to guarantee an aircraft avoids visible ash is also problematic. Other than taking off or landing close to an erupting volcano, it is almost impossible to know in advance whether ash along a specified flight plan will be visible or not. As stated above, concentrations between 0.01 mg/m^3 and 10 mg/m^3 may or may not be visible, and that is in good light. A cautious approach would be to avoid all airspace which is forecast to contain VA at concentrations greater than 0.01 mg/m^3

[4] ICAO - IVATF Task TH-SCI03 Progress Report (Part 1) - Understanding "Visible Ash" - International Volcanic Ash Task Force 2nd Meeting. IVATF/2-WP/08, 2011

– the threshold concentration for ash visibility – but most experts would agree that such an approach is needlessly conservative.

In an effort to remove the confusion over what visible ash means and to help address some of the flight planning difficulties posed by avoiding visible ash, ICAO defined in 2013[5] what visible ash should mean and introduced the concept of discernible ash:

> *Visible ash is defined as "volcanic ash observed by the human eye" and not be defined quantitatively by the observer;*
>
> *Discernible ash is defined as "volcanic ash detected by defined impacts on/in aircraft or by agreed in-situ and/or remote-sensing techniques"*

A list of the defined impacts on or in the aircraft is included in the ICAO manual on Flight Safety and Volcanic Ash (Doc 9974). The list is essentially made up of phenomena that are detectable, or discernible, from the aircraft flight deck or cabin, such that the aircraft would have to be in the ash cloud before the ash could be discerned. Clearly guaranteeing avoidance of a phenomenon that is only apparent once an aircraft has actually entered it is a Catch 22 situation. Figure 2 shows the ash concentrations where Rolls-Royce believes the phenomena listed in ICAO Doc9974, along with others that are known to occur, will start to become apparent. The information in Figure 2 is based on evidence collected from ash cloud encounters and relevant engine tests plotted against the best estimate of the ash concentration at which the encounter or test took place. Noting that it is difficult to know exactly the ash concentration of an encounter, there is inevitably some uncertainty associated with Figure 2 – hence the broken horizontal lines used in the Figure – but Rolls-Royce believes the information to be reliable enough to be a useful guide.

The agreed remote sensing technique associated with the definition of discernible ash has been effectively agreed by ICAO as multispectral satellite imagery and this interpretation has been adopted by Rolls-Royce. The range of concentrations over which ash starts to become discernible by multispectral satellite imagery is illustrated in Figure 2. It is worth noting that ash discernible from satellites is especially useful for flight planning, particularly when it is used as part of ash cloud forecasting (see below – Avoiding Visible or Discernible Ash).

Regulator Developments

At a regulatory level, post 2010, ICAO established the principle that when and where to operate in airspace potentially contaminated with VA is the responsibility of the operator. However, flights into VA contaminated airspace should be undertaken in accordance with a VA Safety Risk Assessment (SRA) approved by the operator's state regulatory authority, and under the operator's Safety Management System (SMS). ICAO document Doc9974 (2012) formalises this principle and provides guidance on how it can be implemented.

Also, in 2010 the ICAO European (EUR) and North Atlantic (NAT) regions introduced a joint VA contingency plan[6] which formalised much of what was agreed with respect to air traffic management during the Eyjafjallajokull eruption. One of the plan's key elements is the concept of areas of low, medium and high ash contamination that individual air traffic service provider states can use to define danger areas. The contamination level details were derived from decisions made during the 2010 crisis:

> *Area of Low Contamination: airspace where volcanic ash may be encountered at concentrations greater than 0.2 mg/m^3, but less than or equal to 2 mg/m^3.*
>
> *Area of Medium Contamination: airspace where volcanic ash may be encountered at concentrations greater than 2 mg/m^3, but less than 4 mg/m^3.*

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[5] ICAO IAVWOPSG/7 Report, March 2013

[6] ICAO - EUR/NAT Region Volcanic Ash Contingency Plan, EUR Doc 019, NAT Doc 006, Part II

Area of High Contamination: airspace where volcanic ash may be encountered at concentrations equal to or greater than 4 mg/m^3.

Since 2010 EASA has also progressed its VA position; EASA has updated and modified its VA safety information bulletin (SIB) and introduced an airframe and engine VA certification requirement. Rolls-Royce has been involved in providing input to both initiatives.

The latest update to EASA's VA SIB (EASA_SIB_2010-17R7_1) was issued in June 2015. As well as reiterating EASA's recommendation that operation in visible or discernible ash should be avoided, it extended the recommended use of VA SRAs to cover operations in any level of forecast ash contamination; prior to June 2015 the use of VA SRAs was only recommended for operations in medium and high contamination levels.

In 2013 EASA introduced new airframe certification requirements (CS-25 1593), followed in 2015 with equivalent engine certification requirements (CS-E 1050). Both essentially compel airframe and engine manufactures to declare a susceptibility to volcanic ash, the susceptibility actually declared for a particular product being left to the product manufacturer; EASA have not defined a minimum VA resilience level that has to be demonstrated.

The FAA in effect has not changed its position since before the events of 2010.

Relevance to Rolls-Royce Products

All the above developments are worth noting due to their influence on flight operations in airspace contaminated with VA. Some of the developments also make it appropriate to revise the guidelines Rolls-Royce issued in 2010 and 2011. Specifically:

- The ICAO definitions of visible and discernible ash,
- The break between the visible ash threshold and 2 mg/m^3,
- The ICAO established principle that decisions over how operations are conducted in VA contaminated airspace is the responsibility of operators and that operations are permissible in regions of forecast contamination (using an SRA approved by their state regulatory authority),
- The need to explicitly define an engine's susceptibility to VA under EASA regulations,
- The recognition that damage to engines is essentially related to ash dose rather than ash concentration,
- The wider variety of, and improvement in, volcanic ash forecast products now available.

The revisions to the Rolls-Royce guidelines have been included in a Worldwide Communication[7] (WWC). Ultimately the content of the WWC will be included in Engine Operating Instructions (EOIs); the EOI Chapter covering emergency situations resulting from VA exposure will be modified slightly, with a new section on VA being included in the EOI Chapter covering normal procedures. There will also be a minor change to the Aircraft Maintenance Manuals (AMMs) and potentially changes to the Flight Crew Operating Manuals (FCOMs) and Aircraft Flight Manuals (AFM).

One of the key elements to be included in the EOIs under normal operations, and covered by the WWC, is the adoption of an ash dose to define engine susceptibility to comply with the new EASA aircraft and engine certification regulations. Although a susceptibility statement is not required for engine types certified prior to 2016, a decision was taken by Rolls-Royce to declare the susceptibility of the existing fleet of installed engines, and where possible to make the susceptibility consistent across all engine types. Consequently a susceptibility statement based on VA dose will be declared for all in-service engines.

[7] WW11365-1 - All RB211 and Trent Engines - Volcanic Ash Limits Guidance – Rolls-Royce plc, 24 May 2017

Revised Volcanic Ash Guidelines

A key element of the revised guidelines is that avoidance of visible or discernible ash remains a principle which maintains in-flight safety margins and minimises any deterioration in engine performance or on-wing life. For this reason Rolls-Royce recommends that operators avoid ash which is visible or discernible. One way of minimising the likelihood of exposure to visible or discernible ash is to avoid all airspace forecast to contain VA. However, as stated above (under Regulator Developments) ICAO has agreed that operators can still elect to fly in airspace forecast to contain VA. To support the SRAs that such an approach requires Rolls-Royce is indicating an ash dose engines can be exposed to which should not lead to a significant reduction in flight safety margins; effectively an engine VA susceptibility. The VA susceptibility statements (see below) have been included in the recently published WWC.

In addition to the susceptibility statements the WWC contains advice on how to avoid airspace forecast to contain VA, through detailed flight planning and by using sources of useful information provided by, for example, VAACs, meteorological watch offices and volcano observatories. The WWC also offers guidance on managing operations in airspace forecast to contain VA, if an operator elects to enter such airspace.

Avoiding Visible or Discernible Ash

As stated above (under Ash Detection and Ash Concentration), developing flight plans that are aimed at simply avoiding visible ash is problematic. A more pragmatic approach would be to avoid airspace likely to contain ash discernible by multispectral satellite imagery. There are three benefits to such an approach: First, satellites can detect the presence of ash along an intended flight path thousands of kilometres ahead of the aircraft, and more importantly, before the flight plan is issued. Secondly, avoiding ash that is discernible by multispectral satellite imagery works as well at night as it does during daylight hours. Thirdly, the volcanic ash advisories (VAA), volcanic ash graphics (VAG) and 0.2 mg/m^3 ash concentration contours produced by VAACs define airspace which the VAACs forecast will contain ash discernible by multispectral satellite imagery. Further, the VAACs produce VAA/VAG forecasts for 6, 12 and 18 hours into the future.

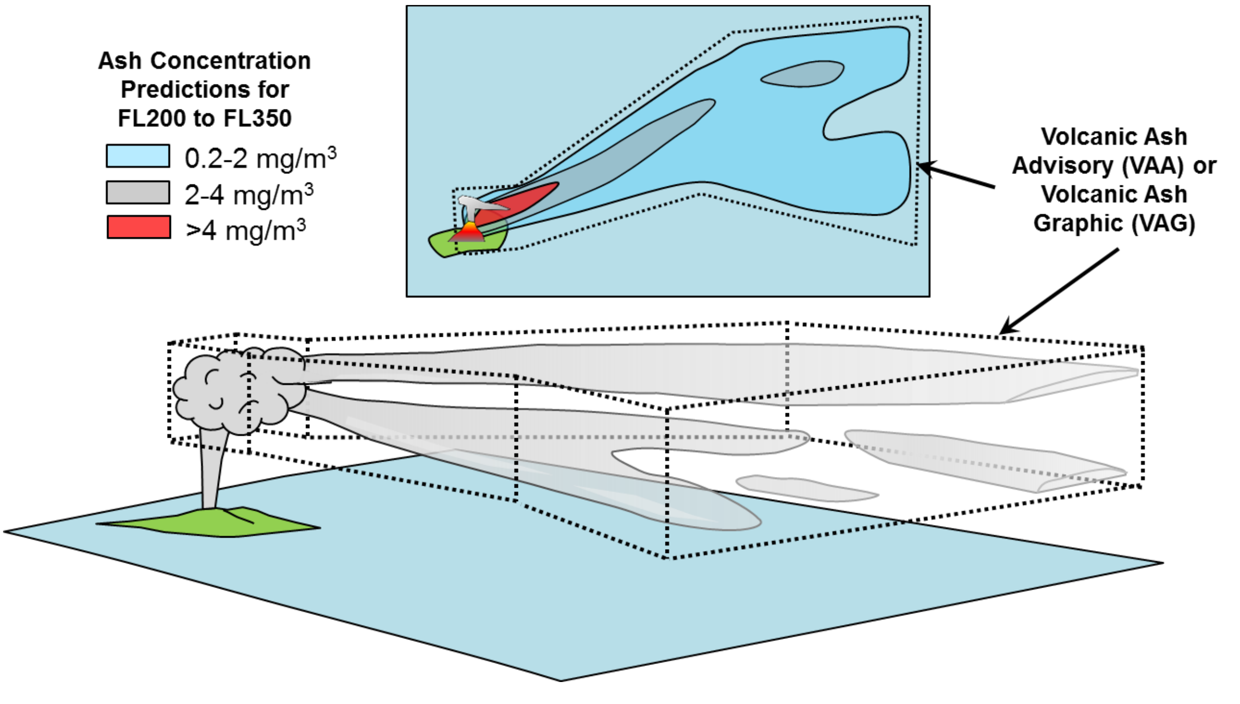

Figure 3 – Possible volcanic eruption scenario, illustrating VAA, VAG and ash concentration contours

It follows that producing flight plans which avoid the airspace enclosed by a VAA, VAG or 0.2 mg/m^3 contour is an effective way of minimising exposure to discernible ash, and visible ash which might represent a problem for engines. Figure 3 is a sketch of a possible volcanic eruption scenario, showing how the VAA, VAG or 0.2 mg/m^3 contour enclose discernible or visible ash clouds. Figure 3 also illustrates, however, that a large portion of the airspace the VAA, VAG or 0.2 mg/m^3 contour enclose may contain effectively no ash. In principle it could be possible to fly through the VAA/VAG enclosed airspace and not expose an aircraft to visible or discernible ash, but even attempting to do so in good light requires detailed preparations, and an SRA.

In addition to the VAAC products, there are other independent forecast and remote sensing products operators can use to support flight planning to avoid ash discernible from satellites.

Engine Susceptibility to Ash

With respect to the new EASA regulations compelling aircraft and engine manufactures to declare aircraft and engine susceptibility to VA, there is overwhelming evidence that engines can be exposed to moderate concentrations of VA for short periods of time and experience negligible damage. What is more, the work conducted on engine VA susceptibility between 2010 and 2016 means that a lowest exposure dose threshold can be defined below which the amount of ash that could be ingested would not result in significant implications for flight safety. It is also possible that larger exposure doses than the defined lower threshold will likewise not have flight safety implications, but with the data available today a maximum permissible dose cannot be defined. However, do note that although ash doses below the lower threshold will not lead to significant safety implications they may result in some economic damage to engines, e.g. increased specific fuel consumption or earlier than anticipated engine overhaul.

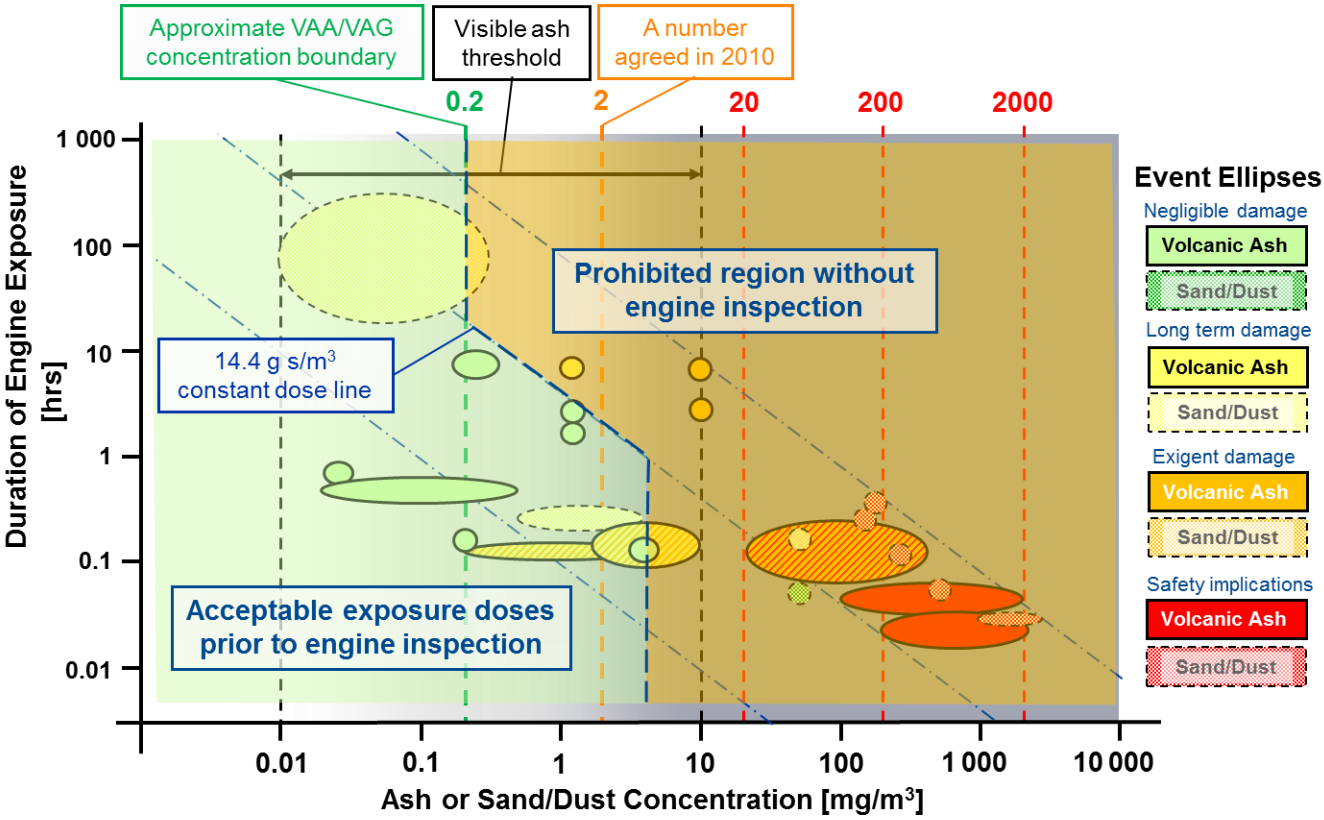

Figure 4 – An ash exposure dose of 14.4 g s/m^3 illustrated on the DEvAC chart.

Using a combination of in-service experience, engine test data and mathematical modelling, Rolls-Royce has established that for all Trent and RB211 engine types an ash dose equivalent to operating for 120 minutes in an actual ash concentration of 2 mg/m^3 will not lead to significant reductions in flight safety margins providing all measures are taken to maximise engine operability margins. Such a dose can be expressed in SI units as 14.4 g s/m^3, i.e. operating in 0.002 g/m^3 for 7200 seconds (7200 x 0.002 = 14.4). Rolls-Royce has also shown that a dose of 14.4 g s/m^3 represents an acceptable dose below which there is negligible impact on engine related flight safety margins across the actual ash concentration range of 0.2 mg/m^3 to 4 mg/m^3. This means that operating for up to 600 minutes in an actual ash concentration of 0.4 mg/m^3, or 60 minutes in actual 4 mg/m^3, will not lead to significant safety implications. However, it cannot be guaranteed that doses equal to or below 14.4 g s/m^3 are acceptable at concentrations substantially greater than actual 4 mg/m^3.

The ash dose that would represent an unacceptable deterioration in engine related flight safety margins at actual ash concentrations below 0.2 mg/m^3 is not known precisely, but evidence indicates that it is so large any exposure to such concentrations will have negligible impact on engine related flight safety margins. Figure 4 illustrates on the DEvAC chart a dose of 14.4 g s/m^3 across the 0.2 mg/m^3 to 4 mg/m^3 concentration range.

(The use of the phrase ‘actual ash concentrations’ in the paragraph above is to emphasise that engine susceptibility only makes sense if defined in terms of actual ash concentrations. Engines are unaware of forecast ash concentrations only actual ash concentrations.)

Operating in Forecast Ash

The above engine VA susceptibility was primarily defined to support operators who elect to enter airspace forecast to contain VA, which is in effect airspace enclosed by the VAAC produced VAA or VAG. Despite the establishment by Rolls-Royce that Trent and RB211 engine types can tolerate a volcanic ash dose of 14.4 g s/m^3 without significant safety implications, current FCOMs and AFMs may still contain explicit statements not to plan flight into visible or discernible ash. EASA also still recommends that operation in visible or discernible ash should be avoided. Operators should continue to comply with any FCOM or AFM instructions and respect EASA recommendations. Also, no fly zones as defined by the relevant authorities must continue to be respected.

Again, irrespective of flight safety margins operators need to recognise that ash doses less than 14.4 g s/m^3 may still result in short or long term engine damage which could lead to a reduction in engine performance and unscheduled maintenance or repair costs. As a consequence exposure to ash doses below 14.4 g s/m^3 could affect engine maintenance and overhaul contracts.

In addition to the use of an approved SRA, when flying in airspace forecast to contain visible or discernible ash, operators need to note that:

- Engines should be operated in a way that maximises the available operability margins, e.g. switch on engine/nacelle and/or wing anti-icing (as appropriate), minimise engine electrical and hydraulic power offtake.
- Whether flight operations are being conducted in clear skies and good daylight (e.g. Visual Meteorological Conditions – VMC), poor visibility (e.g. Instrument Meteorological Conditions – IMC) or during hours of darkness, if the presence of ash becomes discernible through the ICAO defined impacts on or in the aircraft, or effects such as sparks discharging from the icing indicator (see Figure 2), the contaminated airspace should be exited as soon and safely as possible.
- Even if exposure to visible or discernible ash has been successfully avoided, an assessment of the potential exposure dose to any ash which was neither seen nor discerned should still be made. This is particularly pertinent during hours of darkness or IMC, but also applies for clear skies and good daylight (remembering that it is possible to enter ash discernible from satellites or ash that could be visible, in good daylight without realising it).
- In the absence of direct measurement of an aircraft’s ash exposure dose, the dose should be assessed using forecast ash concentrations or remote measurements.

- If it is known or suspected that an engine has been exposed to a cumulative volcanic ash dose of 14.4 g s/m^3 or greater, accumulated over one or more flights, operators should inspect the engines following the procedures contained in the AMMs covering power plant inspection after contamination with volcanic ash.

Depending on the outcome of an engine's inspection the engine's acceptable exposure dose for future operations can be set back to 14.4 g s/m^3, set at a lower value (e.g. 7.2 g s/m^3), a cleaning regime initiated for the engine before a new permitted dose is set or in the worst case the engine may need to be removed for repair.

Assessing Exposure Dose

Figure 5 illustrates how an assessment can be made of an engine's potential ash exposure dose in the absence of direct on-board measurements. Note that Figure 5 is a hypothetical example of the type of concentration charts the London and Toulouse VAACs might produce for an ash cloud. Shown are three theoretical flight paths for a flight between City A and City B, which traverse the contaminated airspace. To assess whether a dose of 14.4 g s/m^3 could have been exceeded it is recommended to assume the entire airspace between the 0.2 mg/m^3 and 2 mg/m^3 contours was contaminated with ash at an actual concentration of 2 mg/m^3 and that between the 2 mg/m^3 and 4 mg/m^3 contours the actual concentration is 4 mg/m^3 everywhere. This is in effect very conservative (see below) but it does permit an assessment of exposure dose to be made.

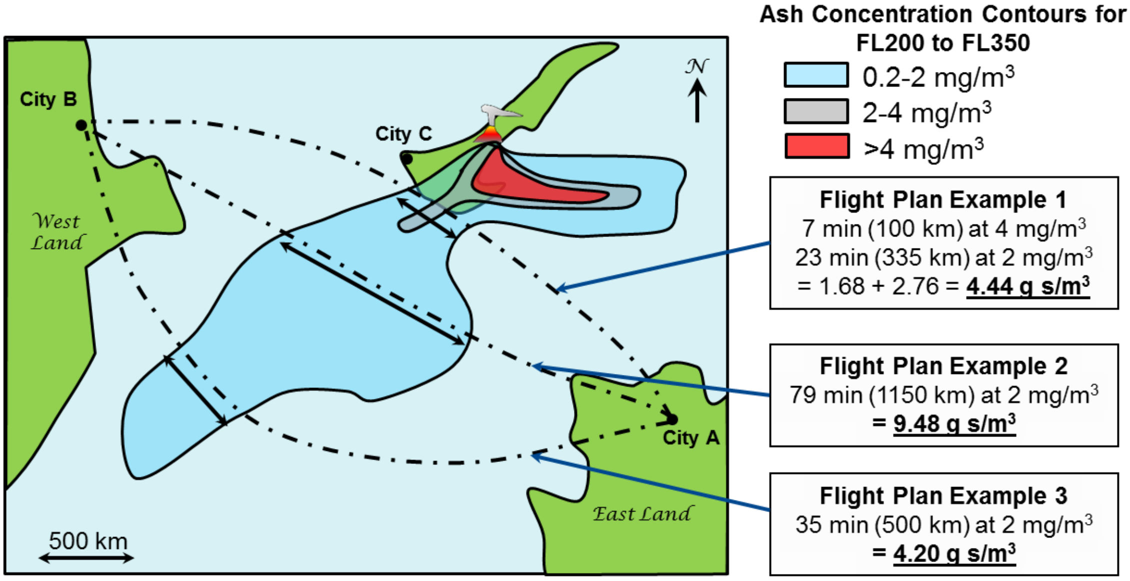

Figure 5 – Hypothetical ash cloud scenario showing flight plan options between City A and City B staying within the 14.4 mg/m^3 limit.

It would be generally advisable to produce flight plans and assess potential exposure dose for operations within the contaminated airspace in a similar way to the examples shown in Figure 5. If flight plan examples 1 or 3 were produced the engines are likely to have sufficient allowable remaining dose (9.96 g s/m^3 for Plan 1 and 10.2 g s/m^3 for Plan 3) to complete a return flight to City A – before an engine inspection is required – should the ash cloud still be present; Plan 2 may leave insufficient allowable remaining dose (4.92 g s/m^3) for a return flight without first performing an engine inspection.

It is worth commenting here that the concentration contours produced by the London and Toulouse VAACs are not necessarily lines that define where the ash concentration is 0.2 mg/m^3, 2 mg/m^3 or 4 mg/m^3. The contours are defined such that the peak ash concentration in the airspace volume between the 0.2 mg/m^3 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 mg/m^3 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 although the peak concentration between two contours should not exceed 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 (see Figure 3 above); it is likely much of the airspace will contain no VA. Consequently the assumption that the actual ash concentration between the 0.2 mg/m^3 and 2 mg/m^3 is 2 mg/m^3 everywhere is very conservative with respect to calculating exposure dose, even allowing for the possibility that at some locations ash concentrations could be greater than 2 mg/m^3.

Another potential source of information for assessing engine exposure doses are the measurements made by multispectral satellite imagery. To do this it should be recognised that such satellite based techniques do not measure ash concentrations; they measure the ash total column loading, which is the total mass of ash in the column of air between the Earth's surface and the satellite, measured in g/m^2 (see Figure 6). To calculate an appropriate mean ash concentration from a total column loading, an ash cloud vertical thickness will need to be established or assumed.

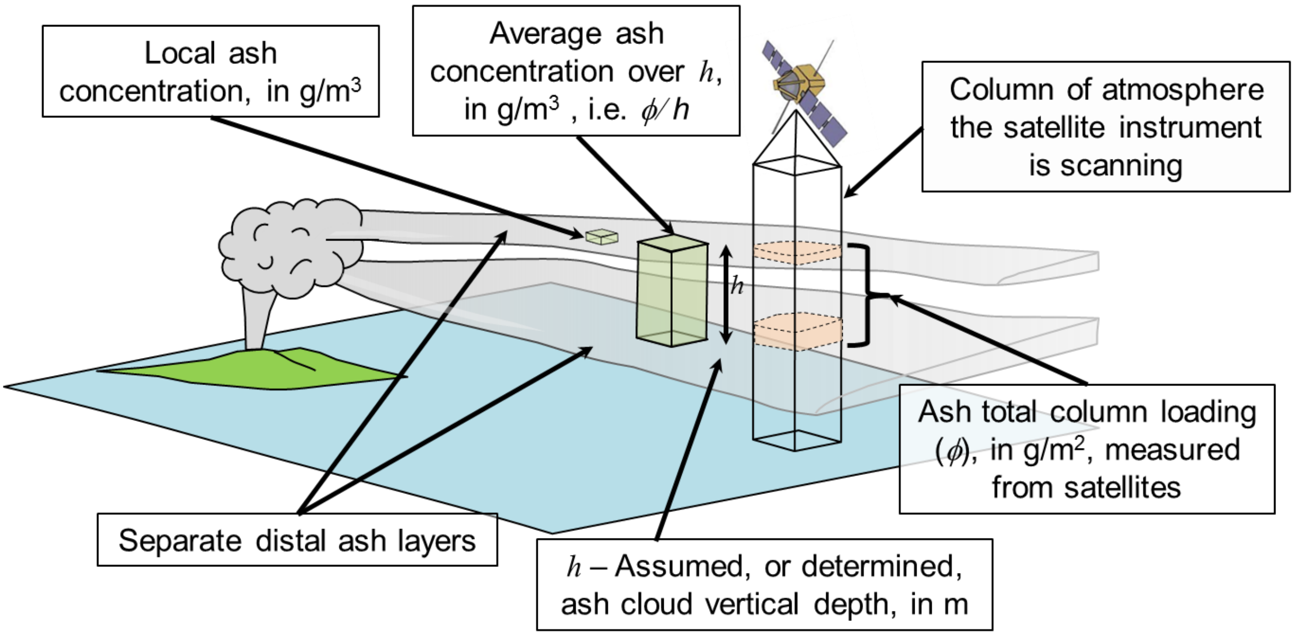

Figure 6 – The difference between an ash concentration within an ash layer and an integrated ash total column loading.

If direct on-board measurements of ash dose are available it is still advisable to construct flight plans in a similar way to the ones illustrated in Figure 5. An accurate knowledge of the remaining available ash dose still needs to be compared against the likely exposure dose along an intended flight path; reaching the lower ash dose threshold before exiting the ash cloud is clearly undesirable.

Further Information

For further information relating to the content of this document contact Rory Clarkson at Rolls-Royce plc (rory.clarkson@rolls-royce.com).