Volcanic Ash Safety in Air Traffic Management
A White Paper

European Safety Programme for ATM 2010-2014 (ESP+)
June 2011 - Edition 1.0

romatsa

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Air Navigation and
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EUROCONTROL

FOREWORD

Volcanic Ash Safety is a project developed in the framework of the European Safety Programme for air traffic management (ESP+) subsequent to the 2010 eruption of the Eyjafjallajökull Volcano. In the aftermath of the second eruption in May 2010, EUROCONTROL with the support of ROMATSA (Romanian ANSP) have sponsored a project research with the University Politehnica of Bucharest Research Centre for Aeronautics and Space and Faculty of Aerospace Engineering. It aimed solely at understanding the phenomena as well as providing objective, relevant and scientifically validated information for future safety decisions concerning the management of air traffic within portions of airspace contaminated with volcanic particulates. It is hoped that the acquired knowledge will better support decision makers in their trade-off for the most fluent air traffic under the given circumstances and with uncompromised flight safety.

This White Paper, while trying to summarise a few hundred pages of research report, also serves two main purposes:

- To develop a theoretical and practical understanding of the basic principles underlying the concept of atmospheric contamination with volcanic particulate matter.
- To assess the hazards, adverse effects and aviation safety risks associated to such contamination phenomena, as well as to present sound risk mitigation strategies.

The results are also made available to the industry and Academia with an invitation for further scientific review and debate.

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Special thanks to all scientific researchers from the *Research Centre for Aeronautics and Space* (RCAS) and *Faculty of Aerospace Engineering of the University Politehnica of Bucharest* (UPB) involved in the project. Their contribution towards improving the general level of understanding of volcanic ash/dust related phenomena was significant. The results presented in this White Paper are based on their research.

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Acknowledgements for working on this paper are also given to Ludovic NOGUES (nogues.ludovic@gmail.com) student at ULB (Université Libre de Bruxelles) Brussels under internship with ESP+ programme for the compilation of the information from the overall Ash Safety Report into this White Paper and to Frederic LIEUTAUD (frederic.lieutaud@eurocontrol.int) for the LIDAR knowledge support.

EXECUTIVE SUMMARY

This White Paper is the fruit of collaboration between EUROCONTROL, ROMATSA (Romanian Air Traffic Services Administration) and a team of scientific researchers from the aeronautics and space research centre of Bucharest. It focuses on the safety issues related to atmospheric contamination with volcanic particulate matter. Its three main objectives are:

1. Clarify the frequently misinterpreted term 'volcanic ash'. Understand what makes it different from 'volcanic dust' and why these two categories of particulate matter should be discriminated in practice.

2. Identify the hazards associated to volcanic ash and volcanic dust. Assess the aviation safety risk of their induced effects. Present the outcome of the hazard and risk assessment process from two distinct perspectives: operation and air traffic management.

3. Assess the mitigation strategies that are or should be implemented to minimize the aviation safety risk.

The present paper is aimed at anyone in the aviation industry concerned with flight safety. It indeed addresses a number of essential issues:

1. Volcanic ash and volcanic dust

- What are the correct definitions of 'volcanic ash' and 'volcanic dust'?
- Why is a size-based discrimination of volcanic particulates relevant, in practice?
- What are the principal characteristics of volcanic ash and volcanic dust?

2. Assessing the hazards, effects and safety risks related to volcanic ash/dust

- What are the identified hazards?
- What are their adverse effects on aviation safety?
- What are the associated risk levels?
- Hazard and risk assessment for operators
- Hazard and risk assessment for ATM industry

3. Assessing the risk mitigation strategies

- What are the recommended actions in case of hazard encounter?
- Concentration measurement vs. concentration forecasting
- Mitigation based on concentration forecasts
- What are the current trends in remote sensing and data analysis?

CONTENTS

VOLCANIC ASH AND VOLCANIC DUST

In volcanology, a clear distinction is made between 'volcanic ash' and 'volcanic dust'. Yet, during the April-May 2010 volcanic crisis, these two categories of volcanic particulates were not always discriminated by the aviation community.

What are the correct definitions of 'volcanic ash' and 'volcanic dust'?

Explosive volcanic eruptions can give rise to various types of pyroclastic entities (tephras), that can be classified into distinct categories. In line with this classification, volcanic ash consists of small jagged pieces of igneous rock and glass shards that have been expelled in the atmosphere at a certain initial height in the course of an eruption.

Grain size is the only element which effectively distinguishes volcanic ash (also known as 'coarse ash') from volcanic dust ('fine ash'). Indeed, whereas the typical size of volcanic ash particles ranges from 1/16 to 2 millimetres, volcanic dust particles are less than 1/16 millimetre across (i.e. 62.5 microns).

Due to their sizes, volcanic particles are able to remain in suspension in the atmosphere for a limited time interval, during which they generally get transported by local winds before settling on the ground. The natural process which allows particles in suspension to settle out of the fluid by which they are borne and eventually come to rest is known as sedimentation. In our specific case, being more 'bulky' than volcanic dust particles, volcanic ash particles possess less opportunity of getting transported by the wind. As a consequence, they will tend to settle on the ground in much less time than the former (greater average falling speed). This natural phenomenon is known as 'segregation by sedimentation'. In order to illustrate its practical implications, let us consider the following scenario. Pretend that a certain quantity of volcanic ash and volcanic dust has been injected in the atmosphere at an initial height of 10 kilometres and that, at this altitude, a horizontal wind of 50 knots is blowing. Based on **Table 1**, **Figure 1** depicts the differentiated sedimentation that ensues.

Equivalent diameter	1 mm (ash)	100 µm (ash)	10 µm (dust)	1 µm (dust)
Average falling speed (m/s)	5.5	0.7	0.005	$7 \cdot 10^{-5}$
Sedimentation Time (h)	0.5	4.0	555.6	39,682.5
Distance travelled (NM)	25	200	27,780	1,984,125

Table 1 –
Practical implications of sedimentation: eruption column height of 10km, horizontal wind of 50kts

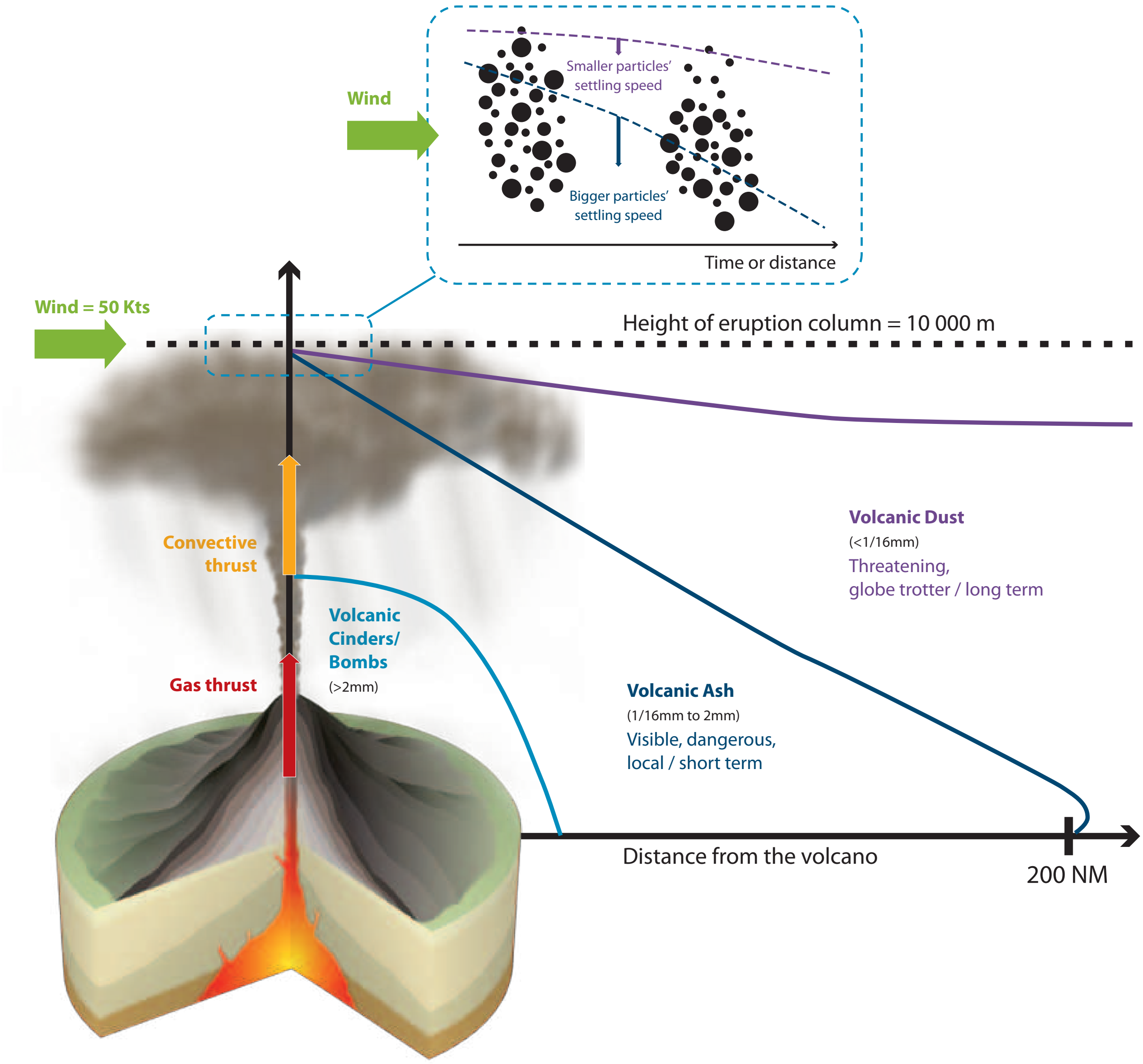


Figure 1 –
Practical illustration of the segregation by sedimentation process

This practical case demonstrates that volcanic ash and volcanic dust are completely different in terms of life span and contamination spread. This is due to their differentiated floatability in the atmosphere. Whereas volcanic ash has a local and short-term impact (high settling speed), volcanic dust is a long-term globe-trotter (low settling speed). This is a critical piece of information in terms of safety and crisis management.

Why is a size-based discrimination of volcanic particles relevant, in practical terms?

The distinction between volcanic ash and volcanic dust is based on particle size distribution. This discrimination between ash and dust as two different types of threat is relevant on several levels. Separate risk assessment, information processing, analysis in the decision making process, and lines of action are appropriate for each type of risks associated with these threats. Mixing or failing to de-couple the two types of threats may lead to economic risk.

Firstly, not all sizes of particles are equally dangerous to human health and turbine engines. All ash particles (i.e. those larger than 62.5 microns) are dangerous. As far as dust is concerned, the most dangerous segment is generally recognised to comprise particles ranging from 1 to 10 microns. Empirical observations corroborate this statement:

- In order to pose a threat to human health, volcanic particulates need to be 'respirable' and reach the alveolar region. Whereas particles larger than 10 microns are naturally filtered out by human body barriers, particles smaller than 1 micron are not retained in one's lung and can easily be expelled through expiration (Figure 2). In terms of human health, the dangerous particle segment therefore seems to be composed of particles ranging from 1 to 10 microns.

- Concerning turbine engines, particles larger than 10 microns and particles smaller than 1 micron are in the same range of harmlessness as for human health. Indeed, while the former (i.e. particles larger than 10 microns) are automatically centrifuged in the bypass flow (**Figure 3**), the latter (those smaller than 1 microns) are so minute that they tend to evaporate without melting.

These essential aspects will be addressed in more details in the chapter **HAZARD AND RISK ASSESSMENT PROCESS**.

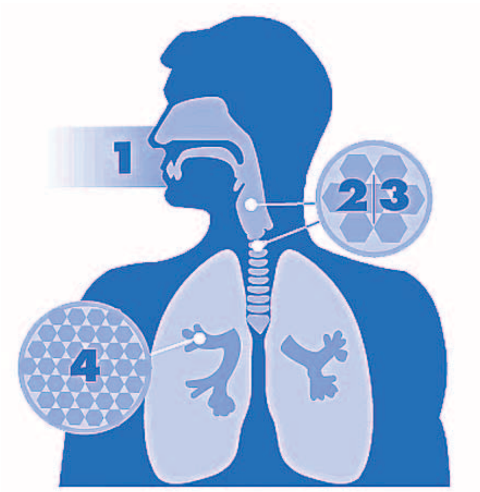


Figure 2 –

(1) Volatile particles can enter our respiratory system through nose and throat;

(2/3) Larger particles (> 10 microns) deposit in one's tracheo-bronchial airways. They can be evacuated through coughing, sneezing or swallowing;

(4) Smaller particles ($PM_{2.5}$) reach the alveolar region and cause lung and heart problems.

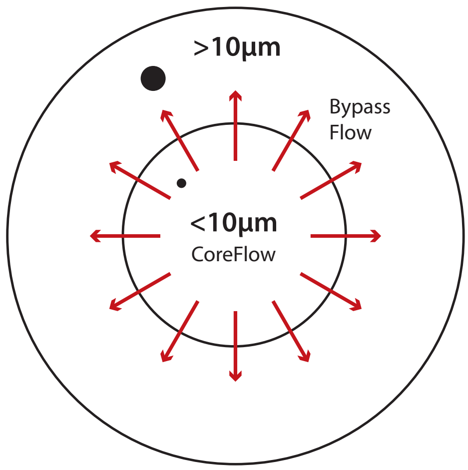


Figure 3 –

A turbine engine is a rotary engine. Therefore, it acts as a centrifugal separator. Particles larger than 10 microns are forced into the bypass flow and become harmless in terms of safety.

Secondly, as it has been illustrated in the previous section, a natural segregation of volcanic particulates occurs through sedimentation. This segregation, which is essentially size-driven, discriminates volcanic ash from volcanic dust in terms of life span and contamination extent.

Finally, atmospheric concentration is a crucial indicator of a contamination's intensity (see **HAZARD AND RISK ASSESSMENT PROCESS**). Yet, a direct link (although non-linear) exists between the concentration of a volcanic particulate matter along a vertical and its particle size distribution.

What are the principal characteristics of volcanic ash and volcanic dust?

From the physicochemical point of view, volcanic ash and volcanic dust are alike. Nevertheless, they differ strongly in terms of floatability in the atmosphere. Analyses conducted on Eyjafjallajökull samples led to the results contained in **Table 2**, which provides a comprehensive summary of the notions presented in this chapter.

	Volcanic ash	Volcanic dust
Particle size range	**1/16 mm – 2 mm** i.e. 62.5 µm – 2000 µm	**< 1/16 mm** i.e. Less than 62.5 µm
Composition	Volcanic ash and volcanic dust are heterogeneous materials principally composed of **quartz** (crystallised silica, SiO_2)	
Shape	Volcanic ash/dust particles are **not uniformly spherical** (presence of sharp edges)	
Melting temperature	Located between **900°C** and **1100°C**	
Life span (sedimentation time)	**Short** (e.g. Half an hour for 1 mm ash)	**Long** (e.g. 23 days for 10 µm dust)
Contamination extent	**Local** (within 1-200 NM of eruption site, greatest value recorded in history being 500 NM)	**Globe-trotter**

Table 2 –
Main characteristics of volcanic ash and volcanic dust

HAZARD AND RISK ASSESSMENT PROCESS

What are the identified hazards?

According to the scientific researchers from RCAS Bucharest, there are three separate types of direct threats to aviation safety in connection with volcanic activity: volcanic pyroclastic eruptions (VPEs), volcanic ash clouds (VACs) and volcanic dust contamination (VDC). This White Paper focuses on the two latter.

The term '**volcanic ash cloud**' refers to a dense, definite and clearly visible dark cloud made of volcanic ash, dust and fumes (**Figure 4**). On the other hand, '**volcanic dust contamination**' refers to a widespread concentration of dust and fume, forming thin layers in the atmosphere. Contrary to ash clouds, dust contamination possesses no definite boundaries and is visible only from selected angles or satellite imagery (**Figure 5**). **Table 3** summarises the main characteristics of these two hazards, in comparison with sand areosols.

	Volcanic Ash Cloud	Volcanic Dust Contamination	Sand Aerosol Contamination
Visibility	**Clearly visible** (from all angles) and easily identifiable due to dark colour and definite boundaries	Visible only from selected angles or satellite imagery: **hard to distinguish**	Visible only from selected angles or satellite imagery
What does it contain?	**Volcanic ash** particles **Volcanic dust** particles Volcanic fumes	**Volcanic dust** Volcanic fumes	Sand particles
Where?	Within 1-200 NM of the eruption	Very large areas (>1000 NM in size)	Large areas
Typical atmospheric concentrations	**1000 kg/hm^3**	**1-100 kg/hm^3**	**1-100 kg/hm^3**
Particle size range (μm)	1-2000	1-40	1-50
Floatability in atmosphere (age)	**1-2 Days** (due to ash-dust differentiated sedimentation)	**6 Days** (traces remain for years)	**3 Days**

Table 3 –
Main characteristics of volcanic ash clouds (VACs), volcanic dust contamination (VDC) and sand aerosol contamination

From **Table 3**, it may also be observed that volcanic dust contamination is very similar to sand aerosol contamination (**Figure 7**). The only significant difference between the two phenomena is that the former can occur at considerable heights whereas the latter cannot. This is due to the fact that, as opposed to sand which has to be lifted from the ground by wind and other convective phenomena in order to gain altitude, volcanic dust is initially ejected in the atmosphere at an important height (explosive volcanic eruption).

The aviation community could certainly benefit from the similarities that exist between volcanic dust and sand as atmospheric pollutants. Indeed, much experience was acquired by flying in sand contaminated atmosphere through the years (e.g. Cairo or Riyadh airports). This experience could be used to better estimate the risks associated to volcanic dust contamination. This particular point will be addressed further in this paper.

Figure 4 – Volcanic ash cloud rising from Eyjafjallajökull's crater (April 14, 2010)

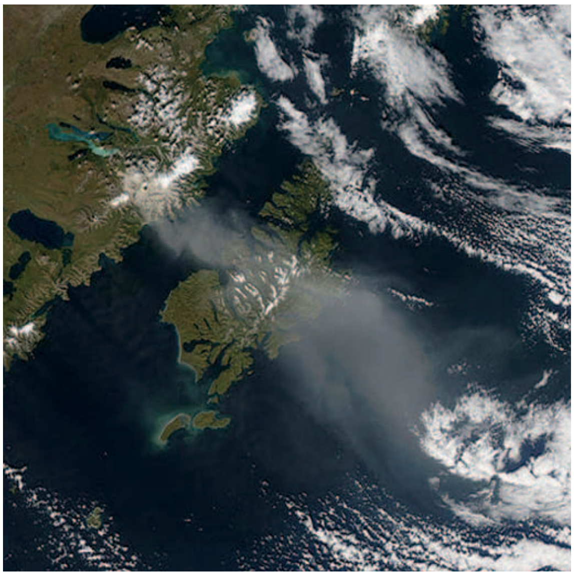


Figure 5 – Volcanic dust contamination over Kodiak Island, Alaska (September 21, 2003)

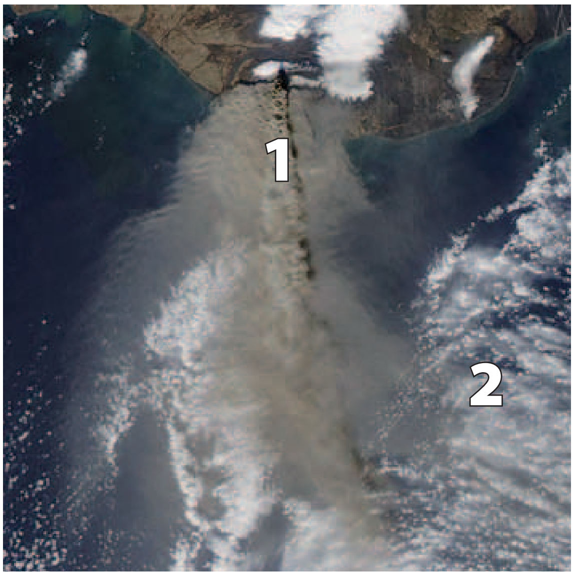


Figure 6 – (1) Volcanic Ash Cloud (VAC); (2) Volcanic Dust Contamination (VDC)

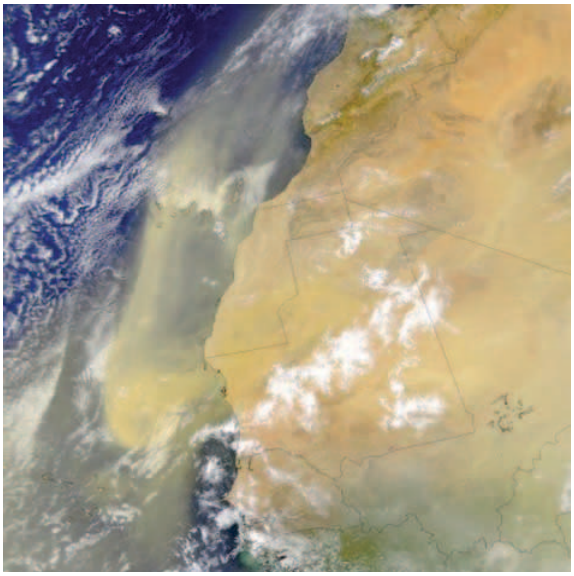


Figure 7 – Sand aerosols of Saharan origin over the coast of Africa

What are the adverse effects of these hazards on aviation safety?

Volcanic ash clouds and volcanic dust contamination interfere with aviation safety on different levels. Their adverse effects on aircraft components are presented in this section. It is important to bear in mind that the severity of these effects directly depends on the air breathing order of magnitude as described in **Table 4**.

Air Breathing Order of Magnitude	Description	Affected Hardware or Liveware	Severity
1,000 m^3/s	High flow non-filtered air breathing	Turbine engines	**High**
100 m^3/s	Directly exposed to airflow	Windshield, empennage, body and wing	**Moderate**
0.01 m^3/s	Low flow non-filtered air breathing	Human occupants, Pitot-static sensors, computers, electrical engines and other air-cooled parts	**Low**
Irrelevant	Air breathing through filters	Piston engines, air-cooled parts through air filters	**Extremely remote**

Table 4 –
Vulnerability proportionality with the air breathing flow

1. TURBINE ENGINES

A turbine engine (or jet engine) is a continuous-flow propulsion system whose role is to generate thrust. By definition, thrust is the force that propels an aircraft forward by compensating for the aerodynamic drag. It is a reaction force that appears when a high velocity mass flow of air is expelled in the direction opposite to flight (**Figure 8**).

Based on these assumptions, so as to deliver thrust, a turbine engine needs to ingest ambient air, increase its velocity and finally expel it in the atmosphere. Classically, the process can be split into four successive phases:

- First, the ingested ambient air undergoes a compression phase (fan and axial compressor stages). The aim is to bring the air flow to optimal conditions of pressure and temperature in preparation for the combustion phase.
- The air then reaches the combustor – heart of the engine. At this point, fuel is injected and the air-fuel mixture is ignited. The temperature of the fluid increases significantly.
- During the compression and combustion phases, energy has been provided to the air flow in the form of temperature and pressure. By forcing the air into a turbine, a fraction of this energy can be extracted and converted into useful work. This work, generated as the hot gases pass through the turbine rotary blades thereby setting them in motion, is used to drive the compressor stages (high and low pressure compressors) and the

fan. The stationary vanes that ensure the correct guiding of the air flow into the rotary part of the turbine are called nozzle guide vanes (NGV).

- The air flow eventually reaches the engine nozzle. Within this particular section, it undergoes a strong acceleration. As a result, at the outlet of the nozzle, a high velocity flow is expelled in the atmosphere: the engine generates thrust.

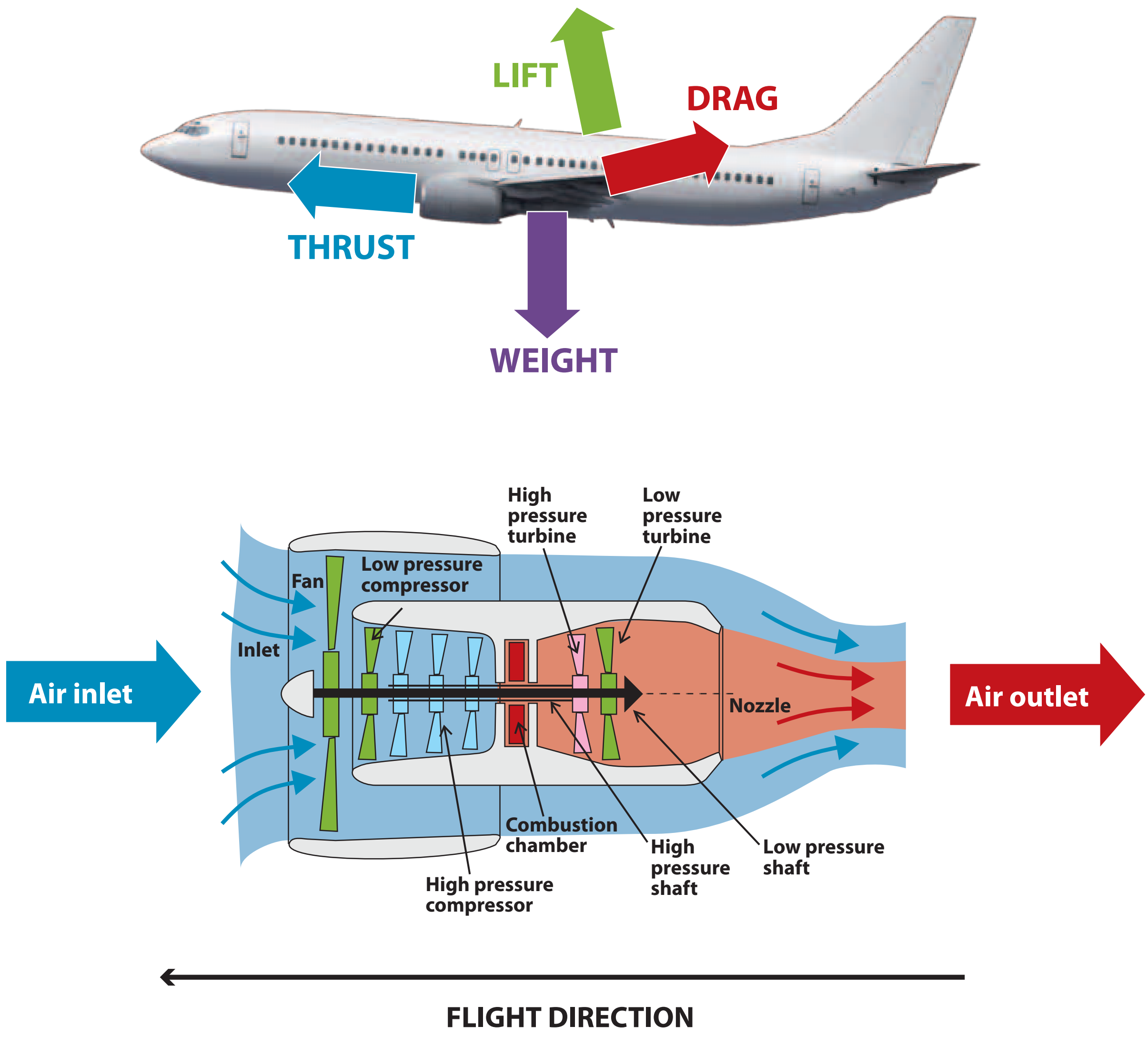


Figure 8 –
The four forces of flight (above)
Cross section of a classic turbine engine (below)

By detailing the process of thrust generation, four essential engine components were mentioned: the fan, the compressors, the combustor and the turbines. Further important facts have to be borne in mind:

- In portions of airspace contaminated with volcanic plume (volcanic particulates and gases emitted into the atmosphere in the course of an explosive volcanic eruption), aircraft engines obviously breathe in a certain quantity of volcanic particulates. The amount of solid particles ingested naturally depends on the atmospheric concentration levels.

- Theoretically, the thermal efficiency of a turbine engine is an increasing function of its combustion temperature. For that reason, turbofans operate at high temperatures, i.e. 1400°C in average. Such levels of temperature imply that potentially ingested volcanic ash/dust particles will tend to melt when travelling through the combustor.

- Nowadays, civil aircraft engines are generally two-spool high-bypass engines. The adjective 'two-spool' comes from the fact that they are composed of two individual mechanical couplings: a high-pressure spool (high-pressure turbine driving high-pressure compressor) and a low-pressure one (low-pressure turbine driving low-pressure compressor and fan). As it can be observed from **Figure 8**, the spools' shafts are coaxial. Another particularity of modern jet engines is that a fraction of the air flow sucked in by the fan bypasses the combustion zone, flowing directly into the main exhaust gas flow so as to provide additional thrust. This discrimination between a 'core flow' and a 'bypass flow' is crucial since volcanic particles borne by the latter do not run the risk of melting and subsequently depositing. This explains why the 'dangerous particle size segment' mentioned in the previous chapter referred only to particles ranging from 1 to 10 microns. Indeed, larger particles tend to get centrifuged in the bypass flow thus becoming harmless to the engines.

1.1 Engine shutdown

Given the important operating temperatures of modern jet engines, volcanic particles generally soften and melt as they travel through the combustor stage. Thus, as they penetrate the 'cold' turbine section, they tend to solidify and deposit thereby causing a clogging of the nozzle guide vanes. Because volcanic ash/dust particles are principally composed of silica, these deposits are often referred to as 'glassy coatings'.

Figure 9 below illustrates the glass coating phenomenon based on the volcanic ash/dust particles size. If the particles are of the volcanic ash size, they will melt and tend to solidify in contact with any cooler surface such as the combustion chamber walls, the high pressure turbine nozzle guide vanes (**Figure 10**) and even the high-pressure turbine cooling vents (see next section). However, if the particles are of the volcanic dust size, the probability of the melted droplets to get in contact with cooler objects is very low. In that case, the glass droplets will exit the nozzle and solidify outside the engine.

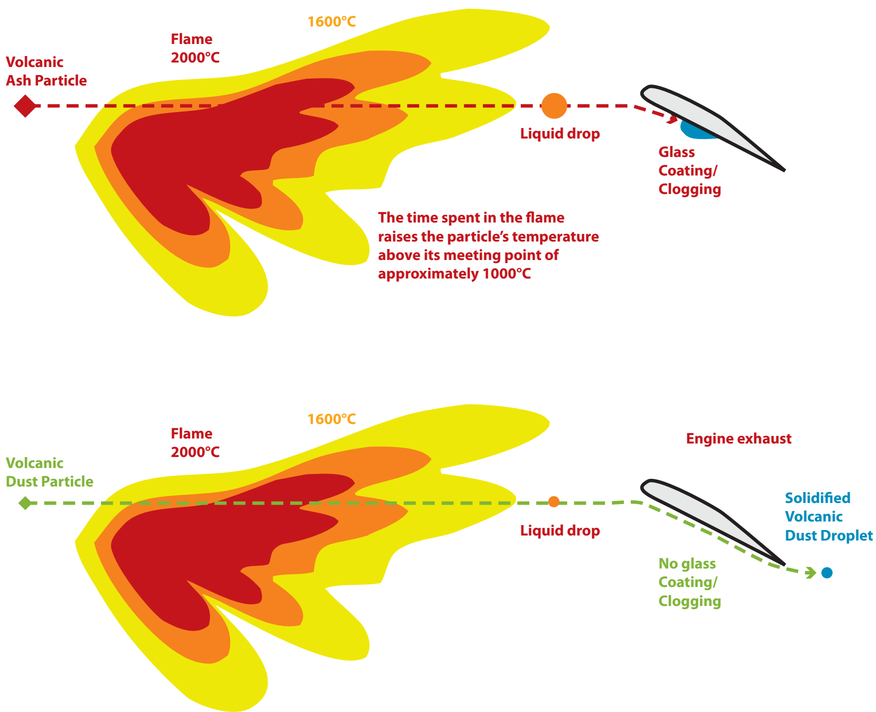


Figure 9 –
Glass coating/clogging by ash vs. dust

Naturally, the larger the quantity of particles ingested, the stronger the clogging effect. As the clogging effect increases, a gradual reduction of the NGVs' throats can ensue, implying that the air experiences more difficulty getting out of the engine. As a result, significant pressure builds up in the combustor. When pressure reaches a certain level, the air flow eventually reverts, which causes the engine to shutdown. In scientific literature, this phenomenon is known as a 'flame-out' due to an 'engine surge'

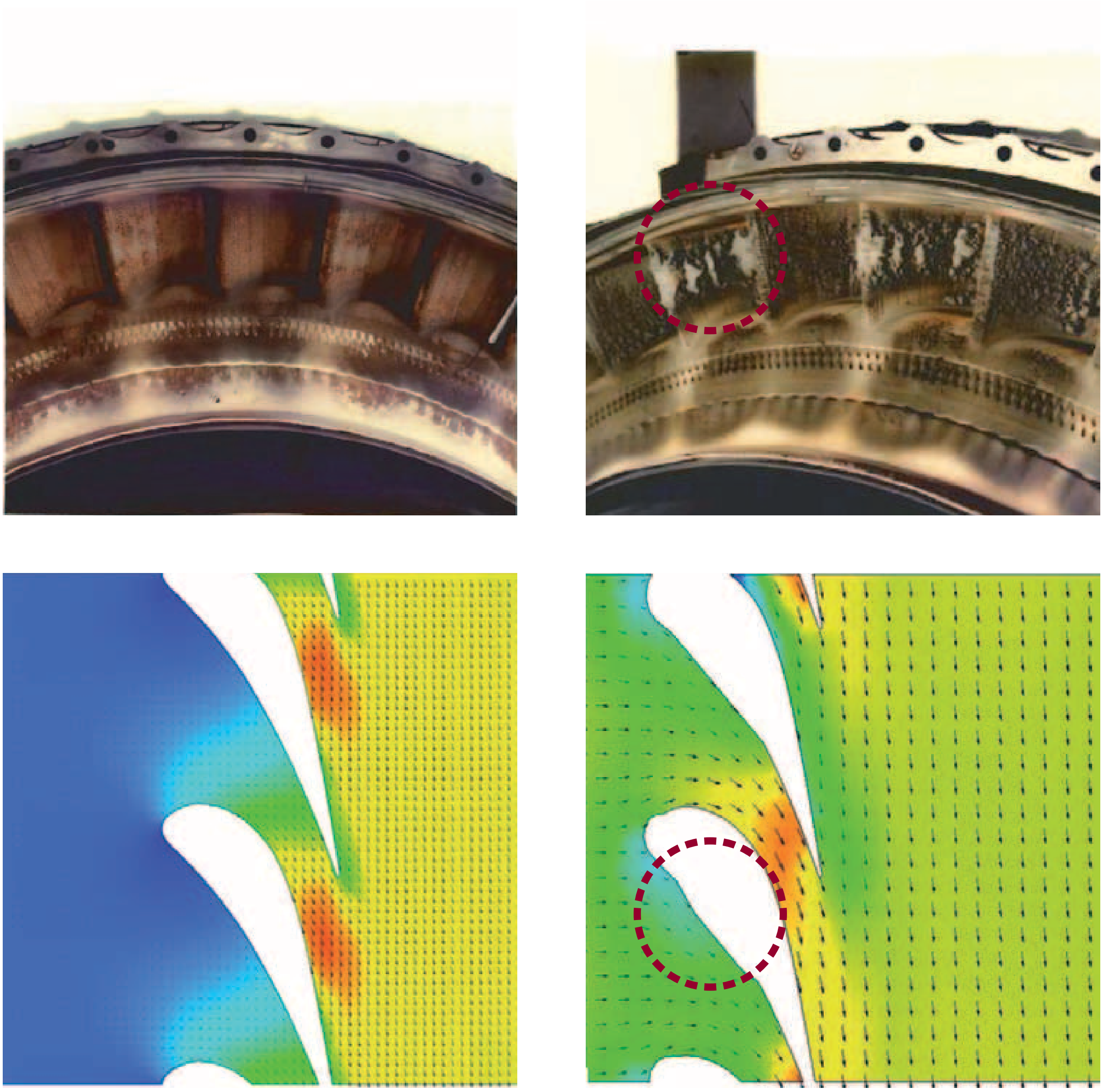


Figure 10 –
3-D and 'unfolded' 2-D views of turbine nozzle guide vanes without deposition (Left) same views but with volcanic dust deposits: the flow cross section is restricted (Right)

1.2 Engine overheating

In modern jet engines, the turbine section consists of several stages, each having both a stationary and a rotating set of blades. To distinguish between the two, one has chosen to denote the stationary airfoils as vanes and the rotating counter-parts as blades. The stationary row, positioned upstream, mainly serves a guiding purpose. Hence the term 'nozzle guide vanes mentioned' earlier.

The highest temperature loads of a turbine engine are found at the exit of the combustor and in the first turbine stage. In fact, the turbine inlet temperature (TIT) is often higher than the creep limit of the nickel alloys used in the conception of the turbine airfoils. A comprehensive cooling system is thus needed. Two methods are generally used in practice: external cooling, which provides the airfoils with a cool protective air-film, and internal cooling, which regulates temperature from the inside by means of convection and conduction. The coolant that is used consists in a fraction of air extracted from the compressor. By guiding this cooling air (around 650°) through the turbine airfoils, their temperature can be lowered to approximately 1000°C, which is permissible for reliable operation of the engine.

By design, turbine cooling systems are prone to accumulate volcanic particles (**Figure 10**). Should the cooling passages within the turbine airfoils be completely clogged, a severe engine overheating would immediately occur.

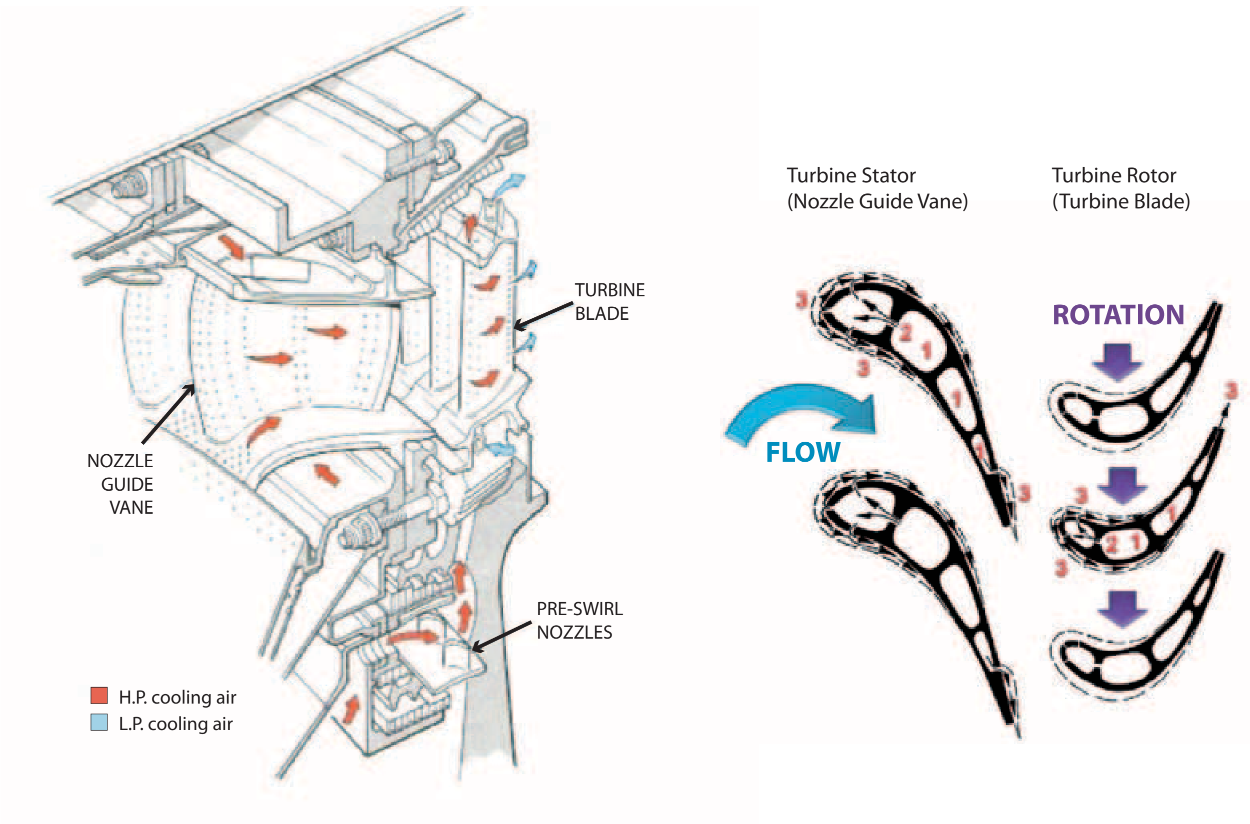


Figure 11 –
3-D illustration of external and internal cooling in the first turbine stage of a jet engine (Left);
2-D 'unfolded view' of first turbine stage (Right): (1) Convection cooling, (2) Impingement cooling, (3) Film cooling

1.3 Other miscellaneous effects on turbine engines

- Due to their shape and hardness, volcanic ash/dust particles prove highly abrasive. Depending on their size, their repeated impact on engines' metallic parts can cause low to severe wear. This process is known as 'solid particle erosion'.
- Finest ash/dust particles may penetrate the sealing of the transmission system, enter into the lubricant and get transported into the gear meshes. An alteration of the transmission's components can ensue.
- Ash/dust particles can lead to a denting of the protective ceramic coatings of the turbine blades.
- Ash/dust particles can lead to a clogging of the fuel injection system and of the labyrinth seals of the shafts.

2. WINDSHIELD, BODY, WINGS, EMPENNAGE, TAILFIN

External aircraft components such as the windshield, body, wings, tailfin and empennage are highly exposed to the abrasive effects of volcanic particles (solid particle erosion). However, due to their extremely low surface roughness, particle embedment is limited.
The abrasive effect is a function of the size of the particles. It is beyond dispute that large volcanic particles (ashes) are extremely abrasive. As the particle size decreases, so does the abrasiveness, down to a certain point where abrasion ceases to occur.

The *Volcanic Ash Safety* final report indicates that ashes (i.e. larger particles) are not capable of travelling over large distances. Therefore, they are essentially located in the vicinity of the eruption site. As a matter of fact, for a typical eruption column height of 10 km, ash does not extend to more than 200 NM downwind a volcano's vent. Thus, operators need to contrast the effect of abrasion on windshields, body, empennage, tailfin with the projected densities and sizes of particles to be encountered.

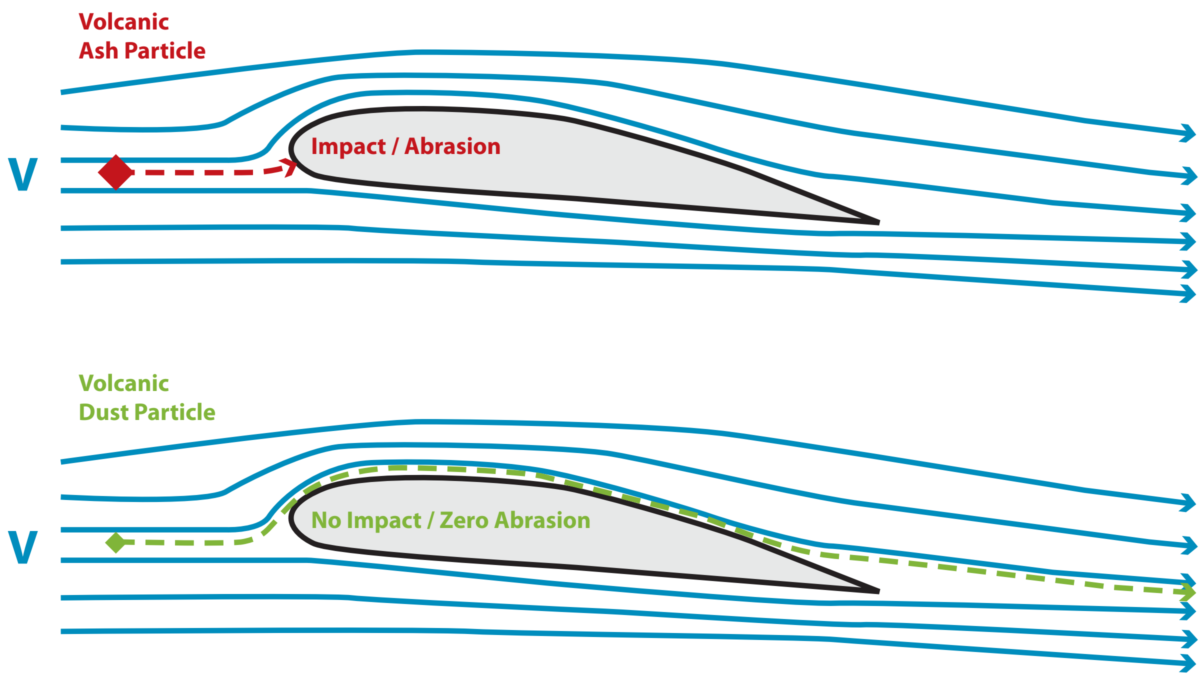


**Figure 12 –
Abrasion caused by Ash vs. Dust**

3. HUMAN OCCUPANTS

As previously stated in this White Paper, silicon dioxide (or silica) is the main constituent of volcanic ash/dust. A thorough investigation of the adverse effects associated to both short-term and long-term exposure to silica is therefore necessary to understand the impact of volcanic particulate matter on human health.

In practice, two distinct types of exposure to silica should be distinguished: environmental exposure and occupational exposure. While the former occurs when ambient air becomes contaminated with quartz aerosols, the second refers to repeated exposure to silica in the context of a professional activity (e.g. quarrying and mining).

In the course of a volcanic crisis, it seems reasonable to consider that aircraft passengers are subject to environmental exposure to silica, while aircraft crews are occupationally exposed. Under such circumstances, epidemiological studies indicate that silicosis and lung cancer are the only adverse health effects that are supported by strong scientific evidence. The manifestation and the development of such disorders however strongly depend on the duration and the level of exposure to silica. This risk issue will be addressed in the next section. In addition to respiratory disorders, it should be noted that volcanic dust could permanently harm the human eye cornea by scratching. Indeed, unlike normal dust, volcanic particles possess considerable hardness (of the order of quartz).

4. AVIONICS, ON-BOARD INSTRUMENTS AND PNEUMATIC CONTROLS

The accumulation of volcanic ash/dust within an aircraft engine can lead to severe malfunctions (see sections **1.1** and **1.2** of this chapter). Yet, jet engines are not the only components that are exposed to clogging: pneumatic controls and on-board instruments are also subject to this phenomenon.

For instance, flying into a portion of airspace contaminated with volcanic particles could potentially pose a threat to Pitot-static probes (**Figure 13**). These instruments provide pilots with reliable air speed indications. Their malfunction can therefore lead to serious incidents (e.g. stalling). This explains why civil aircraft are usually fitted with at least few of them. Yet, this redundancy remains a mere safety net: it does not prevent the sensors from not working.

Figure 13 –
Pitot-static probes on Air France's Airbus A380

What are the risks associated to the hazardous effects?

According to ESARR 4 (EUROCONTROL Safety Regulatory Requirement), risk is defined as '*the combination of the overall probability, or frequency, of occurrence of a harmful effect induced by a hazard and the severity of that effect*'.

Concerning atmospheric contamination with volcanic particulate matter, the risk function depends on the concentration level, the duration of exposure and the size of particles. This result seems quite intuitive for concentration and duration of exposure since both of these parameters are linked to the actual quantity of volcanic ash/dust encountered by the aircraft and its occupants.

1. LEVEL OF EXPOSURE

The level of exposure to volcanic particulate matter is reflected by their concentration in the atmosphere. Concentration is a very noisy physical property. Indeed, it depends of numerous parameters such as the volcano and eruption types, the elapsed time since eruption (age), the position coordinates (latitude, longitude and flight level) etc. So as to determine a representative value of concentration at a given time and place, it is essential to take into account the scale of the contamination phenomenon.

In practice, concentration levels should better be expressed in kilograms of volcanic particulate matter per cubic hectometre of atmospheric air (i.e. kg/hm^3). The choice of using the cubic hectometre as a reference volume is not an innocent one. A cubic hectometre approximately corresponds to the volume of air ingested by a typical aircraft jet engine of mid size aircraft (such as Boeing 737-700) during 10 minutes of flight (**Figure 14**). This time interval of 10 minutes is relevant for atmospheric contamination with particles of volcanic origin. Indeed, should a VAC or VDC encounter occur by accident, pilots would usually want to exit the contaminated portion of airspace by proceeding to an evasive manoeuvre (180°-turn and descent). Yet, 10 minutes represents a safety margin for the successful completion of the latter manoeuvre, even in unlucky configurations.

Based on these assumptions, it seems relevant to consider the cubic hectometre as a reference volume for concentration measures. As a matter of fact, due to the scale of the phenomenon, the cubic meter is simply too small and would lead to noisy and inconsistent values.

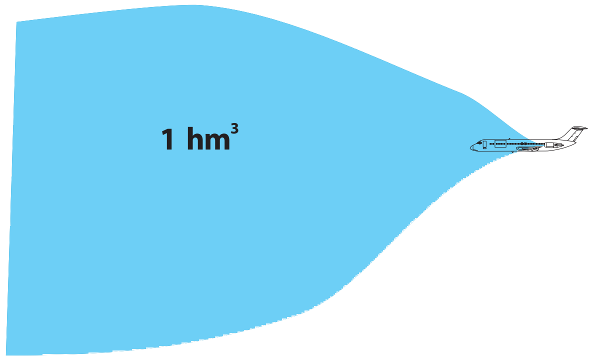


Figure 14 – A cubic hectometre is the order of magnitude of the air volume ingested by a modern jet engine within a time span of 10 minutes. This illustration is not to scale.

In response to the 2010 volcanic crisis, on 17 May (immediately after the events), Rolls-Royce experts produced a 'Safe to Fly Chart' (**Figure 15**). By plotting each known volcanic ash/dust encounter in history on a logarithmic diagram of engine exposure versus concentration, they indeed manage to determine a 'safe flying concentration threshold'. According to their calculation, the concentration required for engine safety is 2x10^{-3} g/m^3 (equivalent of 2 kg/hm^3). Since May 2010, their findings were not invalidated by real life occurrences. This is presumably due to the fact that this initial safety threshold was obtained via a precautionary approach. Indeed, its value is more than one full order of magnitude smaller than the damaging concentration levels that were actually reported in flight aviation history, in order to compensate for the uncertainty of

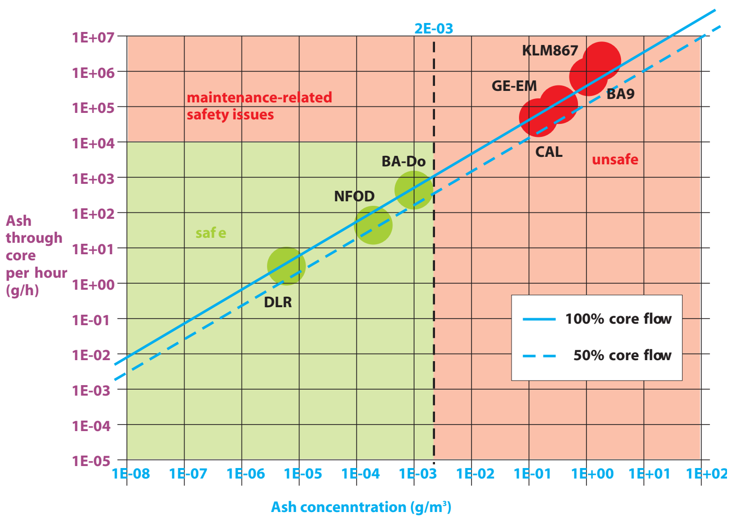


Figure 15 – Rolls-Royce 'Safe To Fly' chart

concentration forecasts. Since the events of 2010, Rolls-Royce experts have inspected hundreds of engines that flew in ash contaminated portions of airspace. During these inspections, no alarming signs of damage were detected, even for engines that had supposedly been operated in concentrations as high as $4x10^{-3}$ g/m³. This explains why certain states nowadays opt for a slightly bolder threshold of $4x10^{-3}$ g/m³ (equivalent of 4 kg/hm³) rather than $2x10^{-3}$ g/m³ (equivalent of 2 kg/hm³). For the purpose of this White Paper we will use further concentration values expressed in kg/hm³.

Bearing this information in mind, two important results need to be reminded:

- Volcanic ash clouds are dense and visible. For that matter, their concentration of volcanic plume is extremely high. Indeed, as per nature, a VAC contains both volcanic ash and volcanic dust. A typical value of concentration within an ash cloud is 1000 kg/hm³ (see **Table 3**). It is much more than the safe flying concentration threshold described above. As such, it is considered unsafe to fly into a volcanic ash cloud.

- Volcanic dust contamination is a low concentration hazard (consequence of 'segregation by sedimentation'). Typical concentration values range from 1 kg/hm³ to 100 kg/hm³. The safety impact of this hazard thus ranges from irrelevant (if concentration is inferior to threshold) to serious (otherwise).

2. DURATION OF EXPOSURE

This parameter is straightforward: the greater the amount of time spent by an aircraft in a contaminated area, the higher its exposure to risk. As previously stated in this White Paper, concerning human health, a distinction has yet to be made between environmental exposure (passengers) and occupational exposure (aircraft crew).

3. HISTORY OF AIRCRAFT ENCOUNTERS WITH VOLCANIC ASH

ICAO's *Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds* (DOC9691) defines in its Appendix G8 an "ash-encounter severity index", which ranges from Class 0 (acrid odour noted in cabin due to the presence of sulphur gas; electrostatic discharge – St. Elmo's fire – on windshield, nose, engine cowls; no notable damage to exterior or interior) to Class 5 (engine failure or other damage leading to crash). In the history of civil aviation, the highest category of ash encounter reported so far is of Class 4 (temporary engine failure requiring in-flight restart of engine). It should be noted that all these Class 4 incidents occurred in areas affected by ash (volcanic ash clouds) and **not** dust (volcanic dust contamination). This observation was graphically illustrated by Jacques Renvier, from CFM/Snecma, in his presentation during the Atlantic Conference on Eyjafjallajökull held at Keflavik in 2010 (**Figure 16**).

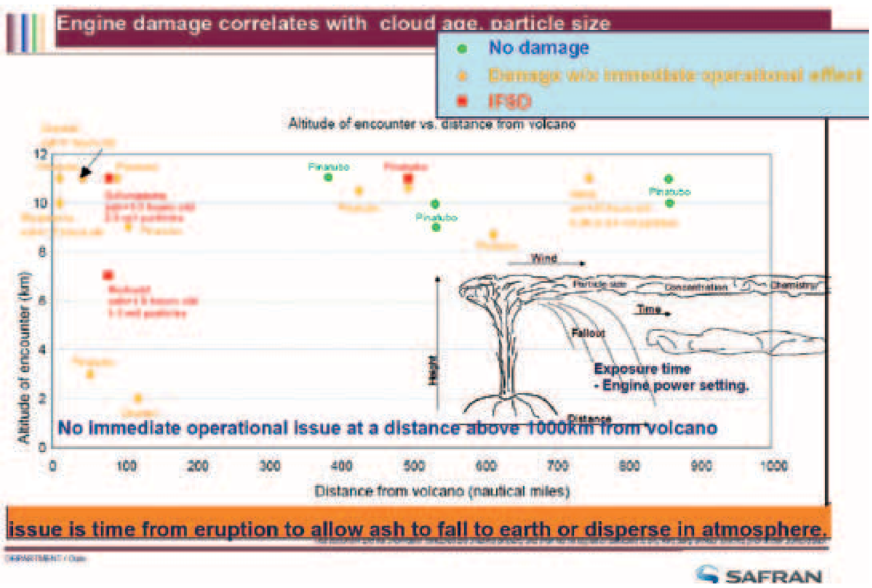


Figure 16 – Altitude and severity of hazard encounter versus distance from eruption site

4. LEVEL AND DURATION OF EXPOSURE DURING THE 2010 VOLCANIC CRISIS

To provide a sound assessment of the risk levels inherent to ash clouds and dust contamination, a correct understanding of the conditions of exposure is required. For instance, during the 2010 volcanic crisis:

- The mass median aerodynamic diameter of volcanic ash/dust particles (MMAD) ranged from 0.1 to 40 microns. This interval comprises the dangerous particle size segment which was previously identified in this White Paper (**Figure 2** and **Table 2**). Such fine particles could have penetrated deep into the occupants' lungs thus provoking an inflammatory reaction. However, as studies conducted on laboratory rats suggest, such reaction can only be observed after being exposed to high doses of silica.

- For aircraft passengers, duration of exposure to silica varied between 2 to 12 hours. For crew members, the situation was similar except that exposure was repeated. Reviewing the scientific data, RCAS researchers concluded that it was reasonable to anticipate that airplane passengers exposed to silicon dioxide by inhalation during flights through volcanic dust clouds were in no danger of developing silicosis. The level of exposure (in terms of concentration and duration) was far from those admitted as capable of inducing pneumoconiosis in the occupational settings. In fact, the level of exposure was even smaller than those measured in ambient air in some cities of the United States. Moreover, respiratory disorders such as silicosis or lung cancer may only develop after prolonged exposure (of the order of an entire working life).

Concentration (which is a consequence of particle size distribution as per the segregation by sedimentation process), duration of exposure and particle size distribution are the main three factors of the risk function. Given the conditions of exposure of the April-May 2010 volcanic crisis, it may be observed with hindsight that the overall safety risk was real but limited to regions located in the vicinity of the eruption site.

In the following section, a general hazard and risk assessment process is presented. Two distinct perspectives are considered: aircraft operations and air traffic management.

Hazard and risk assessment for operators

By aggregating the hazard identification process with the risk assessment process, VACs and VDC safety impacts can be analysed. The results, from an operator point of view, are listed in the **Table 5**.

In this table, the severity hierarchy is consistent with the classification officially endorsed by ICAO (cf. severity index in previous section). Only the most damaging effects are exposed (occurrences of class 2 to class 4). Class 1 adverse effects are left out because their uneven and unsystematic reporting complicates their overall assessment.

The probabilities of occurrence listed above are expressed for a duration of exposure of 10 minutes. This time interval corresponds to the safety margin required to carry out an evasive manoeuvre in case of inadvertent encounter. The values of the probabilities are determined based on a 2010 report produced by the United States Geological Survey (USGS) entitled "*Encounters of Aircraft with Volcanic Ash Clouds: A Compilation of Known Incidents, 1953–2009*". Attention should be brought to the fact that, in the latter document, data concerning both severity and time of exposure is not available for all historic damaging encounters. Moreover, no distinction is made between volcanic ash clouds occurrences and volcanic dust contamination. The probabilities expressed in the table above therefore result of extrapolations considering: the typical concentration levels and particle size range of VACs and VDCs, the air breathing order of magnitude of the exposed components and the comprehensive data contained in the 2010 USGS report.

From the compilation produced by the USGS experts, it can be observed that most damaging encounters with volcanic ash clouds occurred within 24 hours of the onset of ash production or at distances less than 1,000km from the source volcanoes. As a matter of fact, all of class 4 incidents for which complete data was available occurred under these particular conditions. This result is in line with the findings of the researchers from the RCAS Bucharest and needs to be corroborated with the heights of eruptions. Indeed, the overall safety risk proves to be more important 'in vicinity' of the eruption site since, in this region, the volcanic plume is still dense and composed of large volcanic particulates. Nevertheless, ash encounters

Problem	Absolute Severity	ICAO Severity Index	Related Hazard(s)	Probability of occurrence within 10mins	Risk level
Engine flame-out	High	4	VAC	High	High
			VDC	Low to Medium	Medium
Engine overheating	Medium to High	3-4	VAC	High	High
			VDC	Low to Medium	Medium
Plugging of Pitot-static probes	Low to High	2-3	VAC	Medium	Medium
			VDC	Low to Medium	Low to Medium
Abrasion of engine components	Medium	3	VAC	Medium	Medium
			VDC	Low to Medium	Low to Medium
Failure of pneumatic controls	Medium	3	VAC	Low to Medium	Medium
			VDC	Low	Low
Wear of external aircraft components	Medium	2	VAC	Medium	Medium
			VDC	Low	Low
Malfunction of on-board instruments	Medium	2	VAC	Medium	Medium
			VDC	Low	Low
Contamination of air handling and air conditioning systems	Medium to High	2	VAC	Low to Medium	Medium
			VDC	Low	Low
Corrosion of aircraft metallic components	Low to Medium	2	VAC	Low to Medium	Low to Medium
			VDC	Medium	Low

Table 5 –
Sample of Risk assessment of the effects induced by VAC and VDC hazards from operator perspective

can still turn into incidents even if a volcanic plume is more than one day-old or if its distance from the volcano's vent is more than 1,000 km. Therefore, even though age and distance (which are linked as per segregation by sedimentation) enable a quick assessment of the danger area, it would be problematical to solely rely on them as universal thresholds for fly/no fly decisions.

Several interesting results can be derived from plotting different aviation safety threats on a diagram of frequency (damaging encounters per year) versus severity (**Figure 17**). For volcanic dust contamination, the value of these two parameters is considered as almost null. Indeed, according to all sources available, no damaging encounter involving solely volcanic dust has ever been reported in civil aviation history. Even though this fact might be partly explained by the lack of relevant data, there is still no strong scientific evidence today that VDC could lead to severe damages of the airframe or the jet engines in ordinary concentrations. **Figure 17** also underlines the similarities that volcanic dust shares with sand aerosols as atmospheric pollutants.

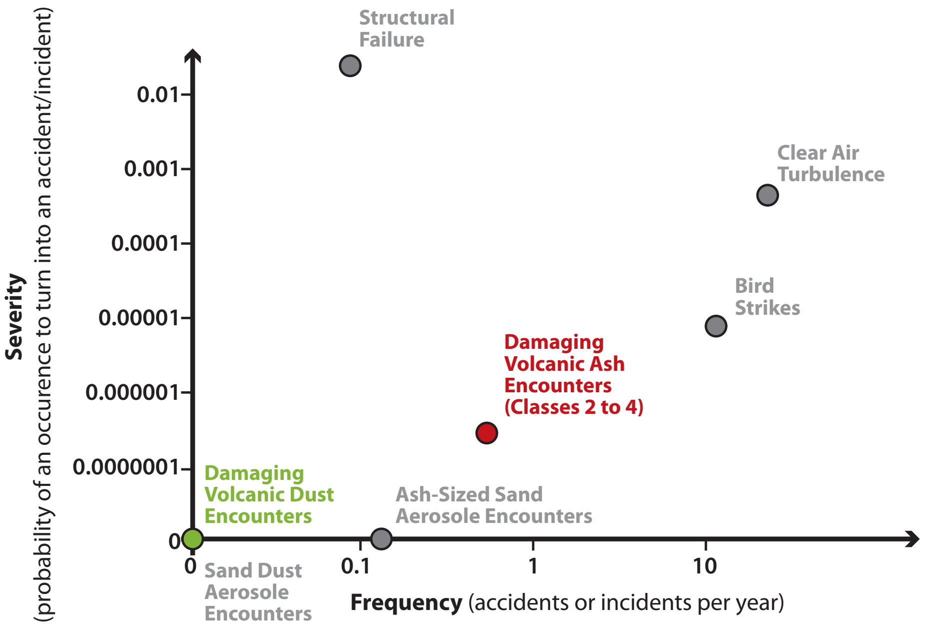


Figure 17 – Aviation safety threats plotted according to severity and frequency

Based on **Table 5** and on **Figure 17**, several remarks can be made:

- Volcanic ash clouds correspond to high risk levels. This is mainly due to their inherent concentration. Indeed, within an ash cloud, the concentration of volcanic plume is extremely high. For that precise reason, flying through such a cloud is highly likely to induce engine failures (shutdown or over-heating). As a matter of fact, during both major VAC encounters of flight aviation history, the jet engines flamed out. However, it should be noted that the latter were restarted successfully once out of the contaminated flight levels.

- Overall, the risk level corresponding to volcanic dust contamination is rather limited. Indeed, the low concentration levels inherent to this phenomenon do not pose a significant threat to flight safety. In practice, no serious incidents related to volcanic dust contamination were reported in aviation history. As a matter of fact, for 'regular' concentration levels (below the safe flying threshold), volcanic dust is very similar to sand aerosols. As such, it does not constitute a safety issue, but rather a maintenance issue.

- In 1986, a WHO study group suggested that below a concentration level of 40 µg/m^3 (equivalent of 0.04 kg/hm^3) occupational exposure to silica is not harmful to humans. In addition, silicosis and lung cancer may only manifest under prolonged exposure (working life) to high concentrations of silica. Yet, RCAS researchers showed that, in some parts of the world (e.g. Riyadh, Cairo), the quantity of silica present in ambient air is higher than the levels of silica measured during the 2010 crisis.

In moderately contaminated areas (concentration below 4 kg/hm^3), aircraft could be operated without experiencing difficulties or presenting visible damages. Indeed, Rolls-Royce experts reported at the *International Air Safety and Climate Change* (IASCC) conference, held in Cologne on 8-9 September 2010, that they had inspected hundreds of engines that flew in ash contaminated portions of airspace and that they did not detect anything abnormal besides an increased amount of the Sulphur in the oil (SO_2 is a good indicator of the presence of volcanic ash).

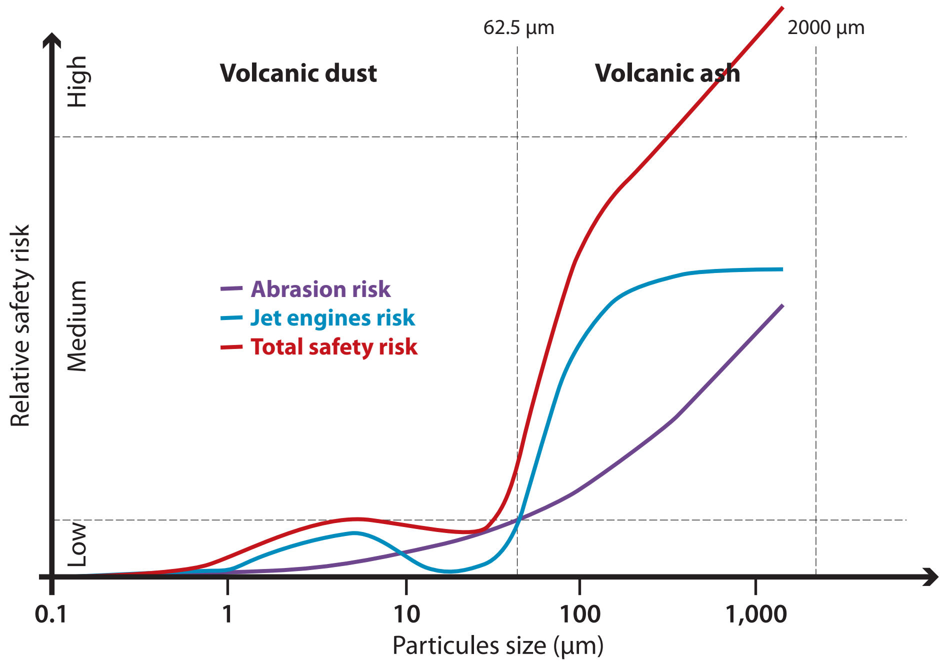


Figure 18 – Qualitative representation of the relative safety risk functions
The overall safety risk (red solid line) is broken down on its principle sources: abrasion risk (purple solid line) and jet engines risk (light blue solid line). The human health risk is negligible and hence ignored.

Consequently, although flying within high concentrations of ash/dust is certainly dangerous, a certain concentration threshold seems to exist below which commercial flights may be acceptable (including from the abrasion point of view), especially if the size of the encountered particles is small (volcanic dust). This is illustrated on **Figure 18**.

Hazard and risk assessment for ATM industry

Today, the exclusivity of the decision for opening or closing a contaminated portion of airspace lies with the national authorities. ANSPs also play an important role, although the approach in the case of the last 3 eruptions in 2010 and 2011 was far from being harmonised from State to State and ANSP to ANSP. Operation safety threats have direct repercussions on the management of air traffic. The question is: 'is the ATM system able to cope with high levels of traffic under a higher risk of flights declaring emergency, or proceeding to surprise descents and 180° turns?'. This complex issue will be tackled in the next chapter, where different preventive actions and mitigation strategies will be investigated.

Nevertheless, let us underline an essential point, namely the discrimination that has to be made between VAC and VDC in terms of ATM. It is a matter of risk segmentation. Indeed, as it has been demonstrated previously, VAC and VDC have differentiated impacts on operation safety. From the ATM point of view, mixing or failing to de-couple these threats might influence decision makers to take inadequate actions in order to cancel out the global risk. In such case, possibly unjustified losses would be endured by civil aviation stakeholders. The events of the 2010 volcanic crisis epitomise this situation.

MITIGATION STRATEGIES ASSESSMENT

Contrary to typical safety-threatening weather or pollution phenomena, volcanic ash/dust contamination cannot be detected by current on-board sensors (see later in **Concentration measurement vs. concentration forecasting section**). The presence of particles of volcanic origin in the ambient air can nevertheless be betrayed by certain particular signs:

- Sudden opaqueness (VAC);
- Particular smell of SO_2 in the cabin and cockpit (VAC / VDC);
- Increased TIT temperature (VAC / VDC).

Under such circumstances, flight safety is jeopardised and immediate actions should be undertaken. It is essential that both the air traffic management industry and the airline companies become familiar with these measures. Indeed, should a volcanic ash/dust contamination situation be encountered during flight, in terms of safety, the responsibility would principally lie with the pilots – who should perform the adequate preventive actions – and the air traffic controllers – who should assist and guide pilots throughout their task.

What are the recommended actions in case of hazard encounter during flight?

1. VOLCANIC ASH CLOUD, VAC

- Immediately reduce thrust to idle. Idle thrust has indeed two capital positive influences: the combustor's temperature becomes lower than the melting point of volcanic ash/dust particles (no subsequent risk of deposition) and the air intake is reduced meaning that potentially fewer particles can be ingested by the engine.
- Immediately descend and make a 180-degree turn (evasive manoeuvre)
- If the aircraft needs to be levelled off, thrust adjustments should be minimised and performed through slow and smooth thrust lever movements, due to the reduced surge margins (cf. **section 1.1** of the previous chapter).
- Switch turbine engine and wing anti-ice on, auxiliary power unit on, and all air conditioning packs on.
- For the pilots, put oxygen mask on at 100 per cent, if required.
- In case of engine flame-out, an engine 'restart' can be considered assuming that the aircraft has exited the contaminated area. Indeed, the vibrations induced by the latter process can help shatter the brittle glassy coatings off the turbine's nozzle guide vanes. A similar result could also be obtained by alternating between a positive and a negative load factor.

2. VOLCANIC DUST CONTAMINATION, VDC

- Gather the most recent information (forecasted concentration maps).
- Become aware of the extension of the contaminated area and its expected movement, knowing that atmospheric winds transport volcanic dust.
- Route as to avoid areas with contamination above the approved safety threshold (i.e. 4 kg/hm^3).
- Delay climbing or execute climbing through a non-equilibrium manoeuvre done manually.

The above actions and manoeuvres should be done in coordination with Air Traffic Control units who should be able to access the latest information concerning the contaminated areas. However the crews should have a deep knowledge of their Airline risk assessment performed prior to the flight and get a full briefing of the situation before departure. At this stage, it should be stressed that dispatching of aircraft with engines close to their operational life limit in VDC areas should be avoided, since their surge margin is limited and the probability of a safety hazard to occur is higher than with new engines.

3. GENERAL VIEW OF THE CAUSES, EFFECTS AND REQUIRED RESPONSES

Parts / Occupants	Cause	Effect	Response
Turbine engines	fuel injection and combustor deposits of melted ash (glassy coatings)	surge, shut-down, difficult restart in flight	idle thrust, evasive manoeuvre
Turbine engines	clogging the turbine cooling vents	overheating	idle thrust, evasive manoeuvre
Pitot-static	clogging the sensors	unreliable air speed indications	attitude-based flying, indicated air speed deducted from ground speed and wind velocity
Turbine engines	abrasion with hard particles	wear of fan, compressor, turbine, transmission	idle thrust, evasive manoeuvre
Pneumatic controls	clogging the vents	failure	evasive manoeuvre
Windshield, body, wings, empennage	cracks, abrasion with hard particles	wear, opaqueness	evasive manoeuvre
Avionics, on-board instruments	clogging air-cooling vents, electrostatic discharges	overheating, malfunction	evasive manoeuvre
Human occupants	breathing contaminated air, eye cornea contact with ash/dust particles	respiratory problems, eye damage	nose breathing, replace contact lenses with eyeglasses
Turbine engines, body and instruments metallic parts	acidity, exposure to associated SO_2 and sulphurous acid	corrosion (in time)	Maintenance check and replacement

Table 6 –
Adverse effects associated to VAC and VDC in decreasing order of severity and required responses

Concentration measurement vs. concentration forecasting

Avoiding a dangerous portion of airspace requires detecting it first. The airborne weather radar (AWR) is a perfect and widespread example of on-board remote sensing device. Yet, contrary to classic weather or pollution phenomena, volcanic plumes do not provide radar response under normal circumstances (virtually no radar echo). This is mainly due to the fact that radar wavelengths (1-10 cm band) are far greater than the actual size of volcanic particles, which implies a weak backscattering of radiations. For that reason, other methods have been developed to detect and measure the concentration of volcanic particulate matter in the atmosphere. Current techniques (**Figure 19**) include:

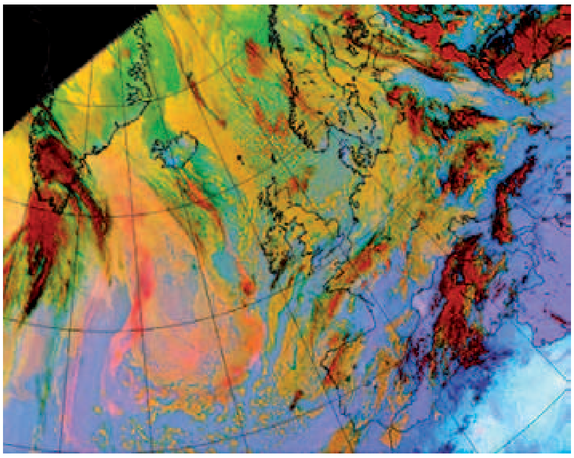
- **Classic *in situ* sampling:** Measurement is conducted via an airborne unit. The procedure simply consists in flying through the dust contaminated atmospheric layer for 5 to 10 minutes. Concentration is then evaluated by dividing the mass of the particles accumulated in the filter of the device by the volume of air that it has ingested.

- **LIDAR:** Measurement can be conducted from the ground (up-looking LIDAR) or from the air (airborne down-looking LIDAR). A LIDAR is an optical remote sensing device whose working principle is analogous to that of radars except that it uses pulsed light rather than radio waves. Thus, smaller wavelengths can be achieved and volcanic particles may be detected.

- **Sun photometer:** As beams of solar light travel through the atmosphere, they are partially absorbed by the particles present in ambient air. Located on the ground and aiming at the sun, sun photometers measure concentration by evaluating the intensity of solar radiation along their line of sight.

- **Satellite imagery:** Measurement is conducted from space by a satellite unit. In the images produced, volcanic particulate matter is associated to a characteristic colour (usually orange/pink). For each point in the image, the colour intensity is proportional to the sum of the concentration values along the line of sight of the satellite (integral).

Airborne unit (classic *in situ* sampling)



Satellite imagery

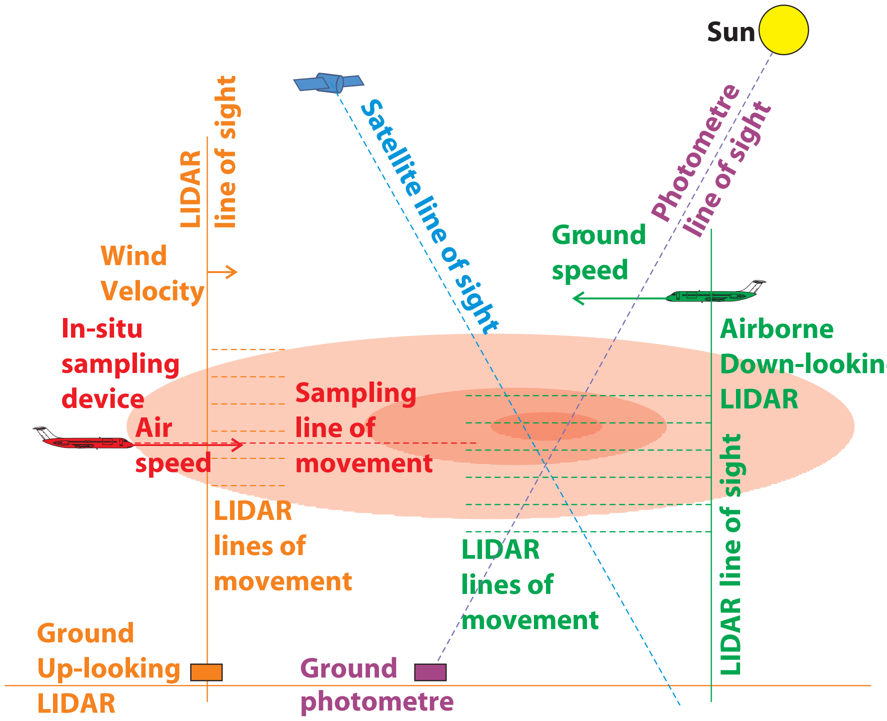


Figure 19 –
Current concentration measurement techniques

However, intrinsic shortcomings are linked to these various measurement techniques:

- **Consistency:** As per nature, a measure represents the value of a certain physical quantity at a given time and place. Concentration being a noisy physical property (random variable), instantaneous measures could have nothing to do with useful mean values (due to variance). This issue is particularly significant with in situ probes due to the microscopic scale on which they measure concentration. By applying the hectometric principle (see **Figure 14**), RCAS researchers came up with the concept of an original in situ measurement device named 'Airborne in situ hectometric concentration measurement unit'. Its design aims at gathering contaminant from a large volume of air (of the order of the cubic hectometre) using an electrical compressor. The measurement noise is thus filtered out naturally (hectometric principle) and the uncertainty of the concentration measurement is minimised.

- **Accuracy:** Current remote sensing methods are generally indirect and based on arbitrary assumptions or coefficients (e.g. LIDAR and sun photometers). As such, they possess inherent accuracy issues. Furthermore, these techniques often integrate concentration along a certain line of sight (**Figure 19**), which leads to an uncertainty as regards the actual ash/dust distribution. Consider satellite imagery for instance. The same colour intensity could be generated by a very concentrated thin layer located at a high altitude or by a very thick but low concentrated layer extending from the ground up, along the line of sight.

- **Geographical Scope:** The coverage of the airspace at the scale of the phenomenon is not achievable by measurements only. Indeed, except for satellite imagery, current sensors are not adapted to the scale of volcanic ash/dust contamination: they possess a poor geographical scope.

- **Timeliness and operational value:** When made available to users, measured values of concentration are already part of history. Thus, although interesting from a scientific perspective, these measures have no significant operational value. Since 2010, several projects have been dedicated to the particular matter of timeliness of empirical measures. For instance, the SAVAA project (Support to Aviation for Volcanic Ash Avoidance) was launched in an effort to address the issue of providing accurate and timely satellite-based information to VAACs (Volcanic Ash Advisory Centres).

Due to these inherent limitations, no certified on-board instrument capable of sensing or measuring volcanic ash/dust contamination has been fitted on civil aircraft yet. Finding suitable avoiding routes thus seems an impossible task for aircraft crews alone. For that reason, ANSPs should play a central role in assisting the pilots in their decisions, by acquiring and sharing information concerning the extent and development of the contamination zone. Powerful and accurate concentration forecasting methods are therefore crucial. However, in practical terms, forecasting methods suffer certain limitations:

- **Consistency and accuracy:** Forecasting methods are based on mathematical models and numeric simulations. Models are designed to emulate complex real-life processes. In practice, they are often based on simplifying hypotheses. Therefore, even the best mathematical model remains a mere image of the real process. In addition, numerical simulations always produce numerical errors. For these reasons, perfect accuracy and consistency can never be achieved.

- **Uncertainty and sensitivity:** In order to produce representative outputs, models require consistent input variables. These variables are not always easily measurable in practice and might necessitate estimation, which is a source of uncertainty. For instance, the injection height of the volcanic ash/dust debris is a central piece of information that has to be matched "by eye" to current or prior satellite images. Little deviations of the eruption column height can lead to very different results (high sensitivity).

In conclusion, when considered separately, concentration measurement and concentration forecasting possess strong limitations. While concentration measures are local and uncertain due to current measurement techniques, concentration forecasts are even more uncertain due to mathematical modelling and numerical simulation. In order to prove efficient and useful, these two approaches need to be combined. One of the best ways to achieve this consists in cross-checking concentration forecasts with actually measured values. If successful, such a method would provide wide-area concentration forecasts with limited overall errors in comparison to blind forecasting. Should they be given well in advance, these forecasts could definitely help in improving airspace and flow management as well as flight planning during a crisis situation. This is illustrated in **Table 7**.

Types of concentration	Actual	Measured	Forecasted with Data Assimilation	Forecasted Blindly (open-loop)
When they are available (hours)	never	T+2H	T–18H (up to T–180H)	T–18H (up to T–180H)
Uncertainty due to initial data of the eruption (orders of magnitude)	-	-	0.2 - 1	2 - 3
Uncertainty due to the Eulerian diffusion model (orders of magnitude)	-	-	0.1 - 0.4	+1 every 24 hours
Uncertainty due to the measurement techniques	-	0.1 – 1	-	
Area coverage	-	Very local (except for satellite imagery)	Global	
Overall errors	0	Significant	Large	Very large (rapidly increasing in time)
Relevance to IFR flight operations	-	Tactical avoidance	Flight planning	
Relevance to ATM	-	Forecasts Validation	Airspace management, Flow management	

Table 7 – Principal characteristics of the various types of concentration

Mitigation based on concentration forecasts

To produce reliable wide-area concentration forecasts, scientific researchers from RCAS Bucharest developed a program, called FALL4D, which can assimilate measured values periodically. This closed-loop validation of the application's outputs enables an almost continuous compensation for the errors inherent to its underlying mathematical model.

When it comes to numerically simulating the motion of volcanic particulates or, to a greater extent, the dispersion of a volcanic plume, two classic approaches are generally used in practice: the Lagrangian approach and the Eulerian approach. Simply put, whereas the former enables to follow particles individually along their trajectory, in the second, particles' properties and behaviour are smeared out and only the concentration field at each point of space and time matters (fixed grid).

Given the fact that they allow to trace particles, Lagrangian models are useful when it comes to simulating the motion of volcanic particulates that have been ingested by a jet engine. However, they seem less suited to simulate large-scale processes such as the dispersion of volcanic plumes. Indeed, due to the considerable number of particles involved, the execution of a Lagrangian model in such circumstances would require excessive calculation time. In practice, Eulerian models are hence preferred when it comes to concentration forecasting. This explains why FALL4D uses an Eulerian model to simulate the dispersion of a volcanic plumes both through time and space (hence the term "4D").

Based on FALL4D, RCAS researchers have developed a tool which could be used in case of volcanic eruption by any national authority, service provider or operator. This software, named **ASH4D**, offers two main applications:

- An Immediate Danger Area (IDA) calculation based on the wind profile at eruption site, the eruption column height, the targeted particle size and the considered flight level. The procedure does not address the VDC risk but rather aims at providing a simple and rapid method to establish a danger perimeter, based on minimal information. The main output of the application is the distance from the source at which the volcanic ash cloud should be found. **Figure 20** illustrates the simplifying hypothesis on which it relies: a linear downwind fall of volcanic ash particles. In this context, the eruption column height plays a significant role in the sedimentation process and consequently in the probability of ash encounter. As it can be observed from **Figure 20**, it is because of its record high eruption height that Pinatubo posed a threat to aircraft that were located as far as 500 NM from its eruption site.
- A simulated visualisation of the volcanic particles' dispersion process. This application enables the user to: interpolate through maps in four dimensions (geographical coordinates, altitude and time); use FALL4D to extrapolate or forecast several days in advance; export contamination maps; superimpose to the maps: concentration measurements, pilots report, flight 4D trajectories, airports, navigation aids, sector boundaries etc.

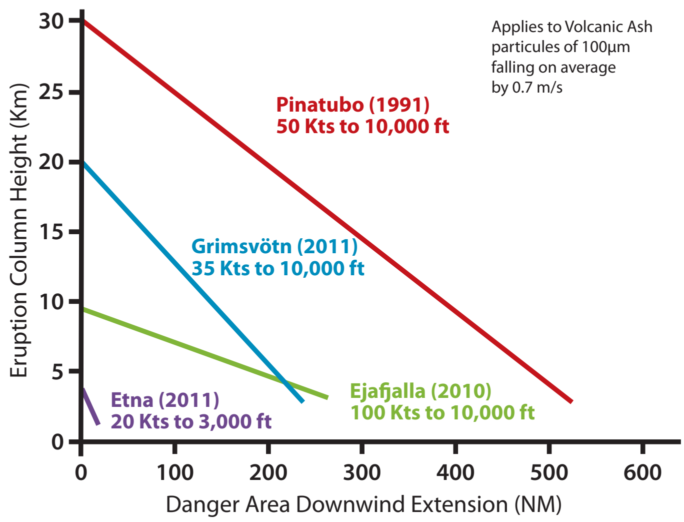


Figure 20 – Illustration of the concept of immediate danger area in few historical situations (Pinatubo, Eyjafjallajökull, Etna and Grímsvötn)

Volcano (eruption date)	Pinatubo (1991)	Grímsvötn (2011)	Eyjafjallajökull (2010)	Etna (2011)
Eruption column (km)	30	20	9	3.5
Flight Level (ft)	10,000	10,000	10,000	3,000
Flight Level	100	100	100	30
Wind Velocity (kts)	50	35	100	20
Danger area (NM)	535	235	236	21

Simulations ran at the RCAS confirmed that all serious safety threats in history posed by volcanic particles occurred within the IDA predicted by ASH4D. The latter tool therefore seems to provide a consistent and economical representation of the zone to be avoided. Hence the idea to use it in order to establish a danger perimeter based on minimal information. The 'first reaction check-list' should be as follows:

1. Find the location of the eruption (or the point source of contaminant) and feed the *latitude* and the *longitude* (LAT, LONG) in the ASH4D software. Future versions of the software could offer a list of active volcanoes, nuclear and chemical plants with coordinates already recorded.

2. *Time coordinates of the eruption* (or the explosion) are also needed: date and UTC time ISO 8601 format: DDMMYYYY and HHMMZ.

3. How tall is the eruption column? How far up does the contaminant go? The eruption *column height* can be expressed as *flight level* (ECFL), height above ground (ECH_{AGL}), or height above sea level (ECH_{AMSL}). Some active volcanoes have a high elevation of the cone above the sea level ($ELEV_{CONE}$), thus it is important to avoid confusion. The height may be estimated easily from photo images of the eruption, comparing the column with the volcano cone. Also, pilots who have visual contact with the eruption could assess the flight level, and could report it through the IAVW[1]. For uniformity, RCAS researchers recommend using metres to express height.

4. Download the *wind profile* in the site area from NOAA[2] site. A forecast over up to 180 hours is available. Input wind direction and velocity (WD/WV) in the ASH4D processor. Wind direction is expressed in degrees measured clockwise from True North of the direction where the wind comes from, and the velocity is expressed in knots.

5. Calculate and publish the extent of the *immediate danger area*, which has a trapezoidal shape (**Figure 21**). The most important parameter of this area is the distance from the source, where the volcanic ash cloud may be found VA_{max}, expressed in Nautical Miles. This may be calculated easily applying a linear formula described below, which considers the average falling speed of the volcanic ash particles of 0.7 m/s. ASH4D offers the facility to calculate and draw this immediate danger area. VA_{max} is not a simple number; it is a function of the flight level where exposure is estimated. Thus, at a low flight level, VA_{max} will be larger than at a high flight level. Depending on the way the eruption column height was expressed:

$$VA_{max}(FL) = \frac{ECH_{AMSL} - FL \cdot 30 \cdot 48}{2520} \cdot WV$$

$$VA_{max}(FL) = \frac{ECH_{AGL} + ELEV_{CONE} - FL \cdot 30 \cdot 48}{2520} \cdot WV$$

$$VA_{max}(FL) = \frac{(ECFL - FL) \cdot 30 \cdot 48}{2520} \cdot WV$$

By way of conclusion to this section, let us mention that a series of simulations were run in an attempt to answer the question 'is the ATM system able to cope with high levels of traffic under a higher risk of flights declaring emergency?'. Results showed that, in the context of a contaminated airspace, the ATCOs' workload would increase substantially even though no effective safety threats were to be detected. Yet, a clear improvement of the systemic response could be achieved by providing the ANSPs with reliable concentration forecasts. Indeed, in such case, ANSPs would be able to determine the areas where flights were likely to request evasive manoeuvres or declare emergency, brief their ATCOs that in turn could promptly inform the flights heading to the same zones about the situation (preventive action).

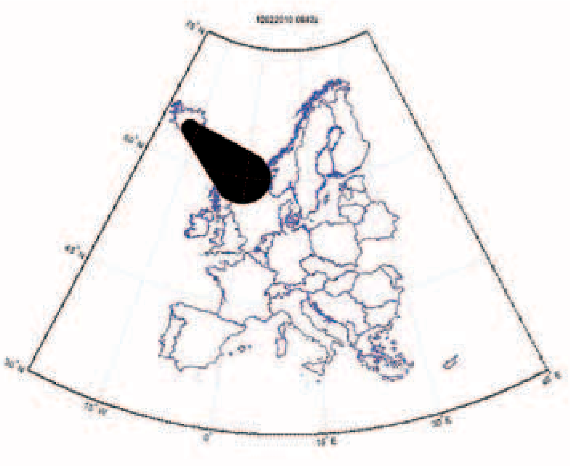


Figure 21 – Representation of the Immediate Danger Area associated to an Icelandic eruption using ASH4D. The danger zone can be exported in NOTAM/ASHTAM format.

1 IAVW = International Airways Volcanic Watch, ICAO

2 NOAA = US National Oceanic and Atmospheric Administration

What are the current trends in remote sensing and data analysis?

During the 2010 volcanic crisis, service providers and national authorities agreed on closing airspaces in an effort to eliminate operational risk. This resulted in an unprecedented disruption of the air traffic over Europe and severe economic losses for the civil aviation community's stakeholders.

Since these events, operators have been active in extending their share of responsibility and authority in the decision of whether or not to fly into a contaminated zone. However, according to ICAO's regulations, the operators' demand of being left alone in charge with this decision is still under discussion and scrutiny. A risk assessment approach is required with an oversight of the national regulators. The information in the full report Ash Safety could help airlines in developing a robust safety case.

As it has been mentioned previously, no certified on-board instrument capable of sensing or measuring the volcanic ash/dust contamination has been developed yet. A number of projects are nevertheless active in this field:

- Dr. Fred Prata of the Norwegian Institute for Air Research (NILU) has been collaborating with easyJet in order to develop an Airborne Volcanic Object Identifier and Detector (AVOID). Based on infrared technology, this system should provide pilots and airlines' flight control a real-time picture of ash/dust contamination with a scope of approximately 100 km forward at altitudes ranging from 5.000 ft to 50.000 ft.

- Airbus plans to install both a LIDAR system (Light Detection And Ranging) and a sampling device on board some of its aircraft. The former should provide measures of volcanic ash/dust concentrations with a look-ahead horizon of 7 km and the latter should help in understanding the long-term effects of exposure to volcanic ash/dust contamination.

- Boeing also has plans of installing sampling devices on board of its British Airways Boeing 747-400 aircraft.

Still, the operational value of these sensors remains limited if not questionable:

- By nature, sampling devices have a zero look-ahead horizon: the crew is warned only after the aircraft has already penetrated the contaminated zone. They therefore seem better suited to maintenance purposes (e.g. automatic triggering of maintenance actions when a certain quantity of ingested particles is reached) than to operational purposes.

- LIDAR and AVOID systems are both optical remote sensing devices. As such, visual meteorological conditions (VMC) may be required for them to operate. Indeed, should it be otherwise, volcanic ash/dust contamination might be masked by normal clouds (**Figure 22**).

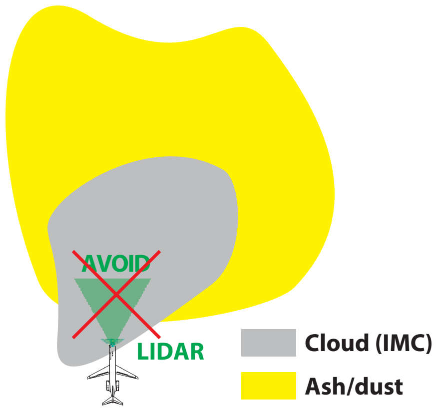


Figure 22 -
Circumstances under which AVOID and LIDAR technology could prove nonoperational

- In order to provide a consistent measure, the scope of an airborne sensing device should be comparable to the size of the targeted obstacle (see scale of phenomenon in **Figure 23**). Yet, VAC or VDC are at least one order of magnitude larger than normal cloud formations. Under this assumption, the look-ahead horizons of both LIDAR system (7 km) and AVOID system (100 km) are too limited, since the targeted phenomena are on a much larger scale (**Figure 23**). The low cost airline easyJet seems to be aware of this problem. To produce an accurate and global-scale image of the contamination area, the company plans to collect and aggregate the real time information sent by different aircraft from a ground station. According to the company's experts, the comprehensive coverage of the entire continent could be provided by fitting 100 European aircraft with AVOID equipment.

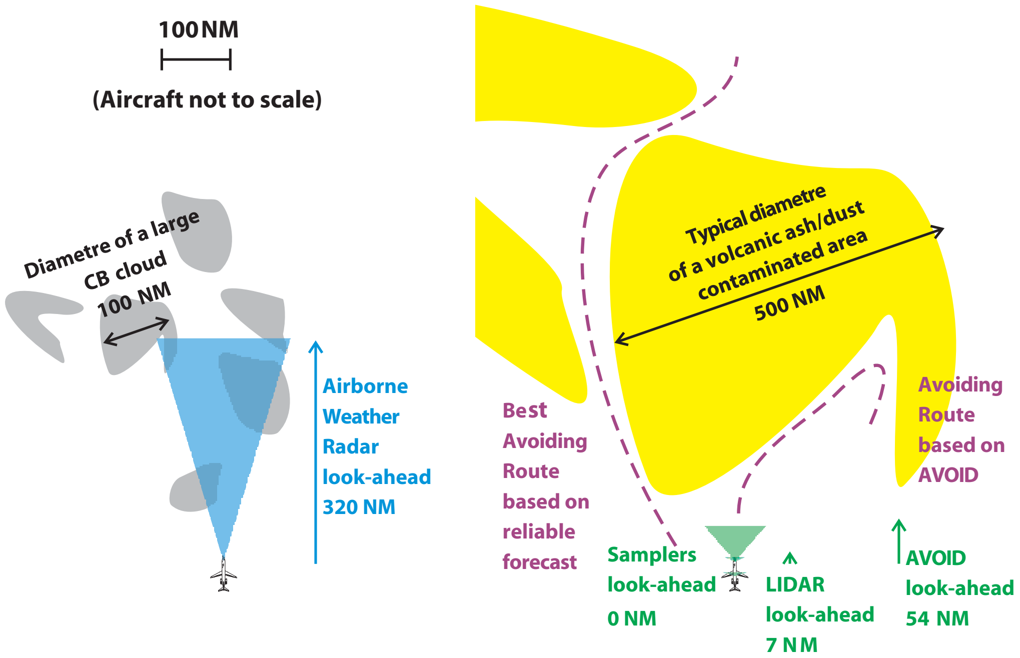


Figure 23 –
Importance of adapting the scope of remote sensing devices to the scale of targeted phenomena

A prototype device for AVOID has been built recently (see **Figure 24**). An in situ validation session should occur and may result in an EASA (European Aviation Safety Agency) certification.

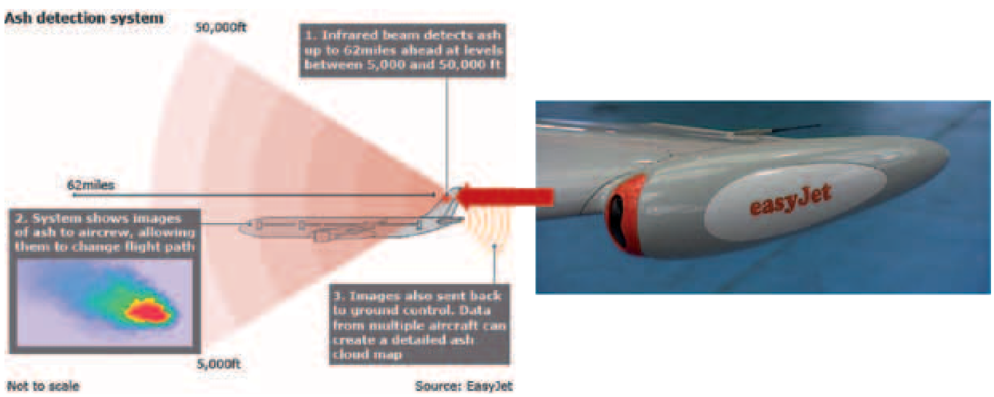


Figure 24 – AVOID system designed by easyJet

SUMMARY

One of the main outcomes of this White Paper concerns the distinction that should be made between volcanic ash (solid airborne particles ranging from 1/16 mm to 2 mm in size) and volcanic dust (solid airborne particles less than 1/16 mm across) both in terms of ATM and airline operations safety. Indeed, although these two categories of particulate matter are alike from a physicochemical point of view, when it comes to the factors that determine their impact on air traffic, they completely differ. Throughout a sound hazard and risk assessment process, this White Paper has shown that:

- In terms of safety, a distinction should be made between volcanic ash clouds as per ICAO's manual ('visible ash') and volcanic dust contamination. The former term refers to dense, definite and clearly identifiable dark clouds made of volcanic ash, dust and fumes. The second designates widespread concentration of volcanic dust and fume, floating in thin layers in the atmosphere. Whereas volcanic ash clouds are usually located 'within the vicinity' of their source volcanoes (e.g. a couple hundreds of NM depending on the height of the eruption column) and generally die out after one or two days, atmospheric contamination with volcanic dust is regarded as a globe-trotting phenomenon whose traces can remain for years.

- In case of hazard encounter, the overall safety risk is an increasing function of both the level and the duration of exposure. The level of exposure is reflected by the atmospheric concentration of volcanic particulate matter. Concentration is generally measured in kilograms of volcanic matter per cubic hectometre of air, a unit adapted to the scale of the contamination phenomena. It is globally recognised that concentrations lesser than 4 kg/hm^3 do not pose a direct threat to flight safety.

- In concentrations less or equal than 4 kg/hm^3, volcanic dust contamination is estimated as risky as sand aerosols contamination. The latter phenomenon is common in various places of the world (e.g. Saharan region) and constitutes a maintenance issue more than a safety issue.

	Volcanic Ash Cloud	Volcanic Dust Contamination	Sand Aerosol Contamination
Aviation Safety Risk	Serious incidents, no injury accidents	None on record	Very low (windshield cracks)
Impact on aviation	Local	Global due to misinterpretation	Maintenance issues

- The RCAS researchers' report confirms the ICAO Manual 9691 (*Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds*) principle to avoid flying into visible volcanic ash clouds. Flying into a volcanic ash cloud is considered unsafe and should be avoided at all costs. Indeed, travelling through a VAC could have severe repercussions such as engine flame-out, engine overheating, clogging of Pitot-static probes, abrasion of external/internal components etc (**Figure 25**). However, this conclusion should not be applied in areas of volcanic dust contamination.

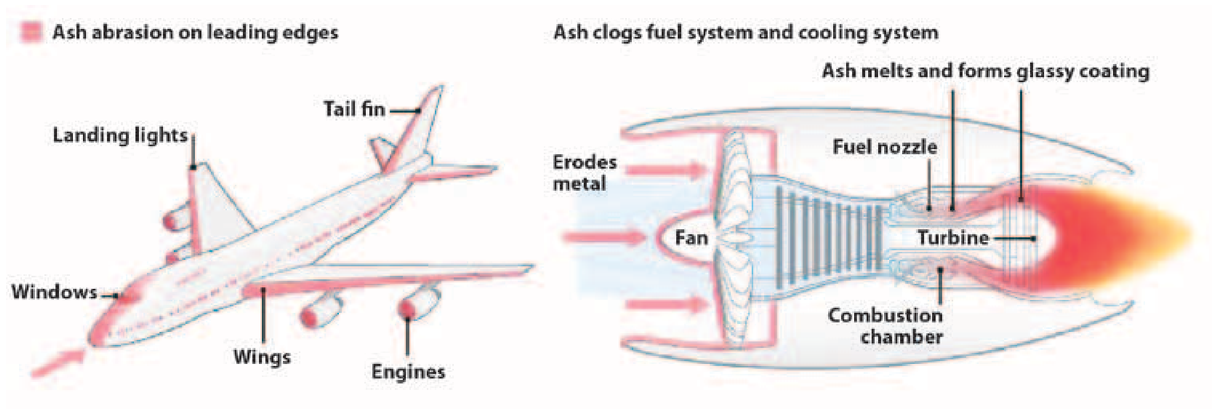


Figure 25 –
Illustration of the aviation safety threats posed by the exposure to volcanic ash/dust particles

- RCAS researchers studied passengers (short-term) and crew (long-term) exposure to volcanic dust concentrations of $4{\cdot}10^{-3}$ g/m^3. The main health and safety conclusions are :
  - It is "Reasonable to anticipate no risk for silicosis or lung cancer in passengers and crew members". Silicosis and lung cancer may only manifest under prolonged exposure (working life) to high concentrations of silica. Yet, RCAS researchers showed that, in some parts of the world (e.g. Riyadh, Cairo), the quantity of silica present in ambient air is higher than the levels of silica measured during the 2010 crisis. Indeed, only the finest volcanic particles (from 1 to 10 microns) represent a danger for the human respiratory system and yet, their atmospheric concentration following an eruption is generally lower than environmental silica levels in certain parts of the world (e.g. Riyadh or Cairo), where they do not pose any threat to the inhabitants' health.
  - Due to the hardness of the volcanic particles, the eye cornea may be affected by permanent scratches especially for persons wearing contact lenses. It is hence recommended for crew and passengers to wear spectacles (eye glasses).
- In case of an in flight encounter with a volcanic ash cloud, an evasive manoeuvre with immediate thrust reduction to idle is recommended.
- Given the fact that actual atmospheric concentration values are beyond the reach of current technology, mitigation strategies should be based on wide-area concentration forecasts. Reliable forecasted concentrations are deliverable using a modern tandem dispersion model with periodical relevant data assimilation of historic concentrations. Should these forecasts be available well in advance (T-180 hours), they could definitely help operators, dispatchers, regulatory authorities and the ANSPs in planning safe IFR flights. In this context, the decision of closing airspaces would not be systematic, which would allow a risk assessment approach between airlines and regulators. As a result, the economic impact of potential future volcanic crises could be significantly reduced.

GLOSSARY

Acronym	Meaning
ANSP	Air Navigation Service Provider. The operational organisation delivering service to airspace users.
ASH4D	Software developed by the scientific team of the Research Centre for Aeronautics and Space of the University Politehnica of Bucharest. ASH4D offers two applications: an 'Immediate Danger Area' calculation and a simulated visualisation of volcanic particles' dispersion process.
ATM	Air Traffic Management
ATCO	Air Traffic Control Officer
AVOID	Airborne Volcanic Object Identifier and Detector. Infrared-based technology developed by easyJet in collaboration with Dr. Prata of the Norwegian Institute for Air Research.
AWR	Airborne Weather Radar. Type of RADAR used for timely detection and analysis of large rain clouds (mainly cumulonimbus) and to avoid severe weather.
CFM	CFM combines the resources, engineering expertise and product support of two major aircraft engine manufacturers: Snecma (SAFRAN Group) of France, and GE of the United States of America. The company (CFM) and its product line (CFM56) got their names by a combination of the two parent companies' commercial engine designations: GE's CF6 and Snecma's M56.
EASA	European Aviation Safety Agency
ECHFL	Eruption Column height expressed as a Flight Level.
ECHAGL	Eruption Column Height expressed as an Altitude above Ground Level.
ECHAMSL	Eruption Column Height expressed as an Altitude above Mean Sea Level.
ESARR	EUROCONTROL Safety Regulatory Requirement
ESP+	European Safety Programme for Air Traffic Management 2010-2014
EUROCONTROL	European Organisation for the Safety of Air Navigation
EVAIR	EUROCONTROL Voluntary ATM Incident Reporting Function
FALL4D	Program developed by the scientific team of the Research Centre for Aeronautics and Space of the University Politehnica of Bucharest. FALL4D produces wide-area concentration forecasts based on an Eulerian dispersion model and periodical data assimilation.
IAVW	International Airways Volcanic Watch. This body, set up by the International Civil Aviation Organisation (ICAO), provides international arrangements for the monitoring of volcanic ash in the atmosphere and for providing warnings to the aviation community.
ICAO	International Civil Aviation Organisation, a special United Nations division tasked with fostering safe and efficient international civil air transport.
IDA	Immediate Danger Area. Area within which an encounter with a volcanic ash cloud is highly probable.
IFR	Instrument flight rules (IFR) are one of two sets of regulations governing all aspects of civil aviation aircraft operations; the other are visual flight rules (VFR). Instrument flight rules permit an aircraft to operate in instrument meteorological conditions (IMC), which have much lower weather minimums than VFR.

Acronym	Meaning
LIDAR	LIght Detection and Ranging. An optical remote sensing device, which can be used in order to measure atmospheric concentration of particulate matter along its line of sight.
MMAD	Mass Median Aerodynamic Diameter. Particles of volcanic origin are not uniformly spherical. The MMAD provides an 'equivalent' diameter based on aerodynamic considerations.
(HPT)NGV	(High-Pressure Turbine) Nozzle Guide Vanes. In a turbofan, these stationary blades ensure the correct guiding of the air flow from the combustion chamber to the high-pressure turbine section.
NILU	Norwegian Institute for Air Research
NM	Nautical Miles. A unit of length which is commonly used in the aviation industry. As per national agreement, one nautical mile equals to 1.852 kilometres.
NOAA	United States' National Oceanic and Atmospheric Administration.
PMX	Particulate Matter composed of particles that are all smaller than X microns in equivalent aerodynamic diameter.
RADAR	Radio Detection and Ranging. Object-detection technology based on electromagnetic waves (radio waves).
RCAS	Research Centre for Aeronautics and Space (of University Politehnica Bucharest – Faculty of Aerospace Engineering)
ROMATSA	Romanian Air Traffic Services Administration
SAVAA	Support to Aviation for Volcanic Ash Avoidance. Project developed by Dr. Prata of the Norwegian Institute for Air Research and addressing the issue of providing accurate and timely satellite-based information to Volcanic Ash Advisory Centres.
SNECMA	Snecma is a major French engine manufacturer for commercial and military aircraft as well as for space vehicles. Up until 2005, its name used to stand for "*Société Nationale d'Étude et de Construction de Moteurs d'Aviation*" (National Company for the Design and Construction of Aviation Engines). In 2005, the Snecma group, which included Snecma (called Snecma Moteurs at this time), merged with SAGEM to form SAFRAN. Snecma is now a subsidiary of the SAFRAN Group and previous Snecma group subsidiaries have been reorganised within the wider group.
TIT	Turbine Inlet Temperature. A critical temperature from many perspectives, notably the overall efficiency of a turbofan engine.
UPB	University Politehnica de Bucharest. University which hosts the Research Centre for Aeronautics and Space of Bucharest, which itself significantly contributed to the Volcanic Ash Safety project.
USGS	The United States Geological Survey (USGS) is a scientific agency of the United States government. The scientists of the USGS study the landscape of the United States, its natural resources, and the natural hazards that threaten it. The Organisation has four major science disciplines, concerning biology, geography, geology, and hydrology. The USGS is a fact-finding research Organisation with no regulatory responsibility.
UTC	Coordinated Universal Time. Time standard by which the world regulates clocks and times. It is closely related to Universal Time and Greenwich Mean Time (GMT).

Acronym	Meaning
VAAC	Volcanic Ash Advisory Centre. A VAAC is responsible for coordinating and disseminating information on atmospheric volcanic ash clouds that may endanger aviation. VAACs are part of the IAVW.
VAC	Volcanic Ash Clouds. Refers to a dense, definite and clearly visible dark cloud made of volcanic ash, volcanic dust and fumes.
VDC	Volcanic Dust Contamination. Refers to a widespread concentration of volcanic dust and fumes, forming thin layers in the atmosphere. VDC is only visible from certain angles or using infrared absorption technology. It is similar to sand aerosols.
VMC	Visual Meteorological Conditions. An aviation flight category in which Visual Flight Rules flight is permitted. Requires sufficient visibility for the pilots to fly the aircraft and maintain visual separation from terrain or other aircraft.
VPE	Volcanic Pyroclastic Eruption. Represents a local threat to aircraft and facilities in vicinity of the eruption site or to aircraft overflying the volcano's vent during the eruption.
WHO	The World Health Organisation (WHO) is a specialized agency of the United Nations that acts as a coordinating authority on international public health.

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