Jet Engines and Volcanic Ash: Rolls-Royce Position and Guidance

ICAO Meteorology Panel QVA Workshop
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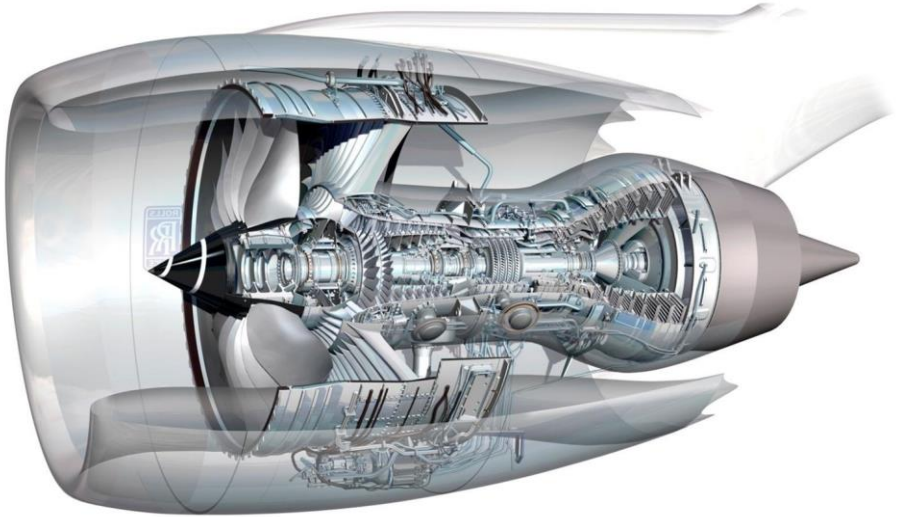
Introduction



A cutaway of a Rolls-Royce Trent 1000 for the Boeing 787

What I'm going to cover:

- What volcanic ash and mineral dust do to engines
- A bit of geology – comparing volcanic ash and mineral dust
- The world of aviation policy and regulation
- Finally, some pragmatic engineering to help aviators

Engine Critical Damage from Volcanic Ash

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- Volcanic Ash Critical Damage Mechanism:

- Both mechanisms lead to reduction in high pressure (HP) compressor surge margin – i.e. operability margins
- HP compressor surge margin is the critical sub-system for safety implications
- There are other longer term economic damage mechanisms (e.g. ceramic coating damage, sulphidation, cooling system blockage, …)
- But desert dust can do all of this too

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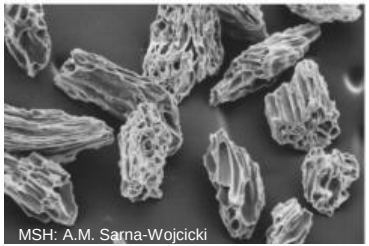
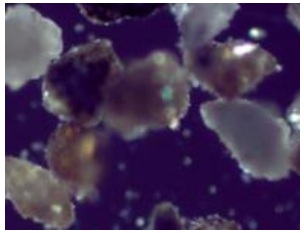
Mineral Dust and Volcanic Ash: Similar Phenomena?

- Volcanic Ash
  - Essentially alumino-silicates (plus sulphate traces)
  - 20%-100% sharp **glassy** fragments

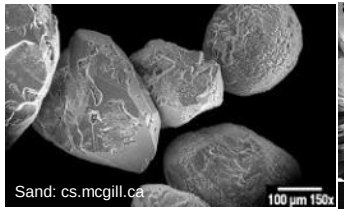


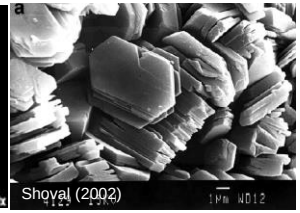


  - **Very abrasive**
- Softening temperatures, across the range of ash compositions:

<900ºC – 1300ºC

- Mineral Dust
  - Lots of alumino-silicates (plus quite a few carbonates and sulphates)
  - Weathered **crystalline** material





  - **Relatively smooth**
- Melting temperatures, for typical **test** sands & dusts:

1350ºC – >1600ºC

Melting Points for Some Dusts

QGCS from PTI (US)	1220 C
Afghanistan sand	1140 C
Afghanistan sand	1125 C
A2 Fine from PTI (US)	1115 C
Aramco (A2 + 10 % salt)	1085 C

- Melting temperatures of some **real** world sands & dusts:

1085ºC – 1220ºC

Mineral Dust and Volcanic Ash: Similar Phenomena?

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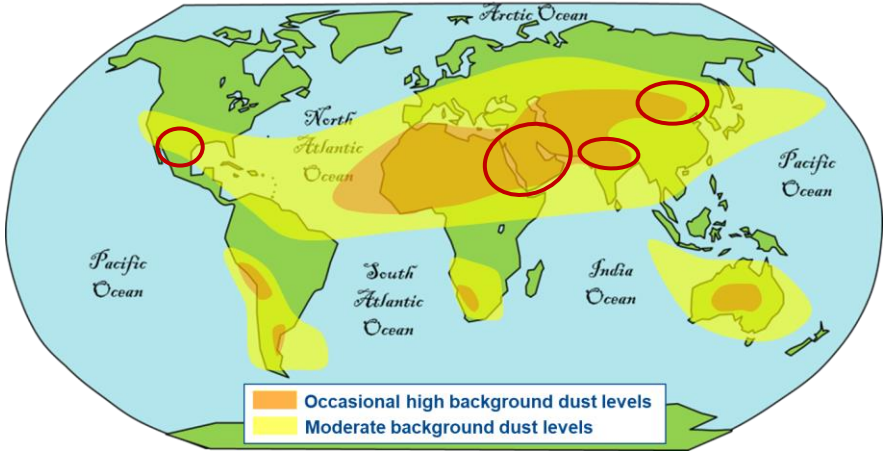
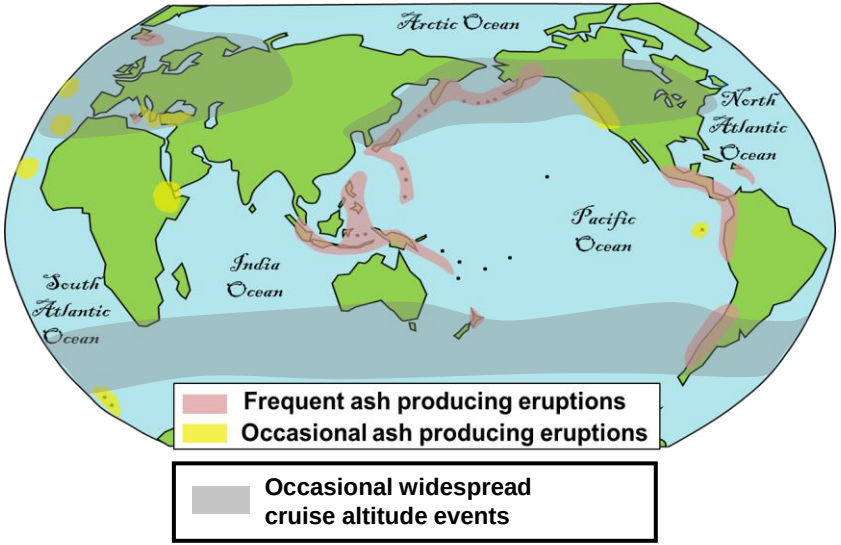
- The science world has known for decades (if not centuries) where dust occurs in the atmosphere

- Volcanologists have been studying volcanoes even longer

The dust belt, which is evolving due to climate change



Volcanoes of the World



Mineral Dust and Volcanic Ash: Similar Phenomena?

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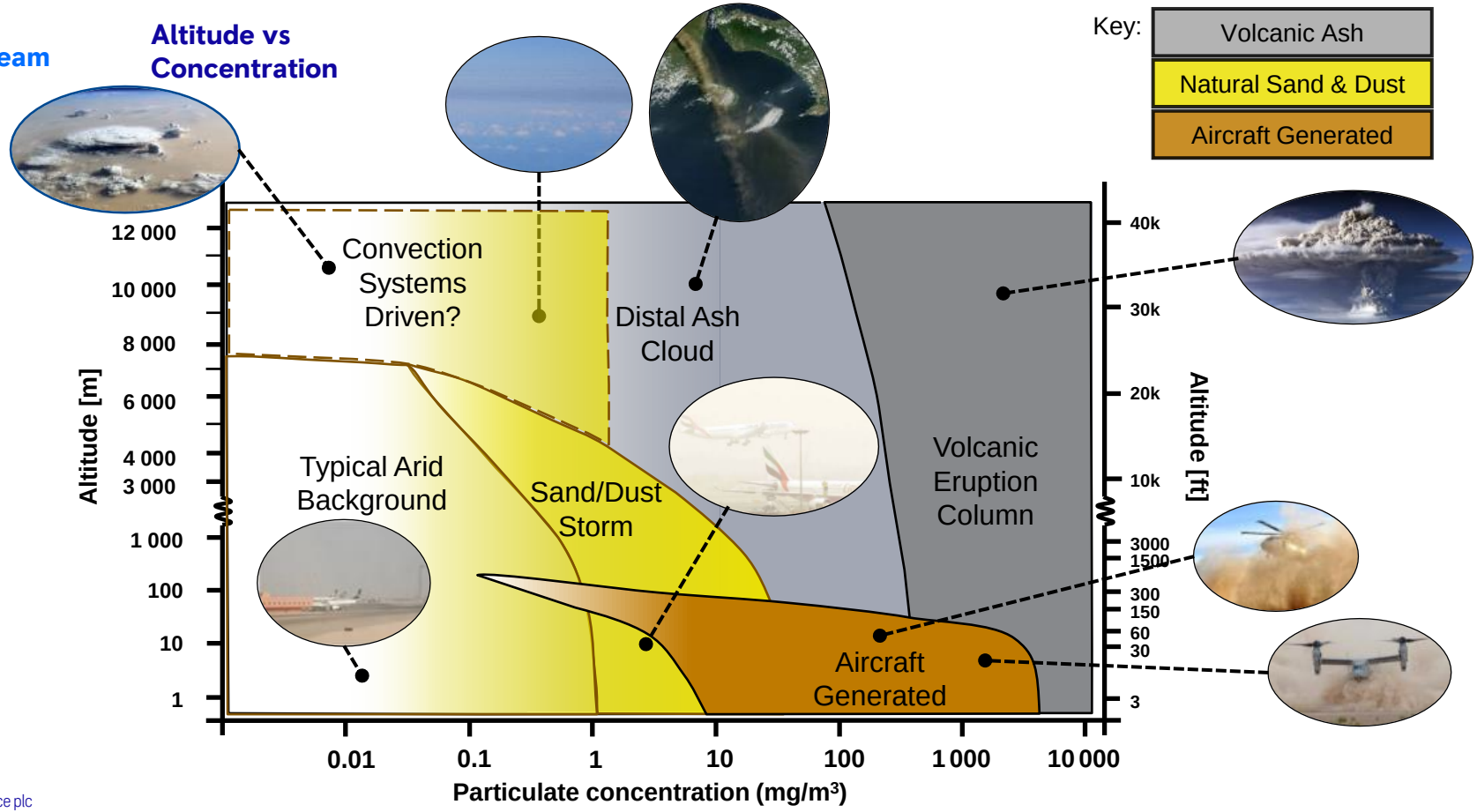

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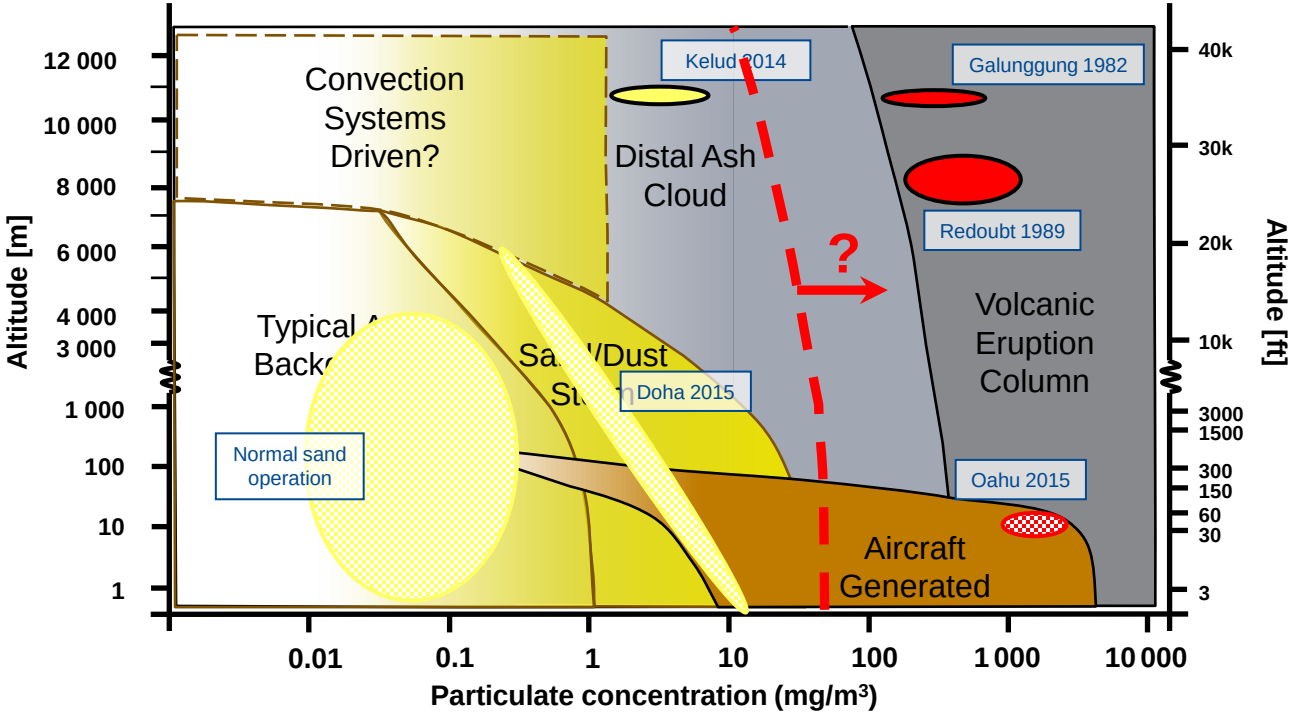
Mineral Dust and Volcanic Ash: Similar Phenomena?

Altitude vs Concentration

- Exposure events:
- Boundary between Economic impact and Safety?

Volcanic Ash
Sand/Dust
Economic impact
Safety impact

Key:
Volcanic Ash
Natural Sand & Dust
Aircraft Generated



Aviation & Volcanic Ash: Key Developments Since 2010

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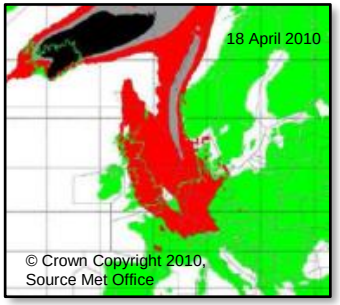
- ICAO and the **2012** IVATF:
  - OEMs wanted to move away from 2010 ash concentrations to avoiding **visible** or **discernible ash**
  - But the principle was agreed that operators – i.e. the airlines – decide where and when they operate in volcanic ash contaminated airspace, provided they do it within their Safety Management System – which is cleared by their national aviation authority

Eyjafjallajökull, April/May 2010

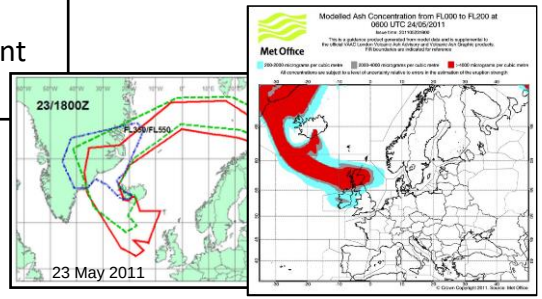


- EASA Regulations:
  - **2013:** EASA introduce CS-25 1593 – applies at airframe level
  - **2015:** EASA introduce CS-E 1050 – applies at engine level

CS-E 1050 Exposure to volcanic cloud hazards (See AMC E 1050)

(a) The susceptibility of turbine Engine features to the effects of volcanic cloud hazards must be established.

(b) Information necessary for safe operation must be provided in the relevant documentation.



- ICAO and Quantitative Volcanic Ash data (QVA):
  - **2018** decision made to move to VAACs producing quantitative volcanic ash data, and away from 'some ash/no ash' VAA/VAGs

Engine Certification: HPC Surge Margin Loss (SML) Model

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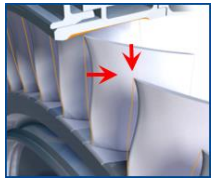
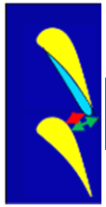
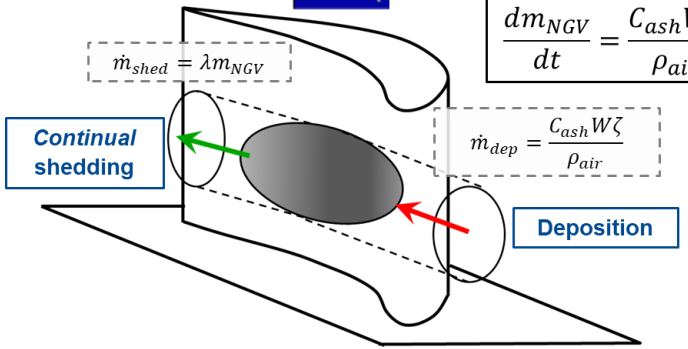


Deteriorated tip clearance & efficiency

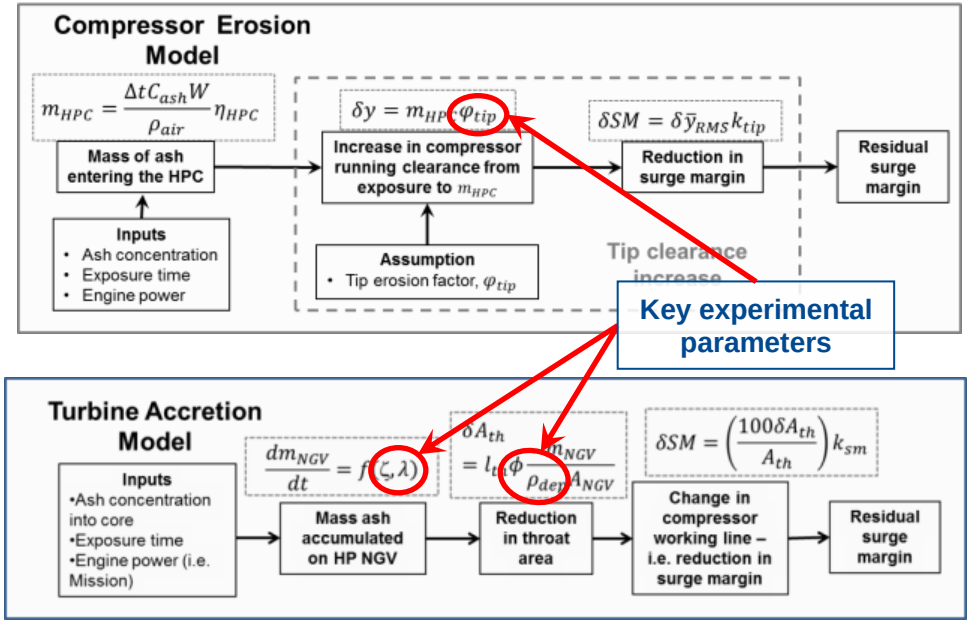


Restricted flow through turbine throat

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



- What Rolls-Royce did – compressor stability calculations using a simple mathematical model to determine time to surge



- The maths model can quantify the effect of the **worst possible ash type** and the **worst engine operating point** – i.e. identify the critical flight condition, and quantify the impact

Verifying the HPC SML Model is Accurate: Holistic Approach

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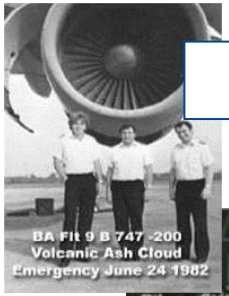
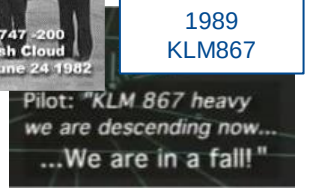
- In-service events and controlled tests are a good source of model validation data



1982
BA009



1989
KLM867

2015 VIPR-III
(NASA, USAF, …

- Define four engine impact categories:

- **Flight safety implications – could result in loss of controllable thrust**

e.g. Deposit sticks in turbine annulus, choking engine

- **Exigent damage – immediate maintenance action required**

e.g. Severe rotor erosion

- **Long term damage – manageable loss of performance or slightly premature removal for overhaul**

e.g. Ni alloy suphidation

- **Negligible damage**

- Key drivers to the level of impact?

Primary Drivers:
Increased duration of exposure [hrs]
and/or
Increased particulate concentration [mg/m^3]

For a given:
Ash particle composition and nature, and engine design, operating point and condition

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Verifying the HPC SML Model is Accurate: Holistic Approach

- There are only 10 volcanic ash encounters – available to Rolls-Royce (but they include non-R-R engine types) – which are suitable for quantitative analysis
- In addition there are:
  - 6 suitable Calspan (US) engine tests
  - 1 volcanic ash engine test (NASA/USAF VIPR-III) – although there are 5 points in all
  - 4 desert sand/dust data points

				Concentartion [mg/m^3]		Duration [min]					
ID No.	Date	Volcano	Impact	Min	Max	Min	Max	Flight Condition	Material	Engine Condition	Date of Engine Development
1	1982 (Jun)	Galunggung	Safety implication	100	2000	2	4	Cruise	Basaltic-Andesite	Mid-life	circa 1978
2	1985	Soputan	Exigent damage[1]	20	400	4	14	Cruise	Basaltic	Mid-life	circa 1978
3	1989 (Dec)	Redoubt	Safety implication	200	2000	1	2	Climb	Dacite	New/Recon	mid 1980s
4	2000	Hekla	Long term economic[2]	0.2	4	7	7	Cruise	Basaltic-Andersite	New/Recon	early 1980s
5a	2010	Eyjafjallajokull	Neg'ble damage	3	5	7	9	Descent	Trachy-Andersite	Unknown	early 2000s
5b	2010	Eyjafjallajokull	Neg'ble damage	0.15	0.35	440	450	Multiple	Trachy-Andersite	Unknown	early 2000s
6a	2010	Eyjafjallajokull	Neg'ble damage	0.2	0.2	10	10	Cruise	Trachy-Andersite	Unknown	1960s

Database of engine volcanic ash/sand & dust exposures events – currently 25 in total

Verifying the HPC SML Model is Accurate: Holistic Approach

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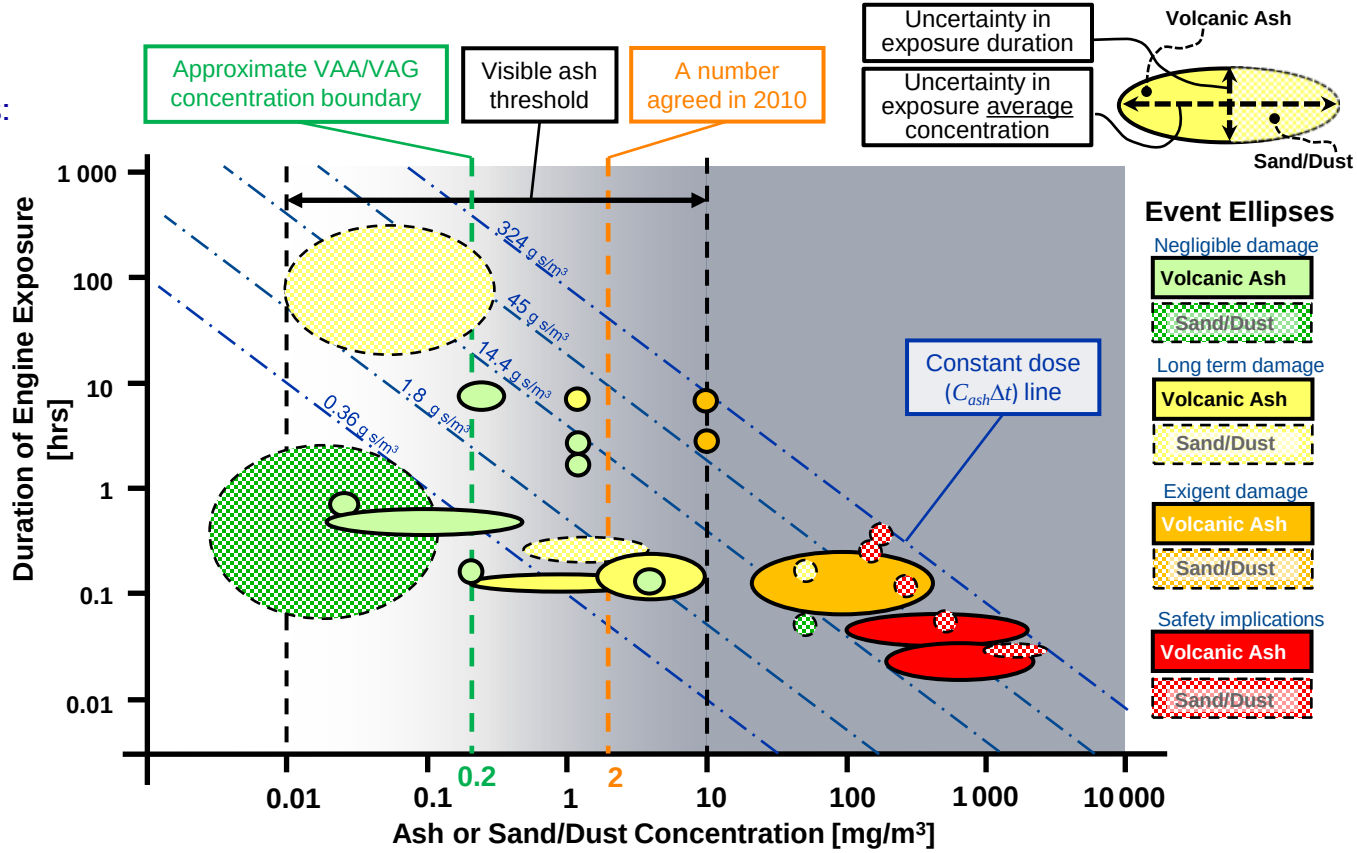
- Plotting the exposure events: the **D**uration of **E**xposure **v**ersus **A**tmospheric **C**oncentration (or **DEvAC**) Chart



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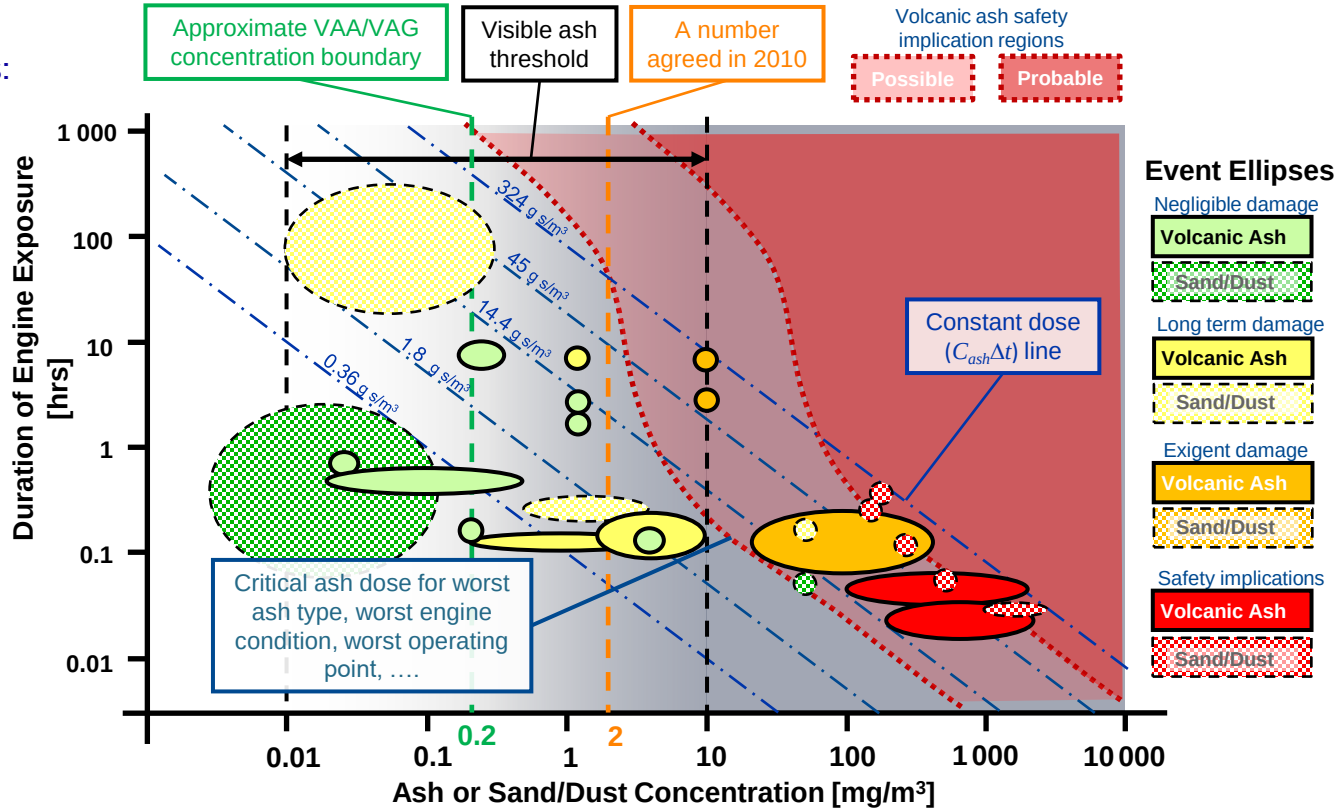
- Safety implication regions – using the SML Model



Verifying the HPC SML Model is Accurate: Holistic Approach

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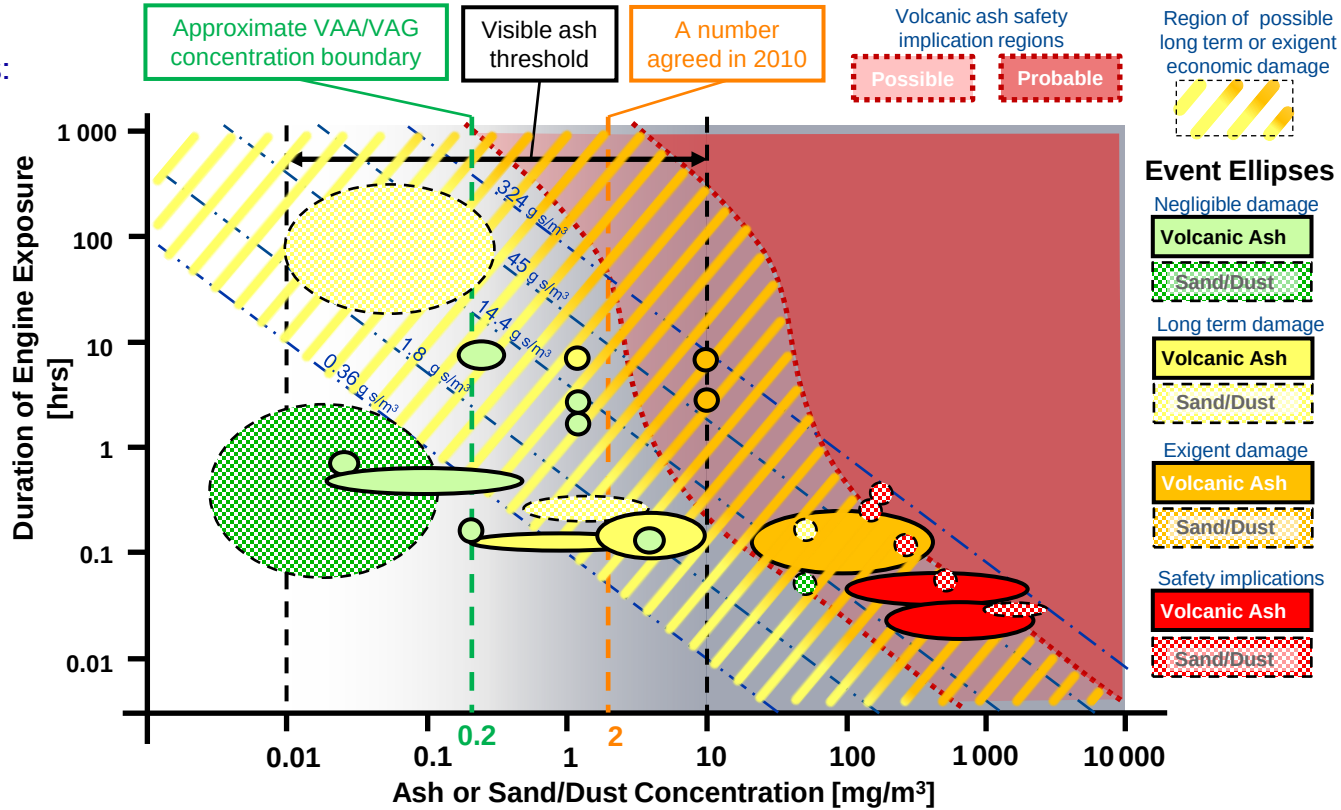
- Plotting the exposure events: the **D**uration of **E**xposure **v**ersus **A**tmospheric **C**oncentration (or **DEvAC**) Chart
- Safety implication regions – using the SML Model
- It's not just about safety – economic damage is a consideration



Verifying the HPC SML Model is Accurate: Holistic Approach

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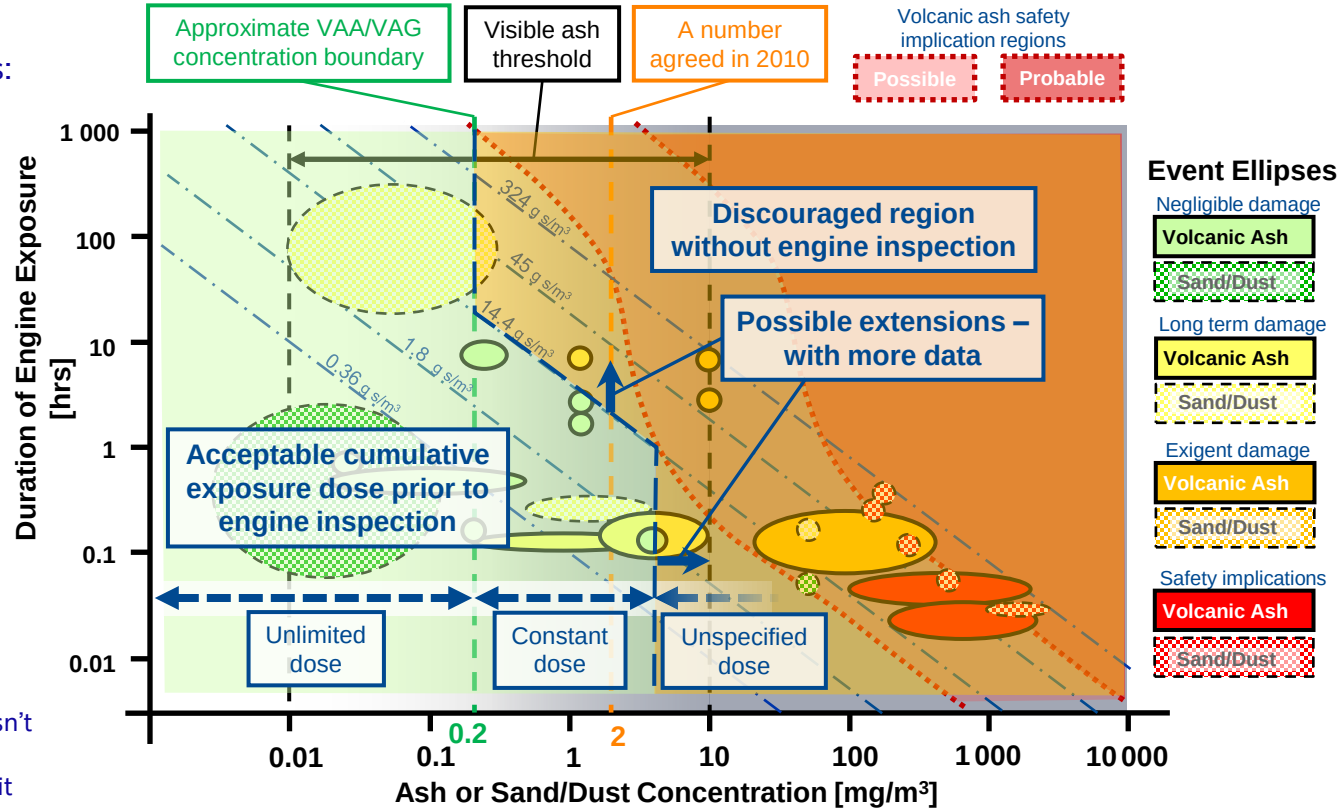
- Plotting the exposure events: the **D**uration of **E**xposure **v**ersus **A**tmospheric **C**oncentration (or **DEvAC**) Chart
- Safety implication regions – using the SML Model
- But for certification it's about safety rather than economic damage
- Declaring engine susceptibility to ash – constant dose approach between 4 mg/m^3 and 0.2 mg/m^3

NB The Rolls-Royce declarations isn't a solid boundary – engines will not immediately fail should they cross it



Declaring Volcanic Ash Susceptibility

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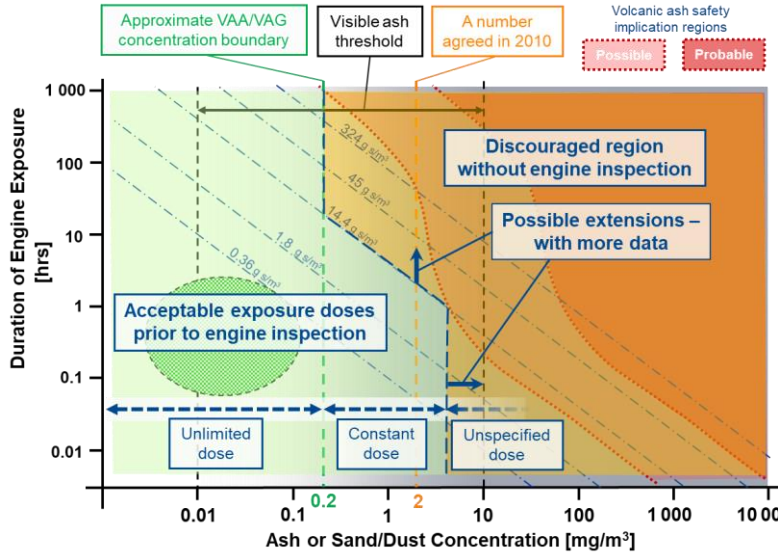
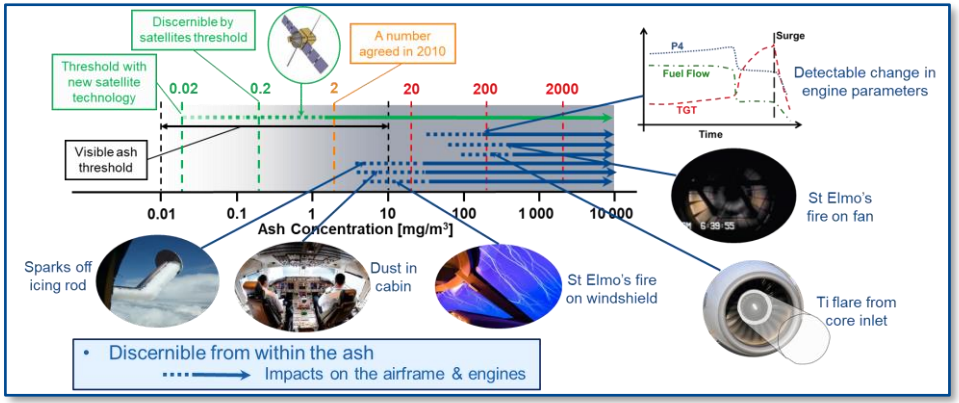
- Current Rolls-Royce guidance for civil and military engines (agreed in May 2016, issued in May 2017):

> Engines exposed to a cumulative volcanic ash dose of 14.4 g s/m^3, between 0.2 to 4 mg/m^3 (e.g. operating for 1 hour in an actual ash concentration of 4 mg/m^3), or lower, should not lead to a significant reduction in engine related flight safety margins.

- If an exposure of 14.4 g s/m^3 is suspected to have been accumulated (i.e. over multiple flights):
  - Engine inspection required
  - Followed by a decision to either:
    1) Set 'clock' back to 14.4 g s/m^3 or a smaller number
    2) Commence a cleaning and monitoring regime
    3) Remove engine for repair

- Supporting operational guidance in Engine Operating Instructions and supplementary information, e.g.:





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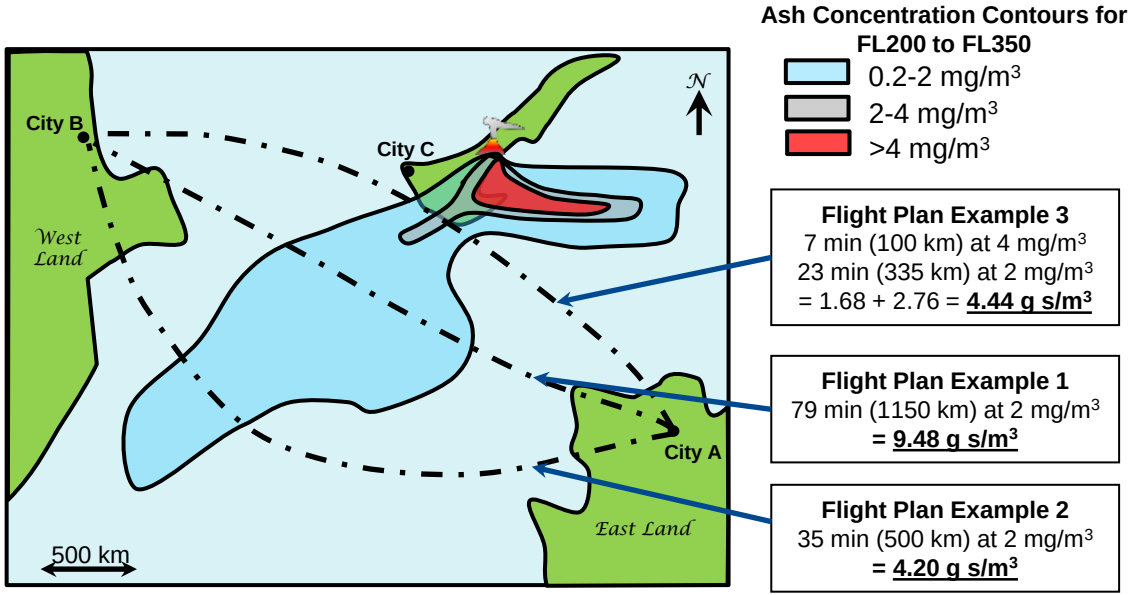
How to Use a Dose Based Approach

- A hypothetical (non-Eurocentric) ash cloud scenario
- Potential flight plans from City A to City B – staying within the 14.4 g s/m³ limit:
- Conservative assumptions: 0.2-2 mg/m³ → treated as = 2 mg/m³
  2-4 mg/m³ → treated as = 4 mg/m³



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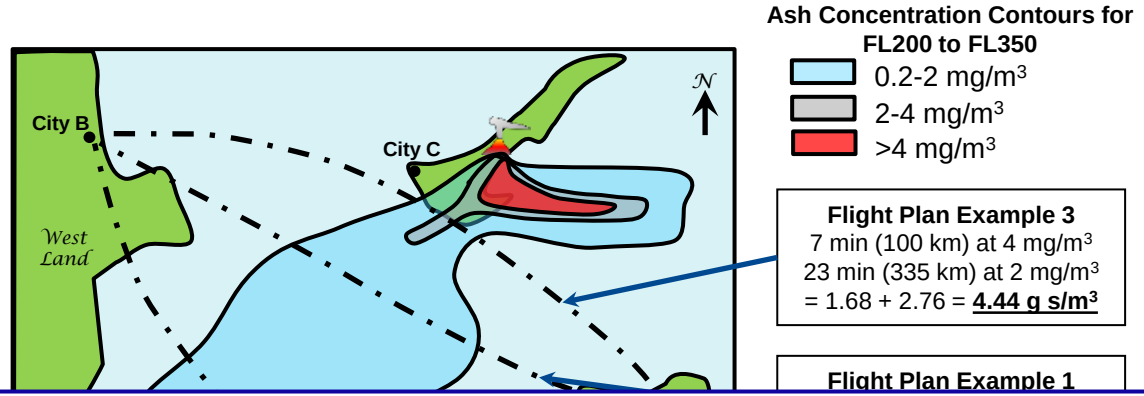

- Planned and actual cumulative ash dose managed by airlines' Flight Operations teams
  - Through appropriate flight planning and fleet management
  - Approach is still needed even if on-board dose meter fitted to aircraft
- Flight crews should keep an eye on surroundings, engine data (or dose meter) and make tactical manoeuvres if needed

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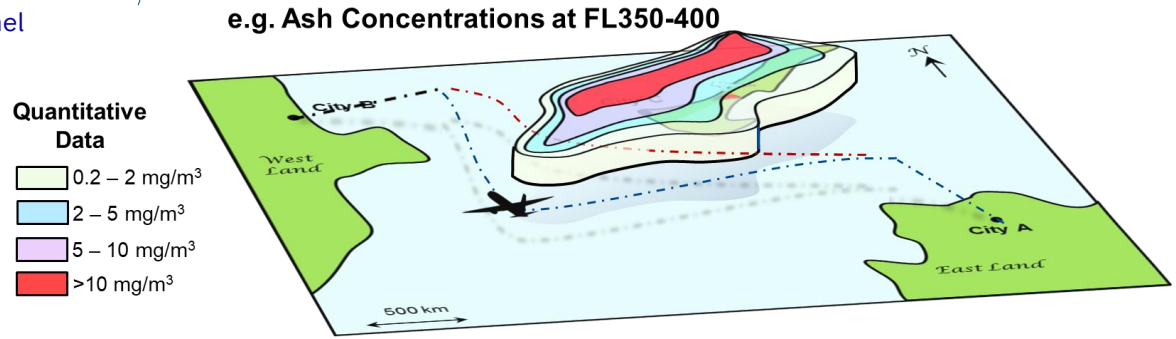
The ICAO IAVW* and Quantitative Volcanic Ash (QVA)

* The International Airways Volcano Watch – part of the ICAO Met Panel

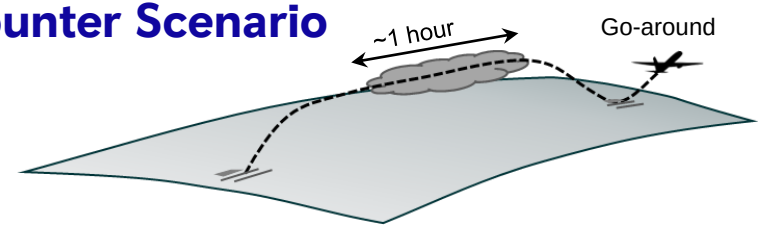
ICAO & the nine VAACs



- ICAO and the nine VAACs are moving to quantitative data (with VAA/VAG initially retained)
  - Vertical resolution: 5 000 ft intervals from surface to FL600
  - Forecast time resolutions: T+0hr, T+3hr, T+6hr, T+9hr, T+12hr, T+15hr, T+18hr, T+21hr, T+24hr
  - Forecast update frequency: At least 6 hourly
- Ensemble relative frequency or probability data also being produced

Data shall be provided with the following thresholds	Designated Description
<0.2 mg/m³	Very Low, i.e. not discernible
0.2 – 2 mg/m³	Low
2 – 5 mg/m³	Medium
5 – 10 mg/m³	High
>10 mg/m³	Very high

The Most Vulnerable Volcanic Ash Encounter Scenario



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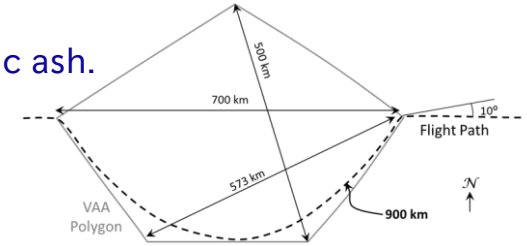
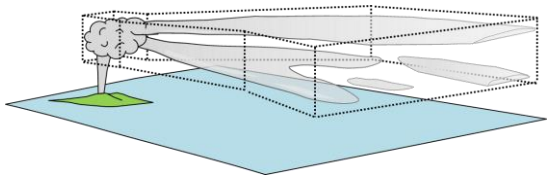
1. The aircraft and its engines are exposed to volcanic ash at the top of climb or cruise
    - i.e. the ash cloud exists at altitudes above 30 kft
2. The ash cloud above 30 kft consists of a high glass content (>80%) basaltic ash.
3. The aircraft is in the ash for ~1 hour, i.e. the horizontal extent of the ash cloud needs to be at least ~800 km across
    - Cruise speeds are approximately 900 km/hr,
4. Whilst in the ash cloud for 1 hour, the aircraft is continually exposure to an ash concentration in the range 3.5 to 4 mg/m^3
5. On completion of the ~1 hour exposure, descent commences within the next 15 minutes
6. On final approach to landing the aircraft needs to do a go-around manoeuvre
7. And both engines – or more than one engine on a quad – are in an end-of-life condition
    - The engines are sufficiently close to needing a major overhaul, they have each lost around 8% of their original 'as new' HPC surge margin through normal in-service deterioration
    - Similar argument applies if descending an approaching with one engine shutdown





The Most Vulnerable Volcanic Ash Encounter Scenario

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Component Scenario Likelihoods

Circum-stance No.	Description	Credibly Pessimistic Likelihood	Probably More Realistic Likelihood
1	An ash cloud above 30 kft is being entered and available exposure dose is close to 14.4 g s/m^3	1.000	0.800
2a	Proportion of ash clouds >30 kft that are basaltic…	0.250	0.250
2b	…of which ash is >80% glass	0.500	0.100
3	…of which ash cloud is large enough to accommodate 900 km at cruise	0.100	0.040
4	Whilst in ash, the concentration is 3.5-4 mg/m^3 for most of the hour	<0.012 (or < 1 in 84)	~0.001
5	Following 1 hr at cruise in ash cloud, descent begins within 15 mins	0.043	0.043
7a	An engine is within 400 flights of a 2000 cycle interval major overhaul (i.e. shop visit)	0.200	0.200
7b	If one engine is within 400 flights of overhaul, a second is too.	0.200	0.200
6	Go around on approach	0.004	0.004
	Combined Cumulative Likelihood	<1.03E-09	~1.0E-12

The Most Vulnerable Volcanic Ash Encounter Scenario

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Conclusions

- The ~1.0E-09 number below represents the critical scenario likelihood at 1 in 10^9 instances an aircraft considers entering an ash cloud under controlled conditions, following an accepted SRA, which is in line with the R-R susceptibility statement

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7a	An engine is within 400 flights of a 2000 cycle interval major overhaul (i.e. shop visit)	0.200	0.200
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6	Go around on approach	0.004	0.004
	Combined Cumulative Likelihood	<1.03E-09	~1.0E-12

- If converted to instances per flight hour, this number would be reduced by several orders of magnitude, i.e. a rate of 1 in $>10^{12}$

- Although this study was for a very specific scenario, it illustrates an approach which could be adapted to utilise QVA and cover less dramatic operations, e.g.:
  - What is the likelihood of being in ash for more than 1 hour?
  - What is the likelihood of exceeding ash concentrations of 4 mg/m^3 when aiming to stay <2 mg/m^3 for 2 hours?
  - …

Thank you