Volcanic Ash Impacts on Jet Engines and Developments Since 2010

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Introduction

- Volcanic Ash (VA) and Aviation
  - The historical context and 2010
  - What happened from 2011-2017
- A New Approach – Based on Engine Ash Dose
- Demonstrating the Approach
  - Implications for Operations and Meteorological Service Providers
- Other Original Equipment Manufacturers' Positions

A Short History – Volcanic Ash & Aviation

- Ash hazard was known about from 1950s – mainly through military experience

- ICAO sets up VAACs & principle of **‘AVOID AVOID AVOID’** established

1970

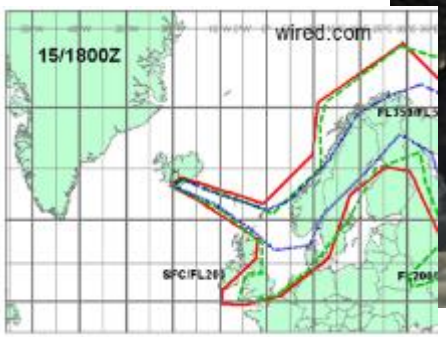
1980

1990

2000

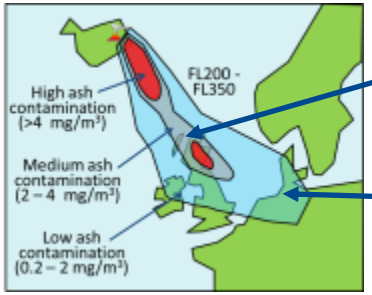
2010

- Mt St Helens 1980 & a L100 (C-130) – T56 engines
- Galunggung 1982 & BA009 – B747 with RB211-524s
- Mt Redoubt 1989 & KLM867 – B747 with CF-6s
- Eyjafjallajokull 2010 – 15th April much of Europe’s airspace shuts down



A Short History – The 2010 Crisis

- 15th to 20th April – UK CAA attempts to get flights going by discussing possible safe concentration level
- 10th May – European regulators agree a formal procedure for operating in VA based around 2 & 4 mg/m^3
- July – ICAO run 1st IVATF



Restricted operation

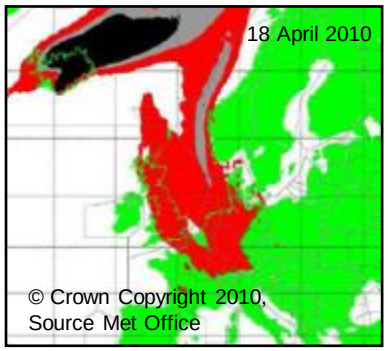
Unrestricted operation

April

May

June

July



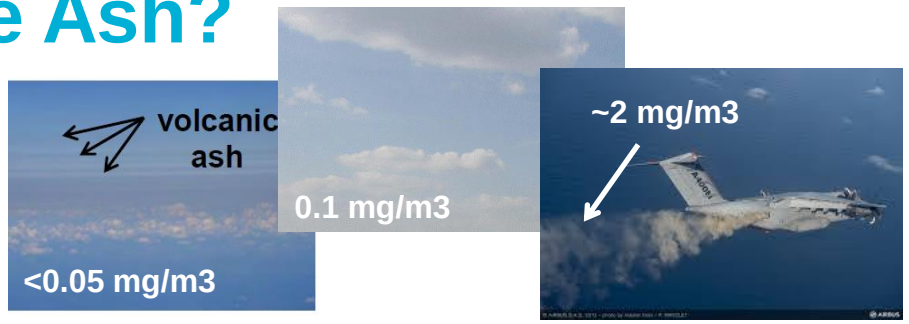
- 21st April – OEMs 'agree' **flight up to 2 mg/m^3 is acceptable**
- Mid-May – OEMs move away from using concentrations and start talking about **avoiding 'visible' ash**
- 19th May – Rolls-Royce produce statement that you can fly in any forecast concentration – **just avoid 'visible' ash**
  - By the way, Rolls-Royce defined 'visible' as effectively actual 2 mg/m^3

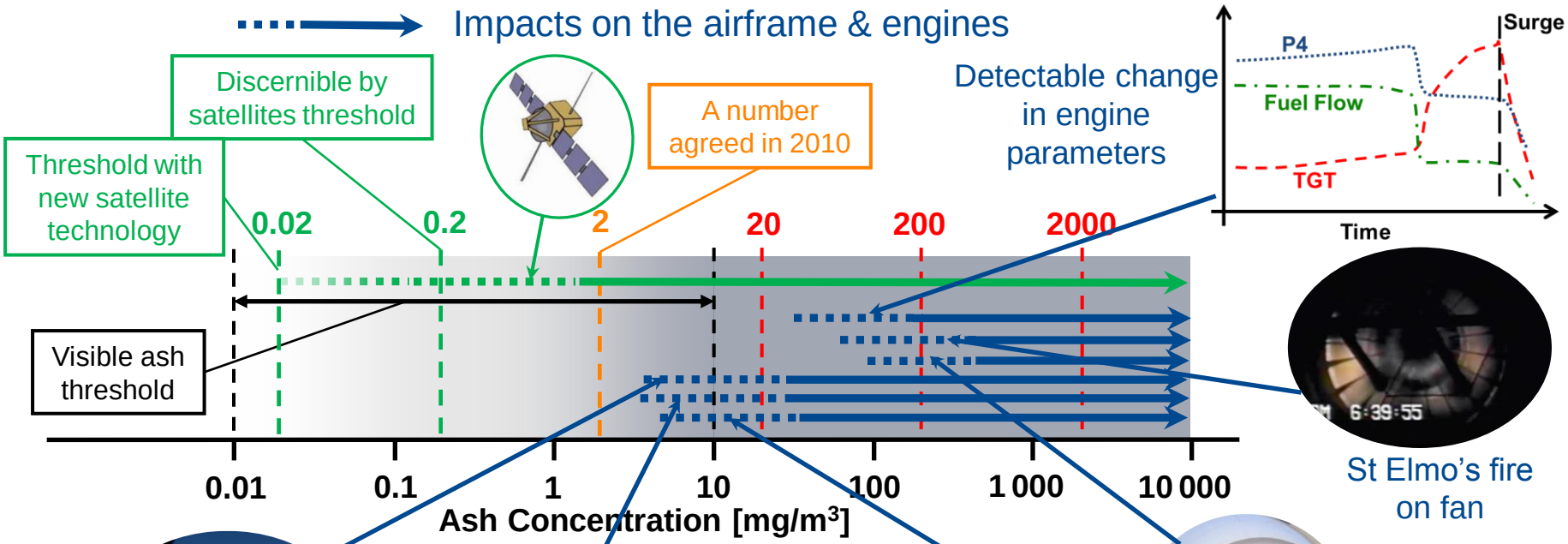
A Short History – 2011-2017

- IVATF concludes
  - Manufacturers get **‘avoid visible or discernible ash’** accepted

Visible and Discernible Ash?

- Visible ash
- Discernible remotely
  - Satellite instruments
- Discernible from within the ash
  - Impacts on the airframe & engines





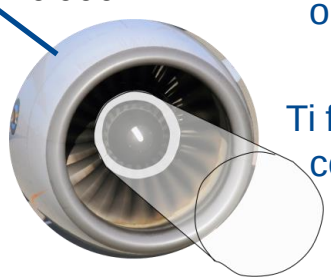
Detectable change in engine parameters

St Elmo's fire on fan

Sparks off icing rod

Dust in cabin

St Elmo's fire on windshield



Ti flare from core inlet

A Short History – 2011-2017

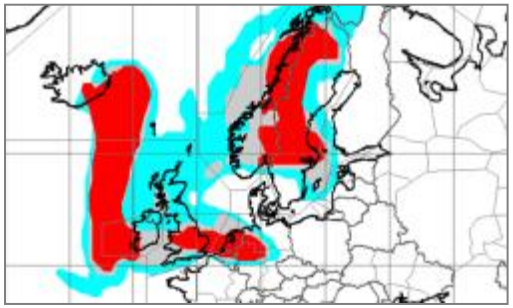
- IVATF concludes
  - Manufacturers get **'avoid visible or discernible ash'** accepted
  - Effectively renders concentration charts unusable – **>0.02 mg/m³ is effectively discernible ash**
- EASA introduce CS-25 1593
- EASA introduce CS-E 1050

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.

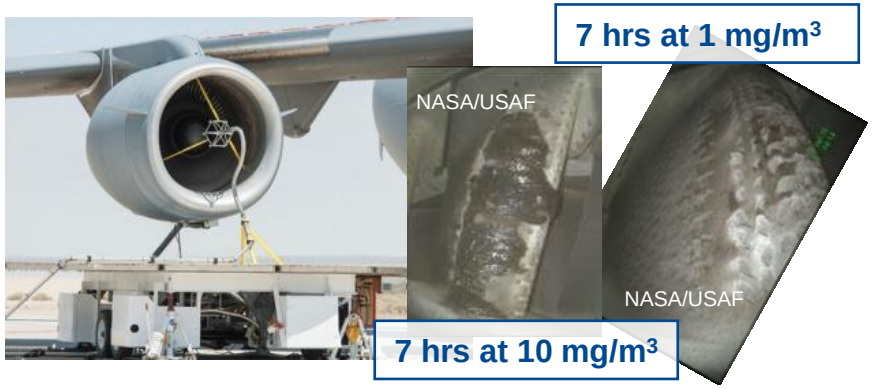
(b) Information necessary for safe operation must be provided in the relevant documentation.

2011 2012 2013 2014 2015 2016 2017



UK Met Office & Meteo France supplementary concentration charts

- Eruptions continue to affect non-European airspace, e.g. PCC, Nabro, Kelud, etc.
- Plus further OEM/Regulator/Gov politics
- Bardarbunga nearly produces ash – stimulates a full review of ash position in Europe
- VIPR-III engine volcanic ash (VA) test



A Short History – EASA Certification

- Demonstrating compliance:

AMC E 1050 Exposure to volcanic cloud hazards

Acceptable means of establishing the susceptibility of Engine features to the effects of volcanic clouds should include a combination of experience, studies, analysis, and/or testing of parts, sub-assemblies or Engines.

Information necessary for safe operation should be contained in the relevant documentation. This information may be used to assist operators in producing operational data and instructions for their flight crews when operating in, or avoiding, airspace contaminated with volcanic clouds. The information should be readily usable by operators in preparing a safety risk assessment as part of their overall management system.

…..

(3) The related pre-flight, in-flight and post-flight precautions to be observed by the operator including any necessary amendments to Engine Manuals, Dispatch Deviation, or equivalents, required to support the operator.

(4) The recommended continued airworthiness inspections associated with operations in volcanic cloud contaminated airspace; these may take the form of Instructions for Continued Airworthiness or other advice.

How to get this information to operators? FCOMs? AFM? …?

This information will be in AMMs

A Short History – EASA Certification

- Declaring a susceptibility – the apparent options in early 2016:

a) The aircraft and its engines are susceptible to visible or discernible volcanic ash.

Essentially avoid volcanic ash

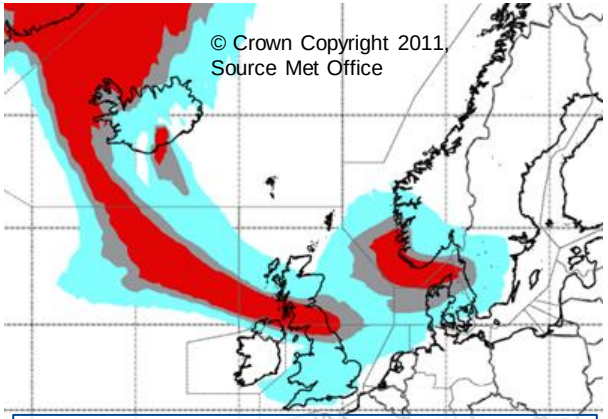
Or

b) Brief exposure to significant ash concentrations, or prolonged exposure to lower levels of ash, may have safety implications. Precisely where the safety threshold lies will vary with engine type, life and operating conditions, as well as the properties of the volcanic cloud that is encountered.

Give it a go if you want, but we aren't offering much help

- May 2016 - Recognition within Rolls-Royce that defining susceptibility around visible or discernible ash is problematic
  - Operationally very restrictive
  - Operators had a perception that up to 2 mg/m^3 was OK - it was in their SRAs

- Request made by Rolls-Royce customers and UK authorities to allow operations – i.e. declare a susceptibility – based around ash concentrations



Grimsvotn – 1800 UTC 24/5/2011

A Short History – 2011-2017

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2011

2012

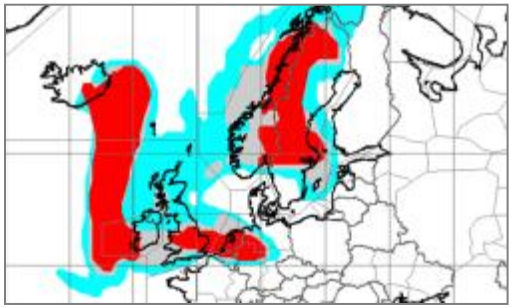
2013

2014

2015

2016

2017



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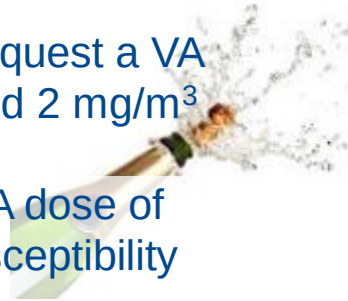
- Bardarbunga nearly produces ash – stimulates a full review of ash position in Europe
- VIPR-III engine volcanic ash (VA) test
- 1st OEM Complies with CS-25 1593: (Boeing 737 MAX – Option (a) on previous slide)
- Rolls-Royce customers request a VA susceptibility based around 2 mg/m³
- Rolls-Royce declares a VA dose of 14.4 g s/m³ as engine susceptibility



Defining Engine Susceptibility

- Sub-system by sub-system assessment of the damage mechanisms

Fuel supply system blockage

Support systems: electronics, heat exchangers. mechanical systems, …

Turbine cooling systems damage (internal & external blockage, TBC & CMAS) reducing component life

- HP compressor surge margin is the critical sub-system for safety implications

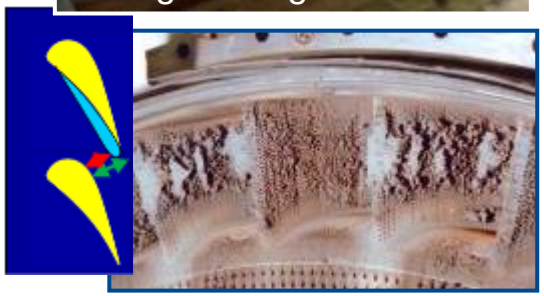
Lubrication system contamination

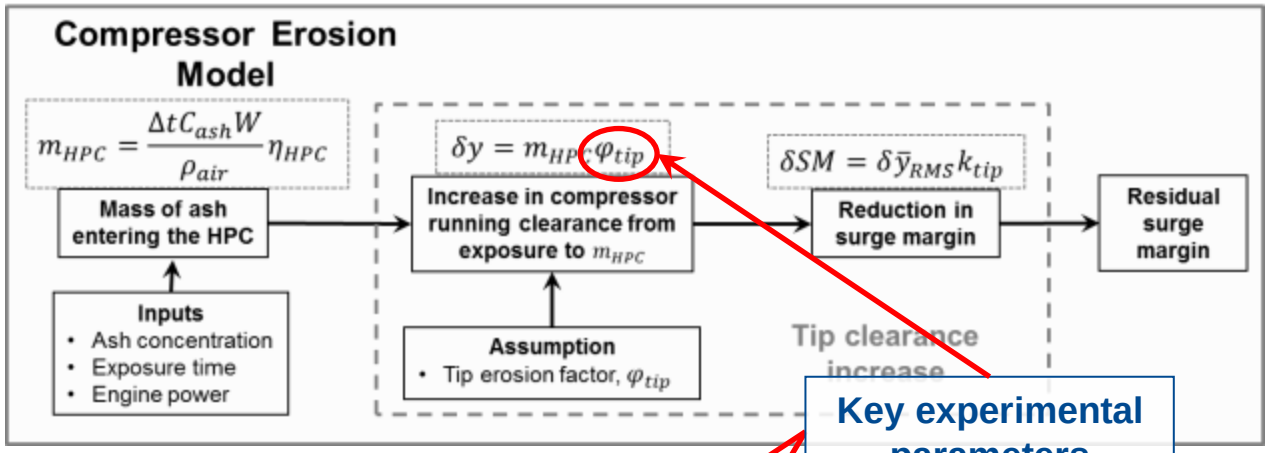
Compressor erosion – loss of efficiency and surge margin

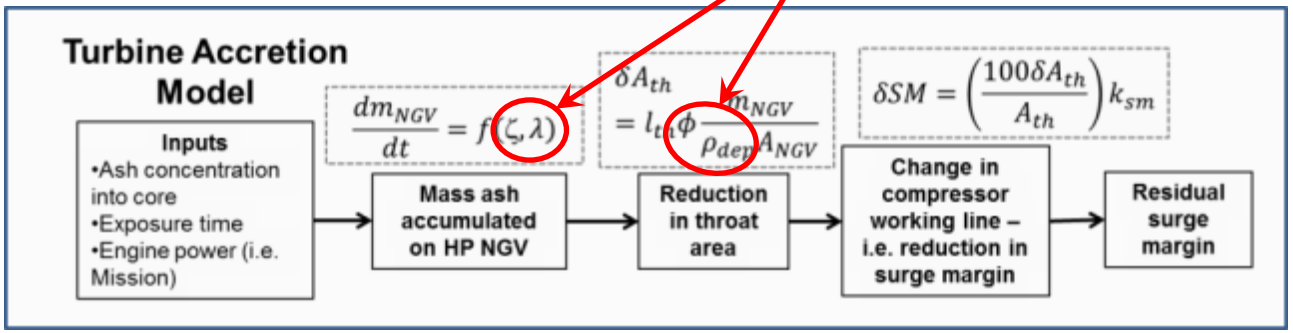
Molten ash sticks in turbine annulus, reducing surge margin

HPC Surge Margin Loss (SML) Model

- Compressor stability calculations – simple mathematical model to determine time to surge







- The SML model can quantify the effect of the **worst possible ash type** and the **worst engine operating point**

Holistic View and Validation Data

- Define four engine impact categories:

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

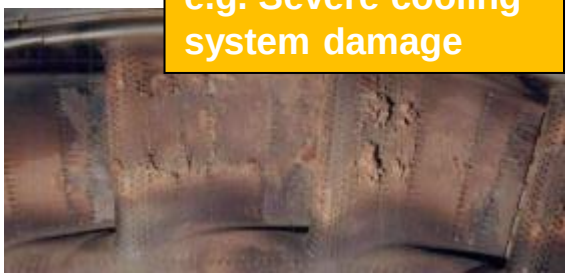
e.g. Deposit sticks in turbine annulus, choking engine

e.g. Blocked fuel delivery system

- Exigent damage – immediate maintenance action required

e.g. Severe rotor erosion

e.g. Severe cooling system damage



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

e.g. Moderate rotor erosion

e.g. Ni alloy suphidation

- Negligible damage

Holistic View and Validation Data

- Define four engine impact categories:

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

e.g. Blocked fuel delivery system

- 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:
Increasing duration of exposure [hrs]
and/or
Increasing particulate concentration [mg/m^3]

For a given:
Particulate composition and nature, design, operating point and condition of engine,…

Holistic View and Validation Data

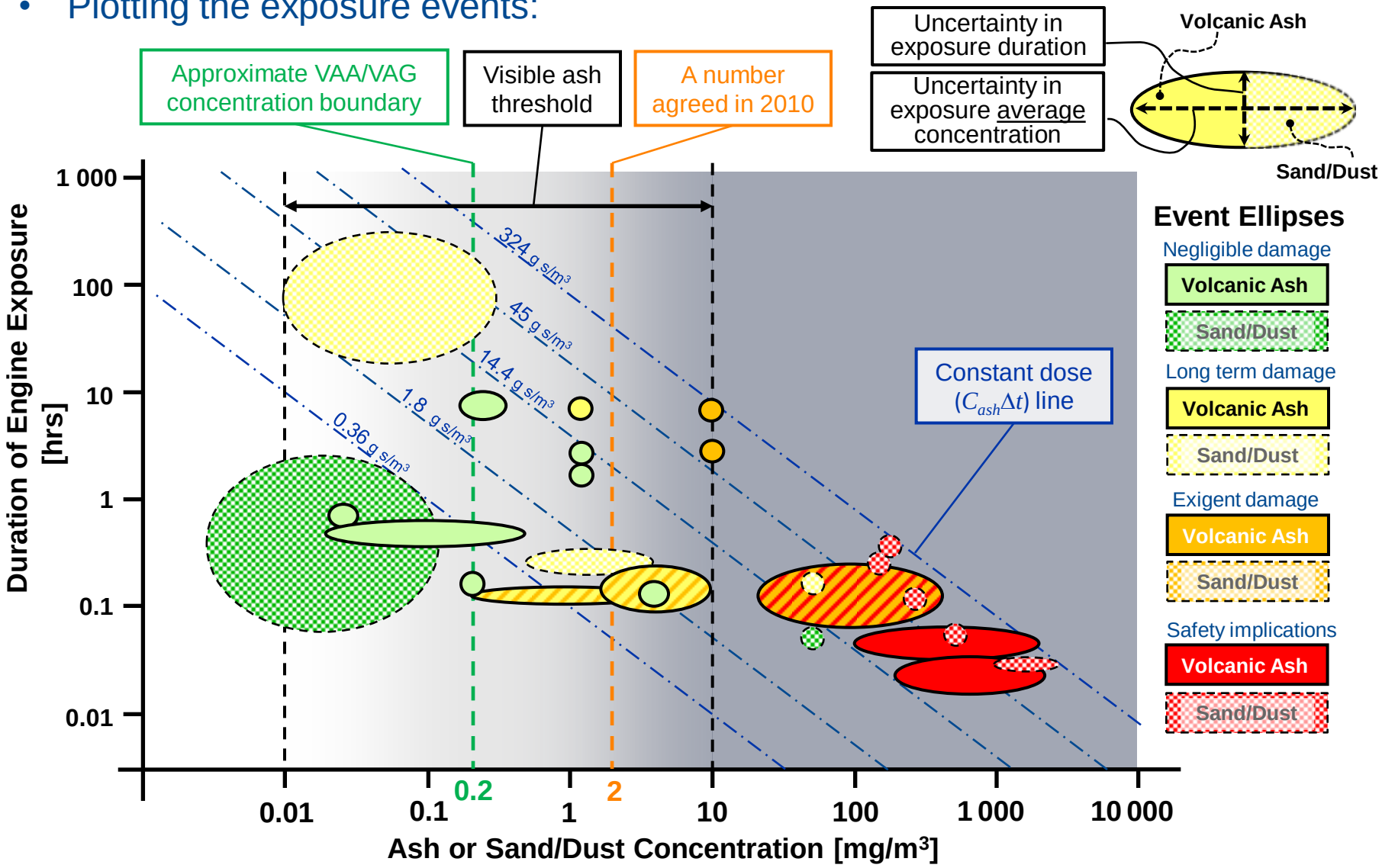
- A good source of data are in-service events
- However, despite there being over 230 know VA encounters since the mid-1970s (and probably the same number, or more, that haven't been reported) –
- There are only 8 VA encounters – available to Rolls-Royce – which are suitable for quantitative analysis
  - i.e. there is enough data/information to conduct quantitative assessment
  - Other OEMs probably have additional examples
- In addition there are:
  - 6 suitable Calspan engine tests
  - 1 volcanic ash engine test (VIPR-III) – 5 points in all
  - 4 desert sand/dust data points

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

				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

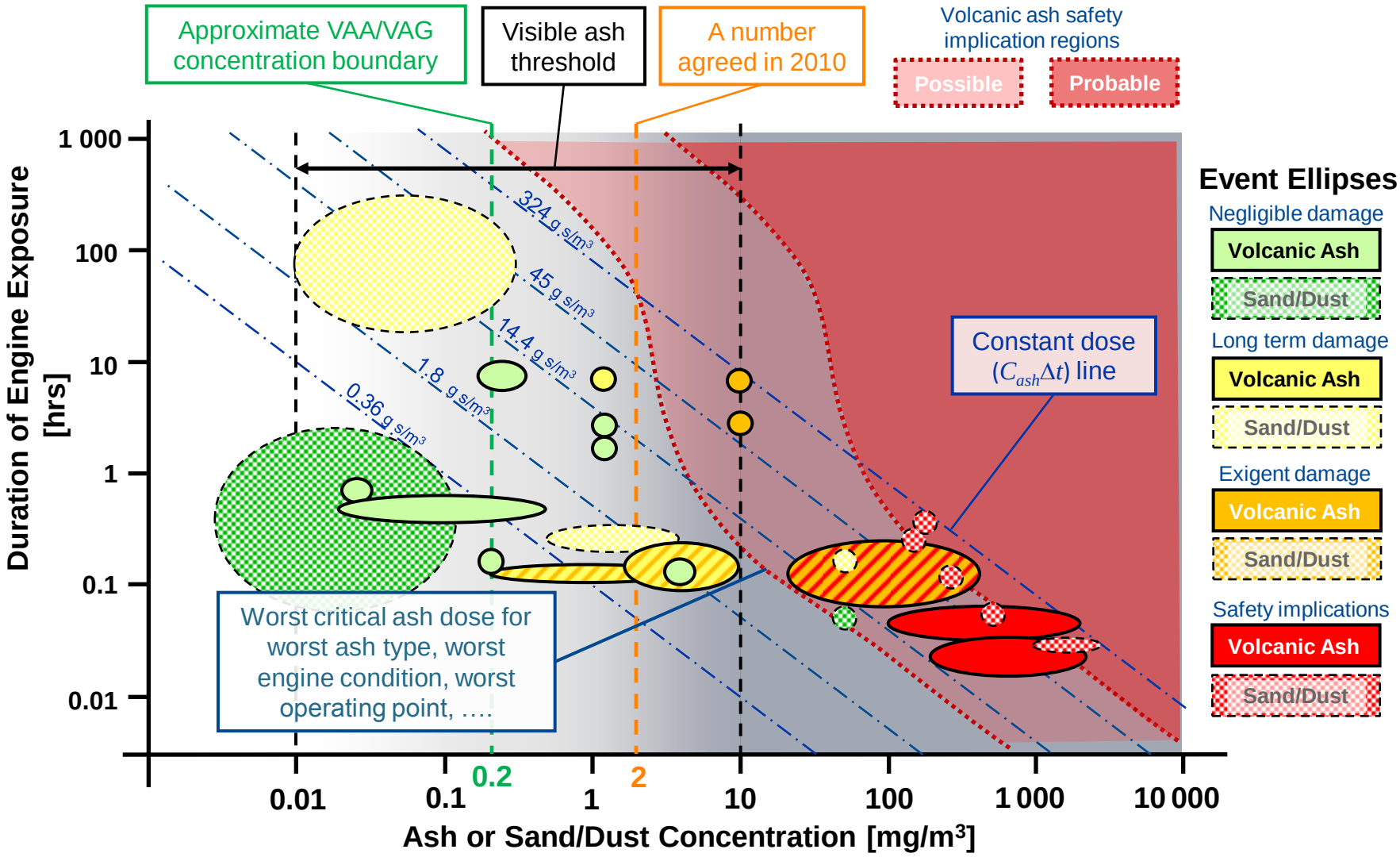
Holistic View – The DEvAC Chart

- Plotting the exposure events:



Holistic View – The DEvAC Chart

- Safety implication regions – using the SML Model



Holistic View – The DEvAC Chart

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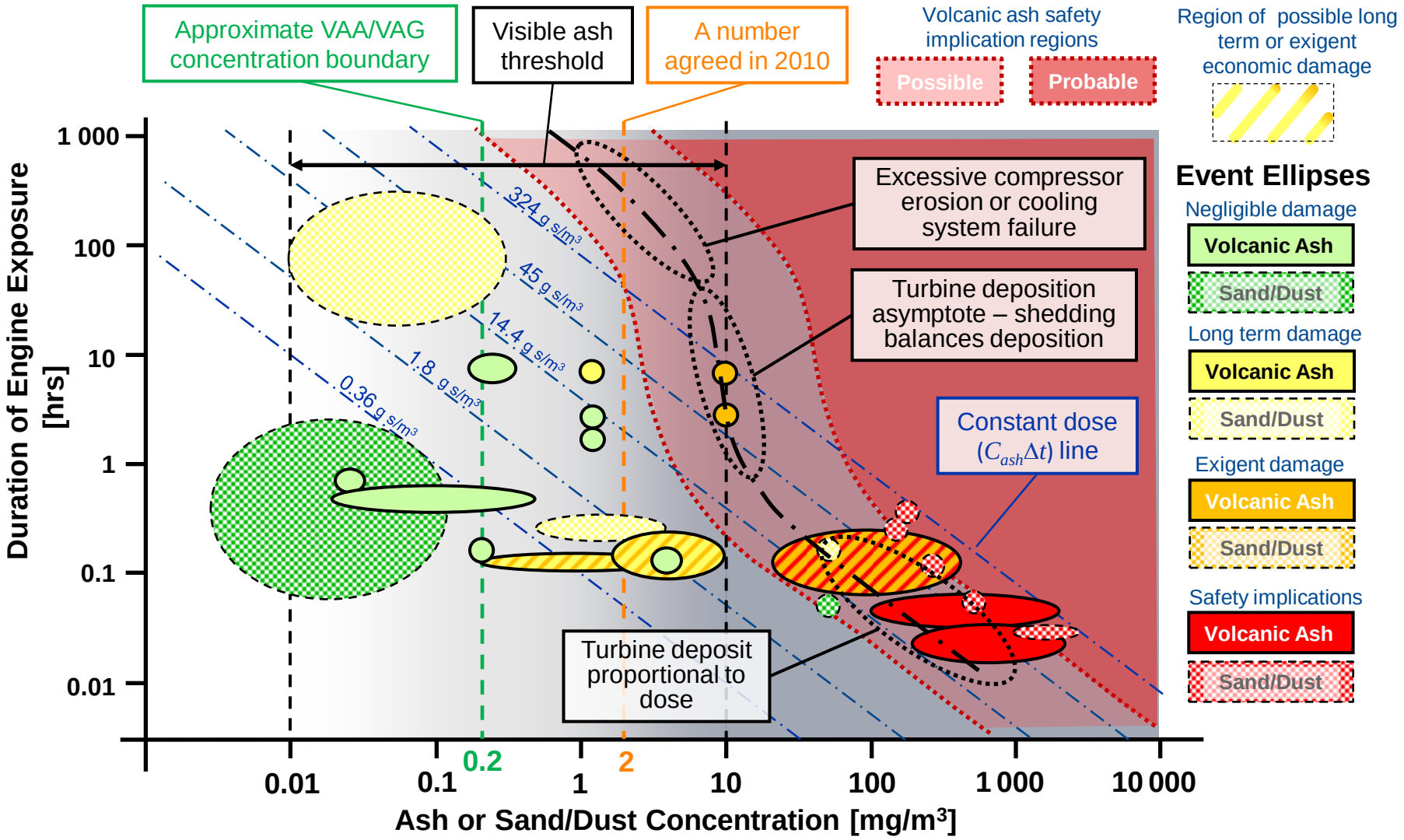
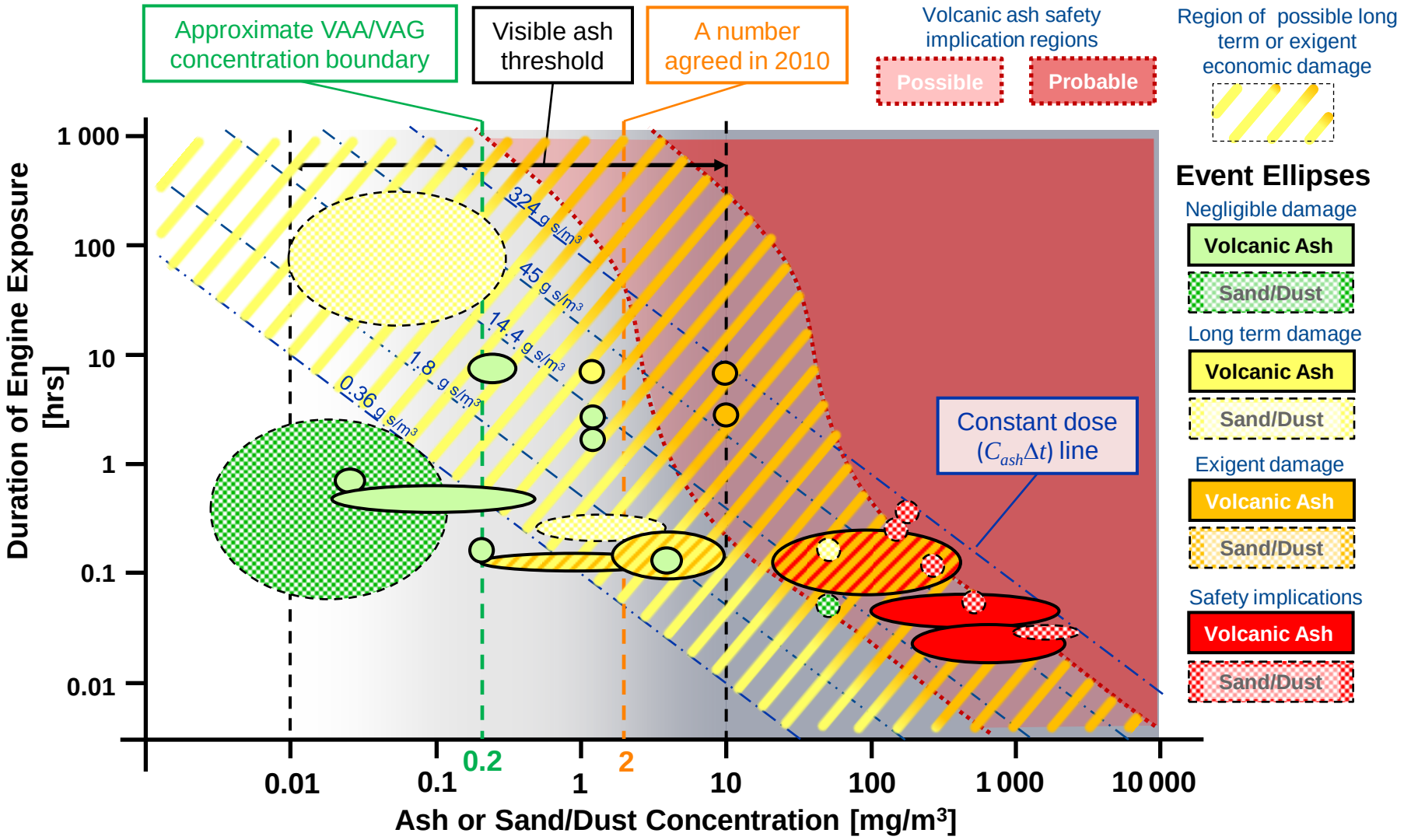


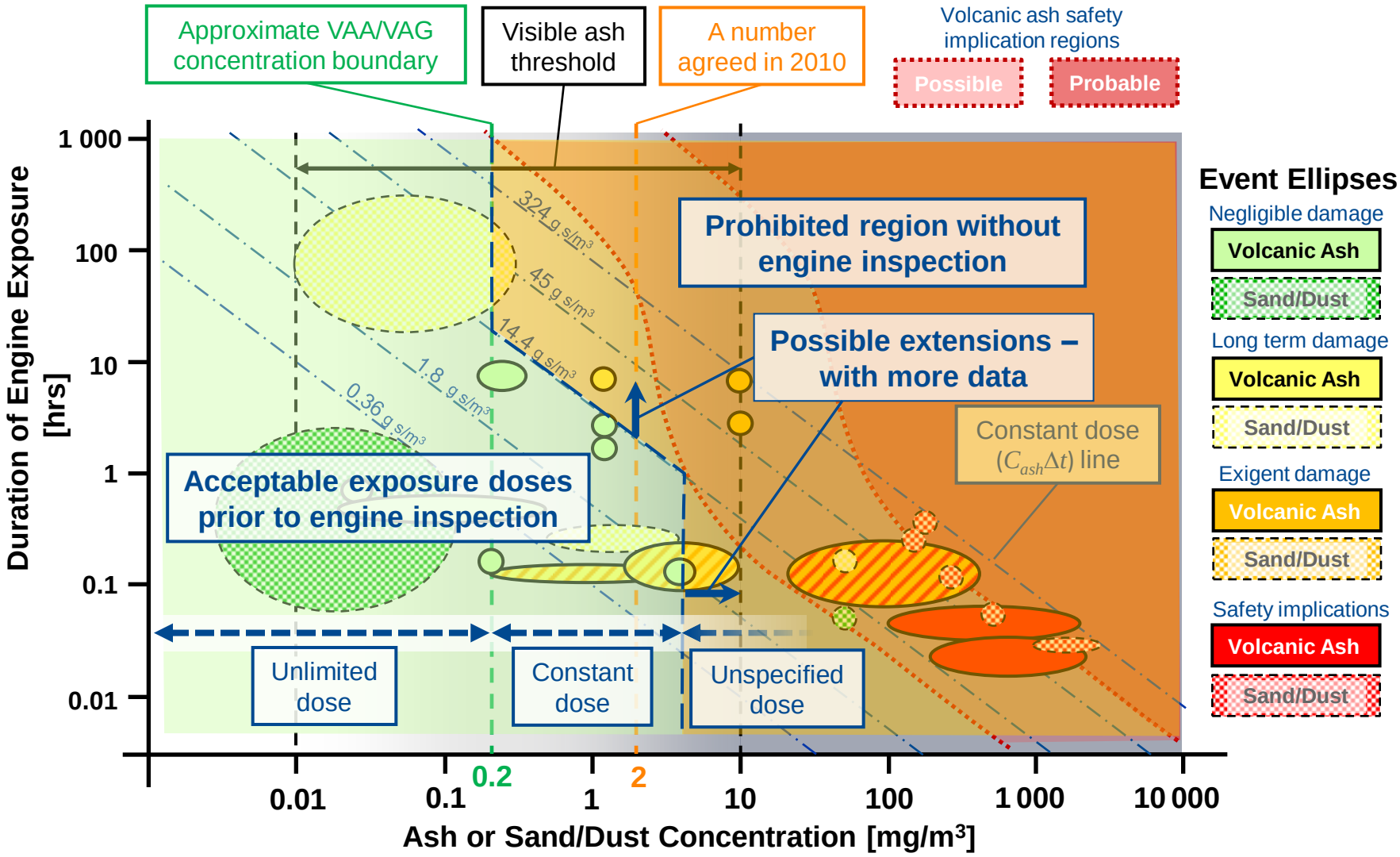
Holistic View – The DEvAC Chart

- It's not just about safety – economic damage needs to be considered



Declaring VA Susceptibility

- Constant dose approach between 4 mg/m³ and 0.2 mg/m³



Declaring VA Susceptibility

- WWC11365-1 (covering RB211 and Trent engines) issued on 24th 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.

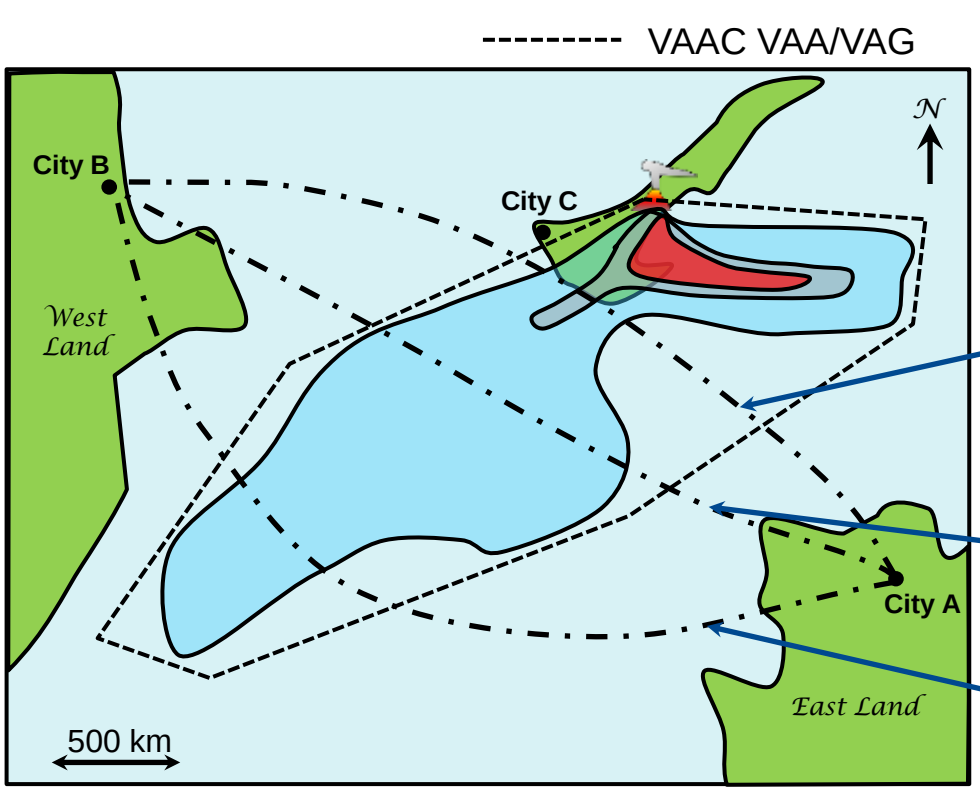
- If an exposure of 14.4 g s/m^3 is suspected to have been accumulated:
  - Engine inspection required
  - Followed by a decision to either:
    1) Set 'clock' back to 14.4 g s/m^3 or a smaller number
    2) Commence a cleaning and monitoring regime
    3) Remove engine for repair

- Susceptibility and guidance is being rolled out across the rest of the Rolls-Royce fleet, and being considered by other OEMs

- Contents of WWC11365-1 need to be embedded in EOIs – to feed into the FCOMs and AFMs

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/m^3 limit:
- Conservative assumptions: 0.2-2 mg/m^3 → treated as = 2 mg/m^3
  2-4 mg/m^3 → treated as = 4 mg/m^3



Ash Concentration Contours for FL200 to FL350

- 0.2-2 mg/m^3
- 2-4 mg/m^3
- >4 mg/m^3

Flight Plan Example 3
7 min (100 km) at 4 mg/m^3
23 min (335 km) at 2 mg/m^3
= 1.68 + 2.76 = **4.44 g s/m^3**

Flight Plan Example 1
79 min (1150 km) at 2 mg/m^3
= 9.48 g s/m^3

Flight Plan Example 2
35 min (500 km) at 2 mg/m^3
= 4.20 g s/m^3

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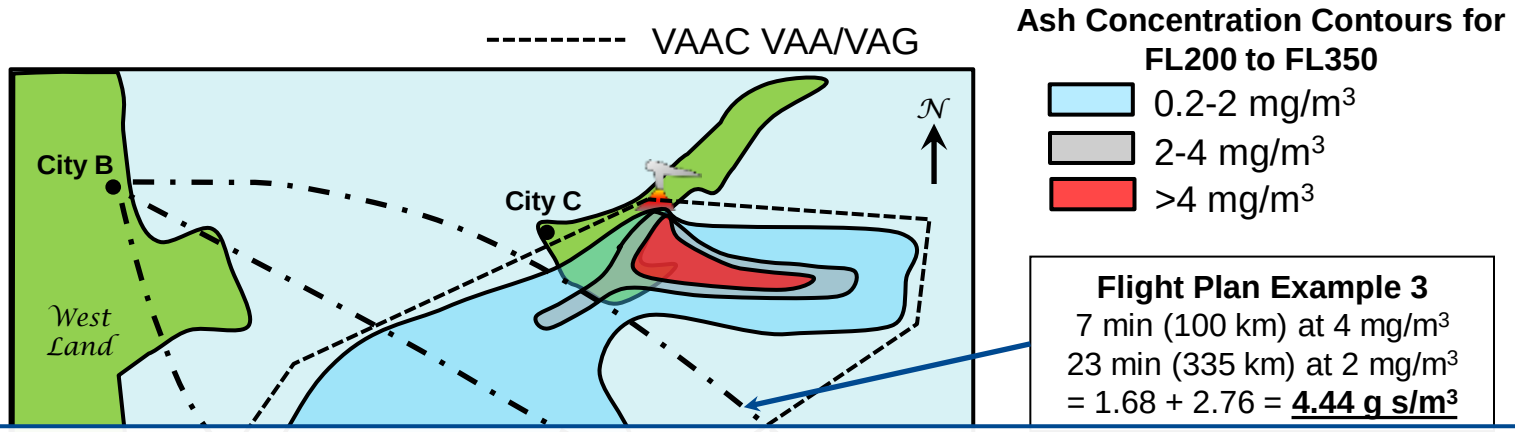
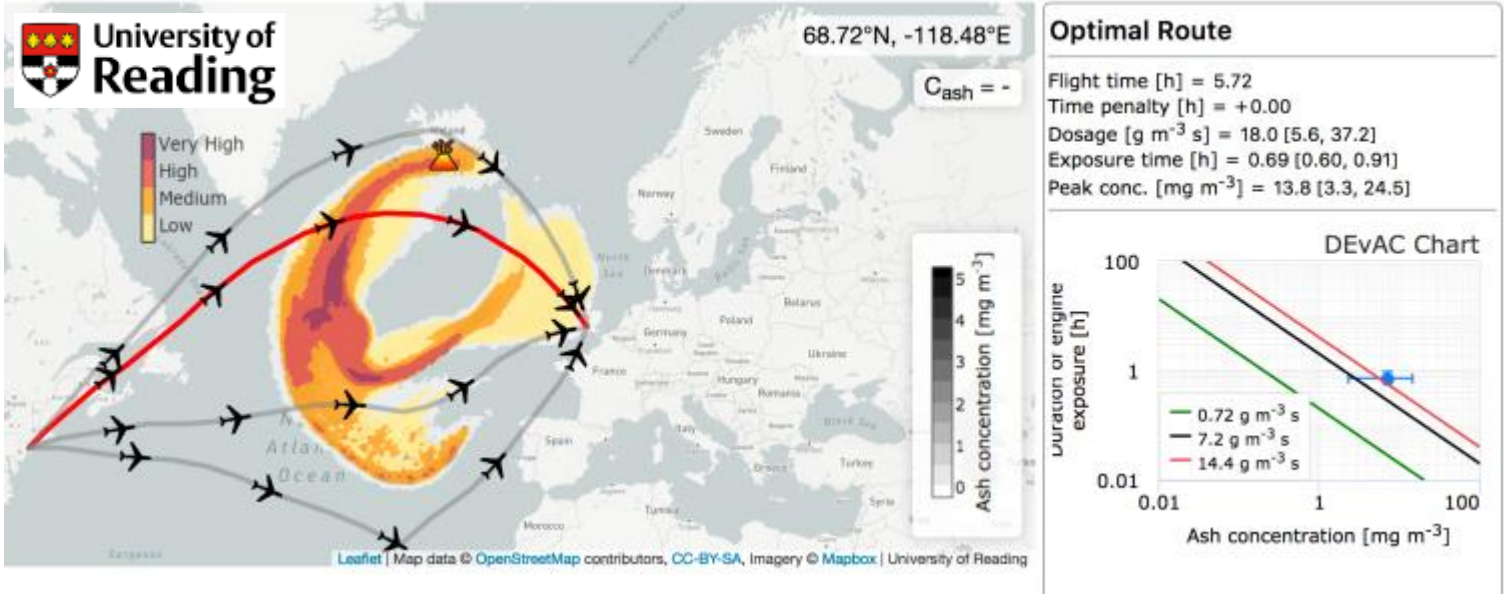


- Planned and actual cumulative ash dose managed by airlines' Flight Operations teams
  - Through appropriate flight planning and fleet management
  - Approach is still needed even if on-board dose meter fitted to aircraft
- Flight crews just keep an eye on surroundings (or dose meter) and make tactical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

How to Use a Dose Based Approach

- Several groups developing tools & products to support a dose based approach
  - WMO and ICAO forums: MET-P MOG & MISD, IAVW, VAACs and VASAG
  - Independent organisations, e.g.

WORLD METEOROLOGICAL ORGANIZATION



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SATAVIA

Other OEM Positions'

- Boeing: Despite B777-x enquiry and presentation to Boeing there has been no follow-up on non-R-R powered aircraft
- Airbus: Interaction on A350 and A330neo projects (see previous slide)
- GE, P&W, Safran, CFMI, Honeywell: No news…
  - Although there is interaction with P&W rep through NATO group
- In summary: Currently only R-R powered wide-bodied (& B757) aircraft are cleared to fly up to 14.4 g s/m^3

i.e. <10% of the jetliner fleet

Aircraft Class	No Aircraft Flying	R-R Powered
Regional Jets: Bombardier, Embraer, Fokker, DC-9/MD-80/B717, …	~4 000	~800
Mid-Market Jets: B737, A320, B757	~16 000	~**400**
Wide Bodied Jets: A330, A340, A350, A380, B747, B767, B777, B787	~5 100	~**2 000**
Jetliner Total:	~25 100	~3 200
Regional Turboprop Total:	>2 000	0

Will rise to ~13% when these are added

And Finally

- The dose based approach to flying in airspace contaminated with volcanic ash is slowly being rolled out across civil and military aviation
- Meteorological service providers are developing more sophisticated products to support the approach
- Work is progressing on embedding the approach in engine, aircraft and flight manuals
  - Some help needed to encourage other OEMs to join in
- Work has started on quantifying the purely economic impacts of operating within the 14.4 g s/m^3 (i.e. 4 mg/m^3 for 1 hour) dose limit

Thank you