Volcanic Ash Impacts on Jet Engines and Developments Since 2010

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Introduction

- Engine ash susceptibility – what happened during and after 2010
- A New Approach – Based on Engine Ash Dose
- Demonstrating the Approach
  - Implications for Operations and Meteorological Service Providers
- Other Original Equipment Manufacturers’ Positions
What We Design Engines For…
What We Design Engines For...

- Ice Crystals – Cumulonimbus cloud seen from 38,000 feet
- Freezing Fog
- Volcanic Ash and Gas Clouds
- Lightning & HIRF
- Birds
- Volcanic Ash has taken up about 5-10% of our team’s time 2010-2019
- Corrosive Gases and Aerosols
- Sand & Dust Storms
- Rain & Hail
Volcanic Ash – What Happened Post 2010?

• In 2010 most stakeholders thought that an ash concentration limit for ‘safe’ operation had been agreed at 2 mg/m$^3$
  - And London & Toulouse VAACs would produce concentration charts to support this approach

• In reality though the engine and airframe manufacturers managed to get agreement – through the IVATF – that avoiding ‘visible’ or ‘discernible’ ash was the only way to operate

• 2013 ICAO definitions of visible and discernible ash:

  Visible ash is defined as “volcanic ash observed by the human eye” and not be defined quantitatively by the observer;

  Discernible ash is defined as “volcanic ash detected by defined impacts on/in aircraft or by agreed in-situ and/or remote-sensing techniques”
Visible and Discernible Ash?

- Visible ash
- Discernible remotely
- Discernible from within the ash

Threshold with new satellite technology

Visible ash threshold

Discernible by satellites threshold

A number agreed in 2010

Detectable change in engine parameters

Satellite instruments

Impacts on the airframe & engines

Satellite instruments

St Elmo’s fire on fan

Ti flare from core inlet

Sparks off icing rod

Dust in cabin

St Elmo’s fire on windshield

Ash Concentration [mg/m³]

Visible and Discernible Ash?

• Visible ash
• Discernible remotely
• Discernible from within the ash

Satellite instruments

Impacts on the airframe & engines

St Elmo’s fire on fan

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EASA Introduce Certification Requirements

- 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.

**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.

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Defining Engine Susceptibility

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

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

Fuel supply system blockage

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

Lubrication system contamination

- All these damage mechanisms are the same for sand and dust as they are for volcanic ash – such that experience from sandy-dusty operations can be used as a proxy for operation in volcanic ash
Defining Engine Susceptibility

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

- Compressor erosion – loss of efficiency and surge margin

- Molten ash sticks in turbine annulus, reducing surge margin

- Both mechanisms lead to reduction in HP compressor surge margin – i.e. operability margins

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

- A good source of data are in-service events
- However, despite there being over 230 known 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
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. Deposit sticks in turbine annulus, choking engine
    - e.g. Severe cooling system damage
    - e.g. Severe rotor erosion
  - 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/m³]
  - For a given: Particulate composition and nature, design, operating point and condition of engine,…
Holistic View – The DEvAC Chart

- Plotting the exposure events:

  - Approximate VAA/VAG concentration boundary
  - Visible ash threshold
  - A number agreed in 2010
  - Uncertainty in exposure duration
  - Uncertainty in exposure average concentration

Event Ellipses
- Negligible damage
- Long term damage
- Exigent damage
- Safety implications

Constant dose ($C_{ash} \Delta t$) line

Duration of Engine Exposure [hrs]

Ash or Sand/Dust Concentration [mg/m^3]
Holistic View – The DEvAC Chart

- Safety implication regions – using the SML Model

- Approximate VAA/VAG concentration boundary
- Visible ash threshold
- A number agreed in 2010
- Volcanic ash safety implication regions
- Possible
- Probable
- Event Ellipses
  - Negligible damage
  - Long term damage
  - Exigent damage
  - Safety implications
- Constant dose ($C_{ash}\Delta t$) line
- Worst critical ash dose for worst ash type, worst engine condition, worst operating point, …
Holistic View – The DEvAC Chart

- Safety implication regions – using the SML Model

Event Ellipses

- Negligible damage
- Long term damage
- Exigent damage
- Safety implications

- Approximate VAA/VAG concentration boundary
- Visible ash threshold
- A number agreed in 2010
- Volcanic ash safety implication regions
- Possible
- Probable

- Excessive compressor erosion or cooling system failure
- Turbine deposition asymptote – shedding balances deposition
- Constant dose ($C_{ash} \Delta t$) line
- Turbine deposit proportional to dose

- Turbine deposit proportional to dose
- Probable
- Exigent damage
- Safety implications

- 32.4 g/sm³
- 45 g/sm³
- 14.4 g/sm³
- 0.36 g/sm³

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Holistic View – The DEvAC Chart

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

- Approximate VAA/VAG concentration boundary
- Visible ash threshold
- A number agreed in 2010
- Volcanic ash safety implication regions
- Region of possible long term or exigent economic damage

Event Ellipses

- Negligible damage
- Long term damage
- Exigent damage
- Safety implications

- Constant dose ($C_{ash \Delta t}$) line

- • 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

- Approximate VAA/VAG concentration boundary
- Visible ash threshold
- A number agreed in 2010
- Prohibited region without engine inspection
- Possible extensions – with more data
- Constant dose approach between 4 mg/m³ and 0.2 mg/m³
- Acceptable exposure doses prior to engine inspection
- Unlimited dose
- Constant dose
- Unspecified dose

Ash or Sand/Dust Concentration [mg/m³]
Duration of Engine Exposure [hrs]
Event Ellipses
Negligible damage
Volcanic Ash
Sand/Dust
Long term damage
Volcanic Ash
Exigent damage
Volcanic Ash
Safety implications
Volcanic Ash
Sand/Dust
Declaring VA Susceptibility

- Current Rolls-Royce guidance for 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 it is being considered by other OEMs…
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

Flight Plan Example 1
79 min (1150 km) at 2 mg/m³
= 9.48 g s/m³

Flight Plan Example 2
35 min (500 km) at 2 mg/m³
= 4.20 g s/m³

Flight Plan Example 3
7 min (100 km) at 4 mg/m³
23 min (335 km) at 2 mg/m³
= 1.68 + 2.76 = 4.44 g s/m³
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](image)

- 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
Other OEM Positions’

- A presentation was made to Boeing in early 2018, but there has been no follow-up on non-R-R powered aircraft (despite some initial interest)
- Airbus: Interaction on A350 and A330neo projects
- GE, P&W, Safran, CFMI, Honeywell: No news…
- In summary: Currently only R-R powered wide-bodied (& B757) aircraft are cleared to fly up to 14.4 g s/m³

i.e. <10% of the jetliner fleet

<table>
<thead>
<tr>
<th>Aircraft Class</th>
<th>No Aircraft Flying</th>
<th>R-R Powered</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regional Jets:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bombardier, Embraer, Fokker, DC-9/MD-80/B717, …</td>
<td>~4 000</td>
<td>~800</td>
</tr>
<tr>
<td><strong>Mid-Market Jets:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B737, A320, B757</td>
<td>~16 000</td>
<td>~400</td>
</tr>
<tr>
<td><strong>Wide Bodied Jets:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A330, A340, A350, A380, B747, B767, B777, B787</td>
<td>~5 100</td>
<td>~2 000</td>
</tr>
<tr>
<td><strong>Jetliner Total:</strong></td>
<td>~25 100</td>
<td>~3 200</td>
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<tr>
<td><strong>Regional Turboprop Total:</strong></td>
<td>&gt;2 000</td>
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</tbody>
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Will rise to ~13% when these are added through 2019
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
  - Might need some help 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