Rolls-Royce 2015 Update

PROVIDA Meeting
14^{th} December 2015

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Engine Environmental Protection

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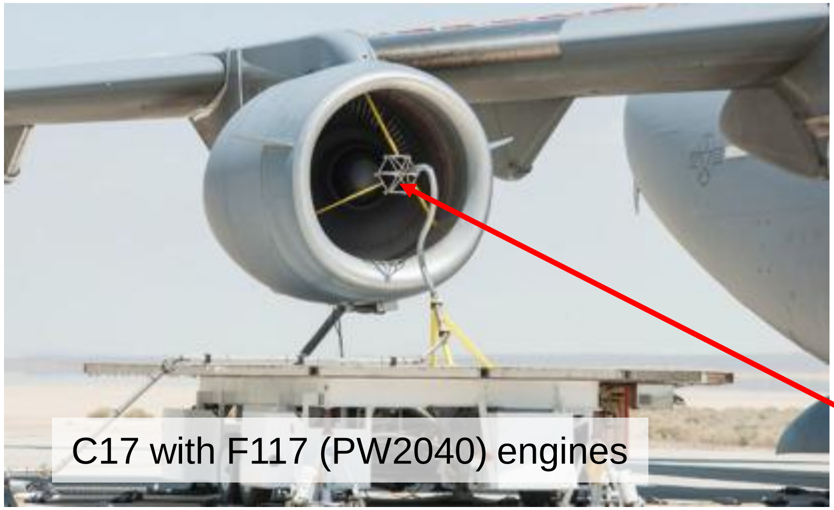
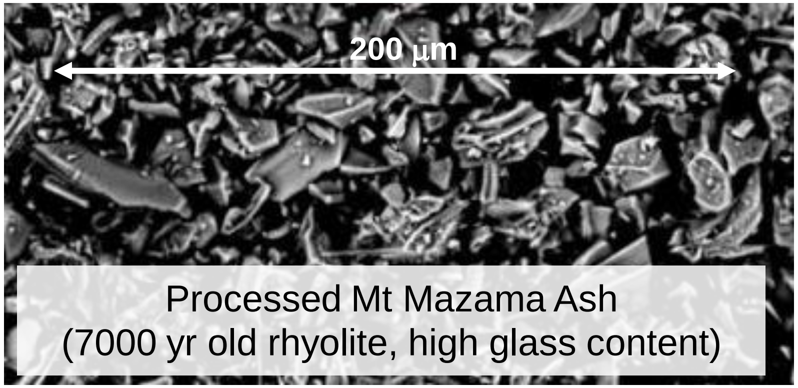
Introduction

- VIPR-III Update
- Latest Ash Concentration v Duration Charts
- Implications for aviation
- Other research going on

Recent Events – VIPR-III July 2015

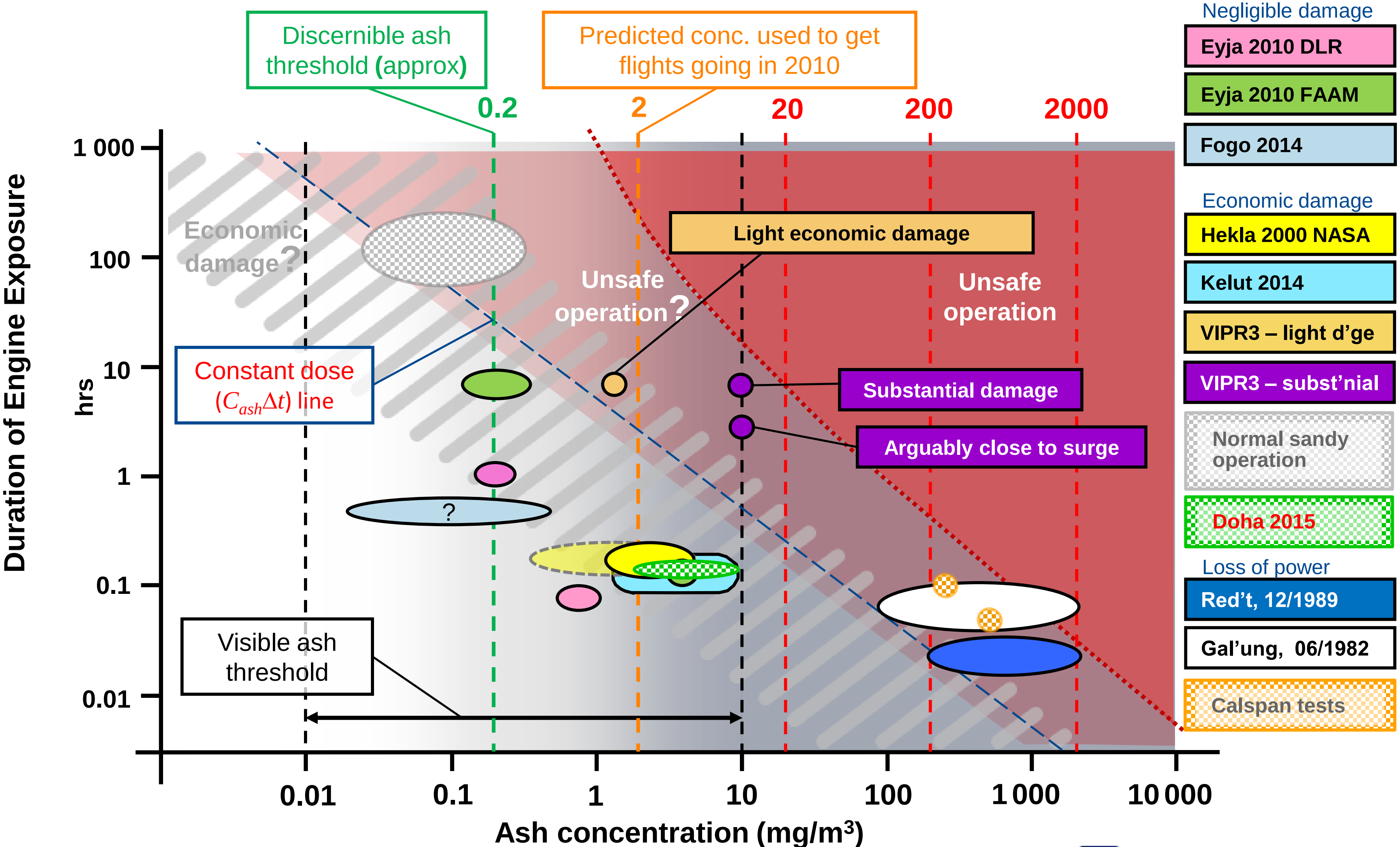




- Ash significantly more erosive than the sand previously used with rig

- 7 hrs at ~1.3 mg/m^3 (spread over at least 4 runs)
  - Initial performance improvement – compressor cleaning
  - Eventually 'ice like' CMAS deposit on HPT
- 7 hrs at 10 mg/m^3 (4 hr and 3 hr runs)
  - Initial 4 hr run – 3 K rise in EGT, compressor erosion, significant deposit in HP NGVs
  - On engine deceleration dust discharged out of exhaust
  - 10 minutes to restart, with more dust discharged
  - Additional 3 hr run, core temperatures continued to rise, but not measured EGT

The DEvAC chart – VIPR-III Update

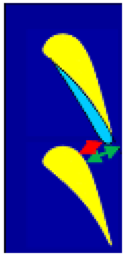


Engine Damage Mechanisms

Three categories of damage:

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

e.g. Blocked fuel delivery system



e.g. Molten ash sticks in turbine annulus, choking engine

- Economic – immediate maintenance action required

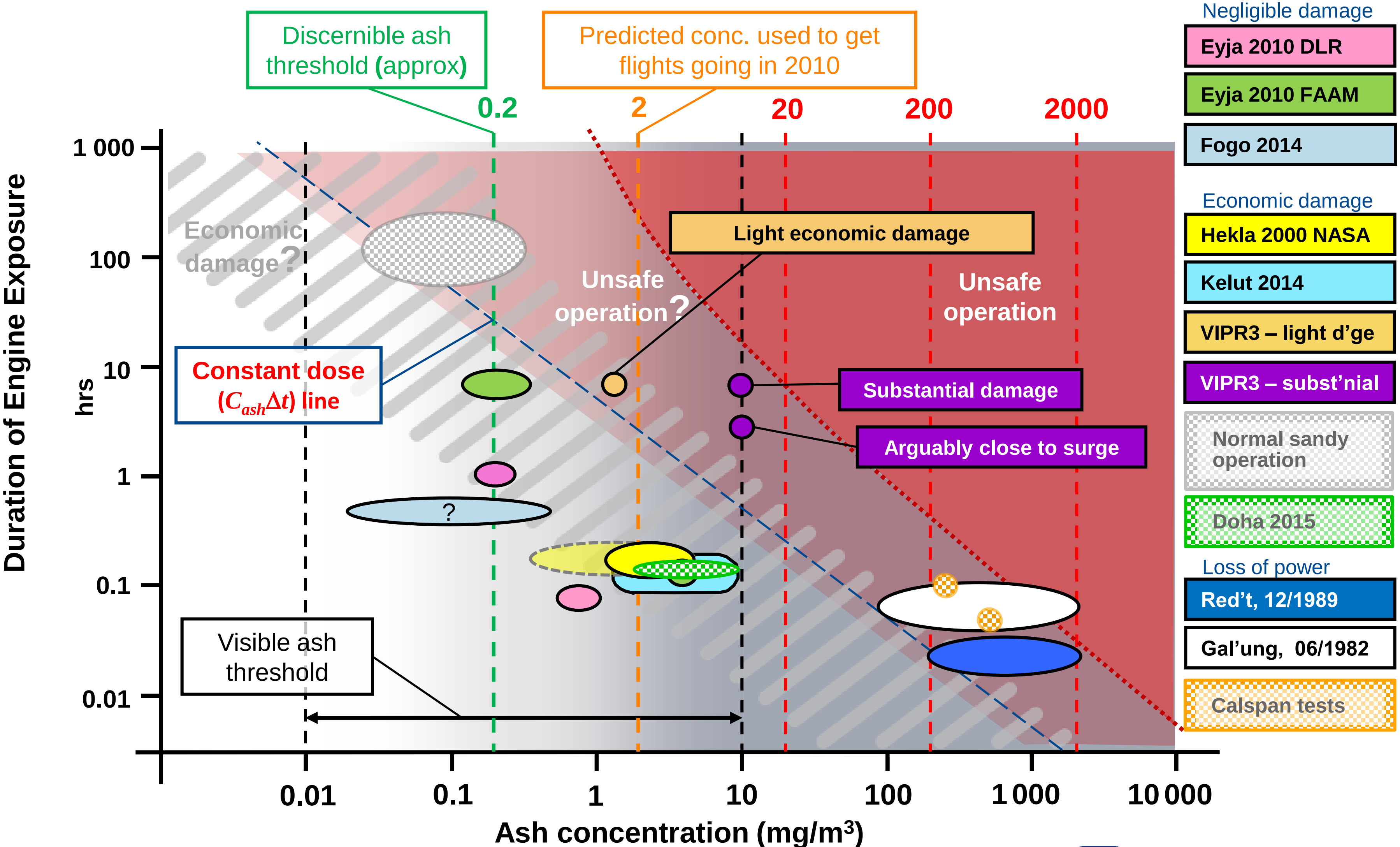
e.g. Severe cooling system damage

- Economic – manageable loss of performance or slightly premature removal for overhaul

e.g. Ni alloy suphidation

e.g. Rotor erosion

The DEvAC chart – VIPR-III Update



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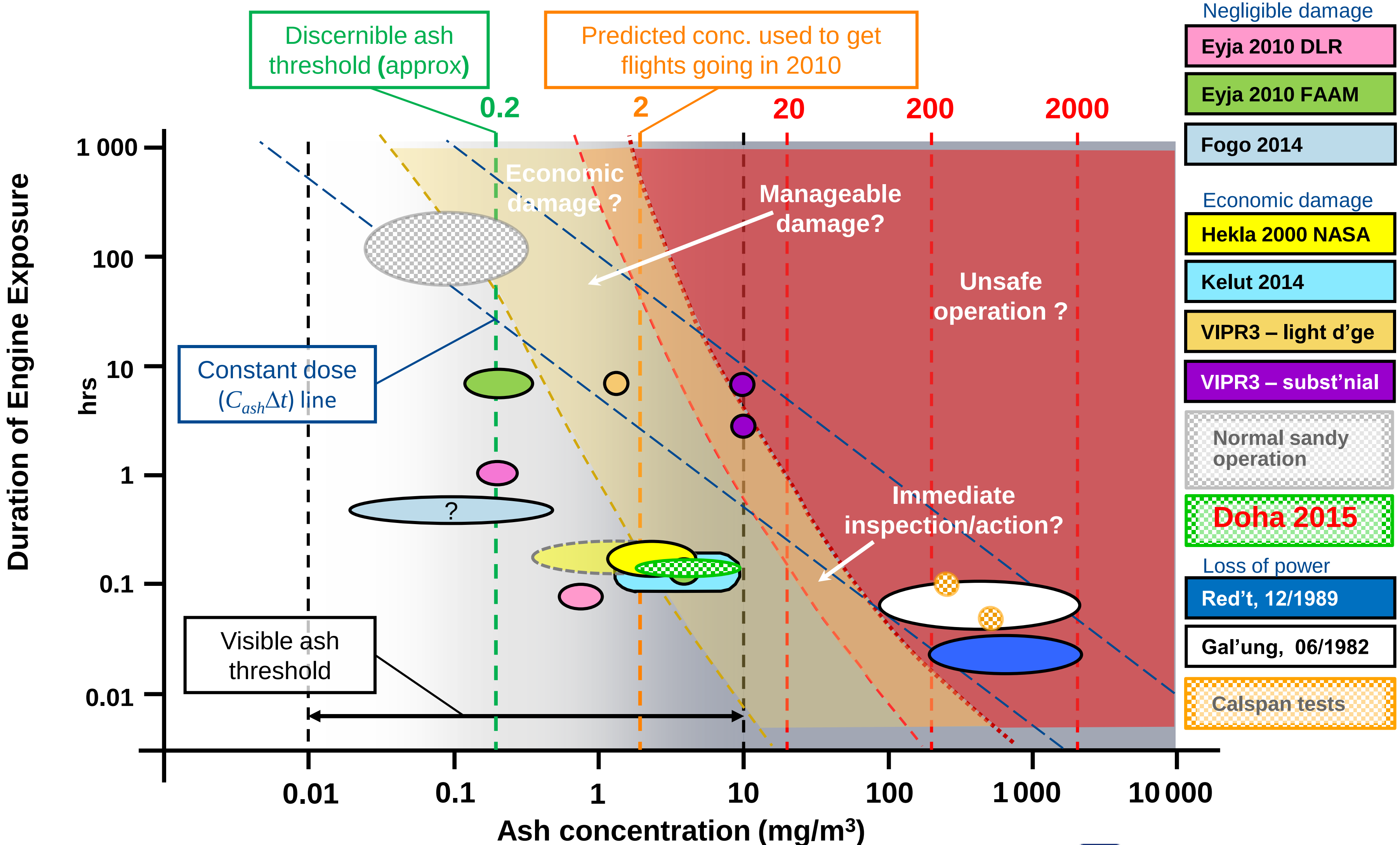
The DEvAC chart – VIPR-III Update

- Speculative rejig of chart



Implications of the VIPR-III and Other Evidence

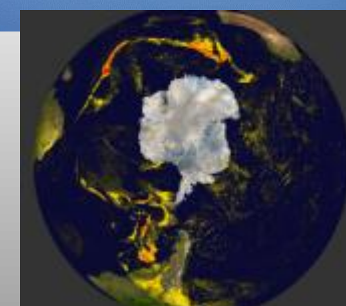
- Airlines, governments and others: Is there a justification for exploring the possibility of operating in visible or discernible ash, potentially up to 10 mg/m^3?

- What annual cost to global aviation and society for avoiding discernible/visible ash?

$1M /yr ?

$10M /yr ?

>$20M /yr ?



- Is there an ash concentration/dose that would reduce this cost to something <$5M /yr?
    - Combined flight disruption and slight engine deterioration costs

- What would it cost to establish such a concentration/dose?

$3M ?

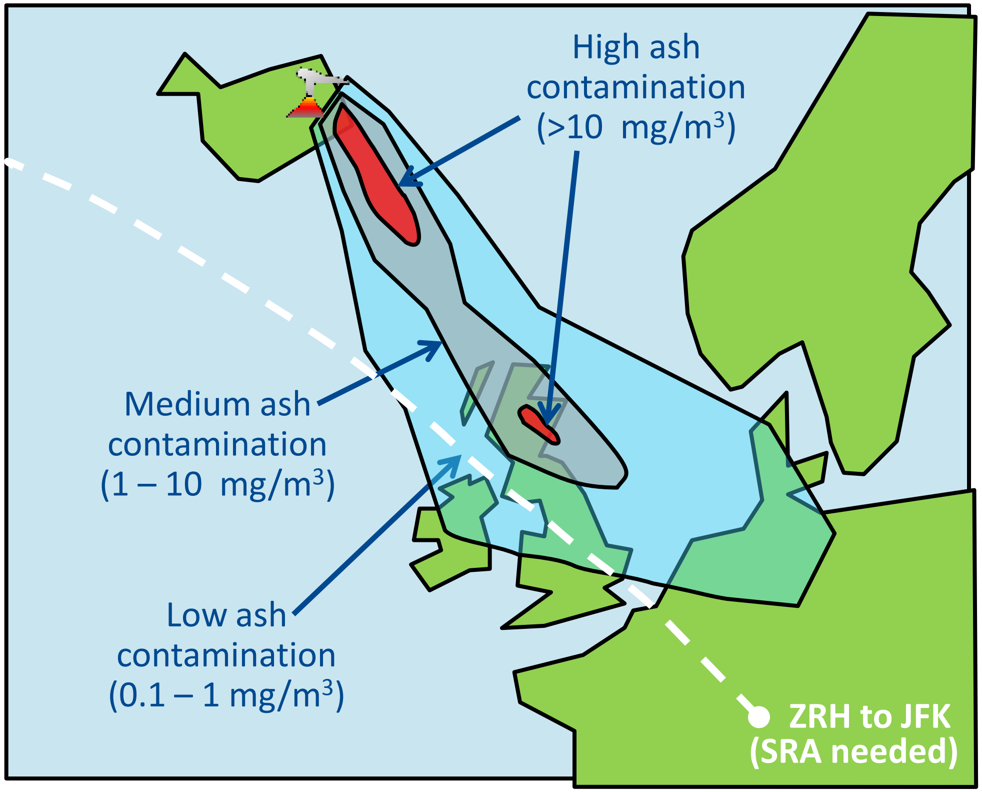
$30M ?

>$300M ?

- Could such a concentration/dose be of practical operational use?

Implications of Potential VA Tolerance

- If 10 mg/m^3 was the 'magic' number?
  - i.e. flight safe for up to say 1 hr in 10 mg/m^3
- How practically useful is such a threshold?
- What likelihood of encountering a significant 'patch' of ash > 10 mg/m^3 more than say 400 km from the volcano?
- Noting that London and Toulouse VAACs want to move to a total column loading approach i.e. 1 g/m^2, 10 g/m^2



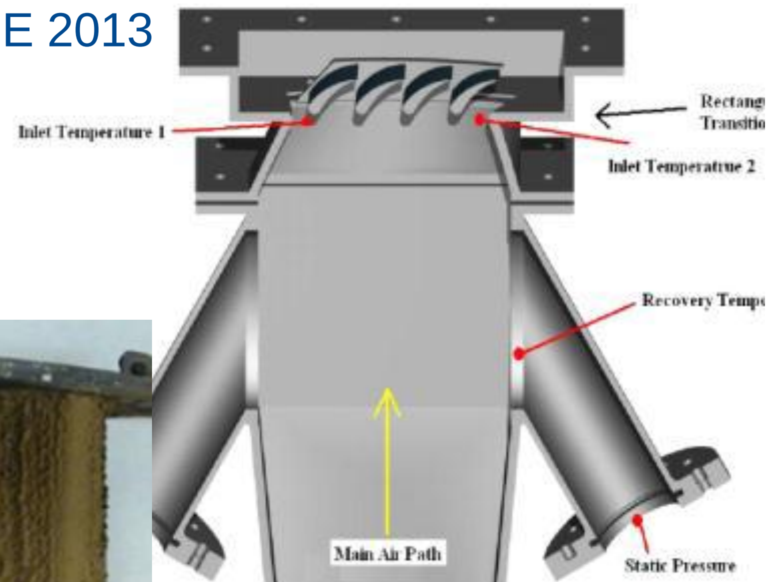
SRA – Safety Risk Assessment

Other Interesting Research Going On

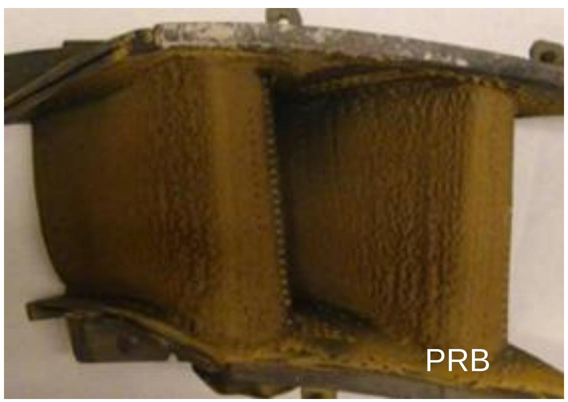
- Experience from coal ash and sand/dust work
- Revisiting past ash encounters where there is substantial engine/airframe data

Hot Section Accretion

- Ohio State – Coal ash deposition on turbine nozzle guide vanes, with and without film cooling air
  - J Webb. B. Casaday, B. Barker, et al. ASME 2013



- CFM56 turbine vanes were studied with 4 types of coal ash in the hot gas stream
  - Gas temperature range of 1317–1385 K

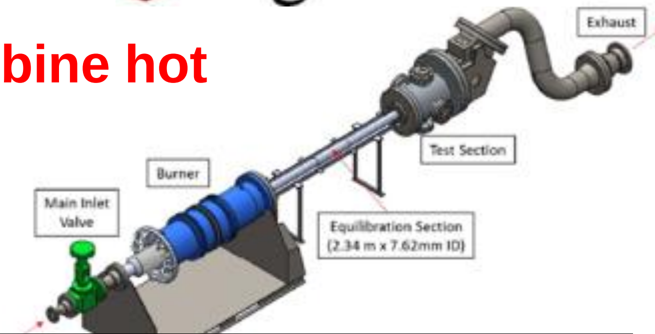


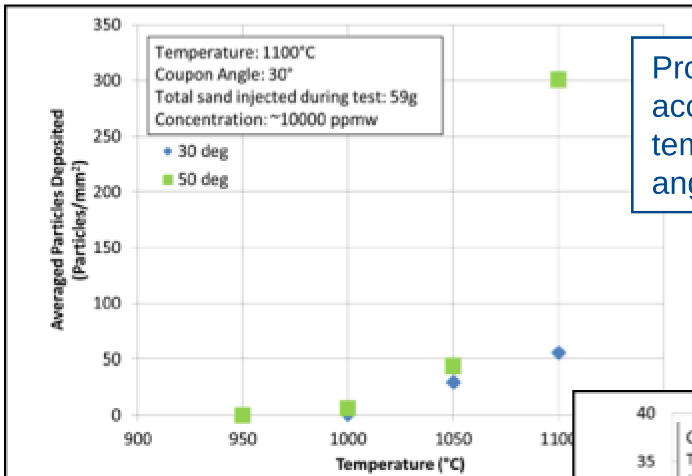
CaO rich (42.2%) coal ash, 76 mg/m^3 (@ 35k ft) for 66 mins	Low CaO (9.4%) , 50% SiO_2 coal ash, 156 mg/m^3 (@ 35k ft) for 15 mins

- Film cooling reduces deposition slightly

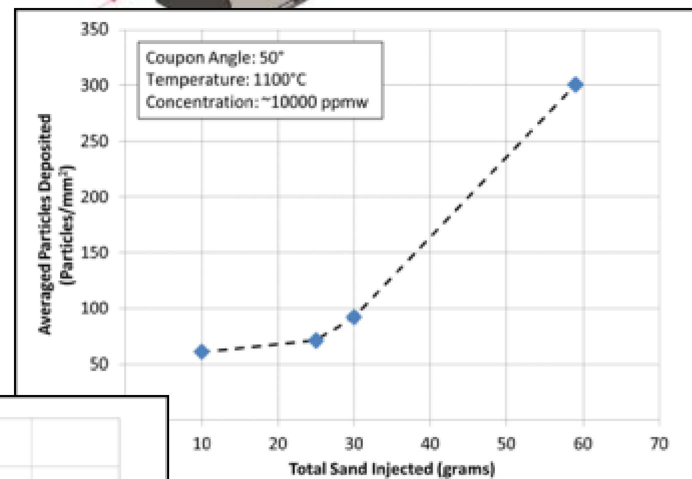
Hot Section Accretion

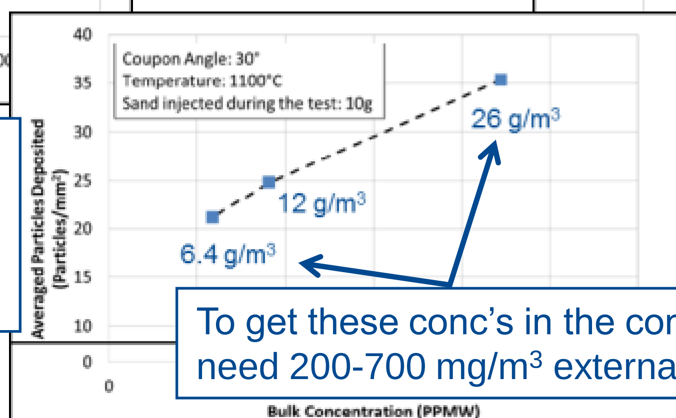
- **Virginia Tech – Sand deposition in gas turbine hot sections**
  - **H. D. Patel, MSc Thesis**
- Similar concept rig to Cambridge Univ but testing with sand – ARD, ~27 μm D_{mean}





Proportion of deposit accumulated increases with temperature and impact angle – not surprisingly





For a fixed mass ingested (10 g), total deposit accumulated increases with concentration – suggests particle interaction (aggregation?) before impact is important

Proportion of deposit accumulated increases as total mass ingested increases – not surprisingly

To get these conc's in the combustor – need 200-700 mg/m³ externally at ~35k ft

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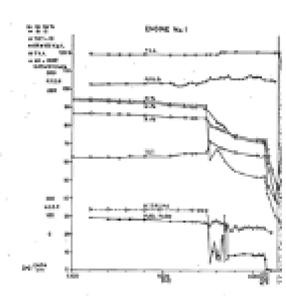
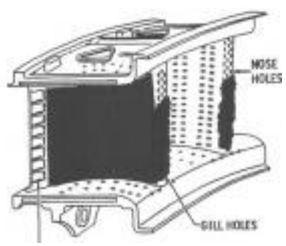
A Source of Data – Actual Ash Encounters

- Galunggung 1982 (BA009) event
  - RR report



- Redoubt 1989 (KLM867) event
  - Z J Przedpelski and T J Casadevall paper



- And there will be others that are worth pursuing…

- Two encounters not on the chart…
- Mt St Helens 1980 (TA C-130) event
  - DNA report

- Soputan 1985 (Qantas B747) event
  - RR report

Actual Ash Encounters

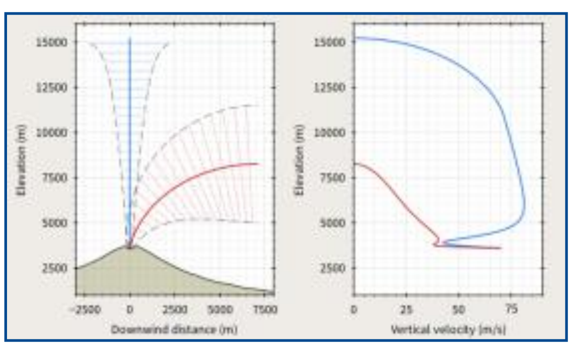
- USGS database of encounters

  Encounters of Aircraft with Volcanic Ash Clouds: A Compilation of Known Incidents, 1953–2009

  By Marianne Guffanti, Thomas J. Casadevall, and Karin Budding

  *pubs.**usgs**.gov/ds/545/Appendix_1B.**xls***

- Previous encounters with good engine/airframe data
  - An understanding of the ash concentration encountered would be particularly valuable
- PlumeRise, Fall3D, or Bursik, Sparks et al. modelling?



Eruption	Year	Aircraft
Mt Spurr	1953	F-84s
Augustine	1976	F-4Es
Mt Saint Helens	1980	C-130 (L-100)
Galunggung	1982	B747
Soputan	1985	B747
Mt Redoubt	1989	B747
Hekla	2000	DC-8
Kelut	2014	A320
Fogo	2014	Lynx

To Summarise

- Real progress in the last 12 months
- Engine data –
  - Kelut, Doha, VIPR-III
- Possible cost/benefit numbers coming out for operation in low concentration visible/discernible ash
- Calls for strategies to be developed for allowing some operation in visible/discernible ash
  - Aircraft and engine safety
  - Passenger and crew health – breathing in ash dust
  - Quantifying rates of economic damage
- Probably look at a small-ish scoping programme (i.e. < £1M)
- Followed by a bigger (i.e. > £15M) programme

Just Before I Finish…..

The impact of volcanic ash clouds on aviation can be highly disruptive to operators and passengers, and can have significant economic impacts on global tourism, trade and the aviation industry.

Rolls-Royce has undertaken considerable research in this area, and we'd like you to think of ways of minimising the impact of a future ash-cloud event on air travel.

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