

Ash deposition and what damage this can cause the engine

IMechE: In Flight Ash Cloud Detection
13 April 2016

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Engine Environmental Protection

Rolls-Royce

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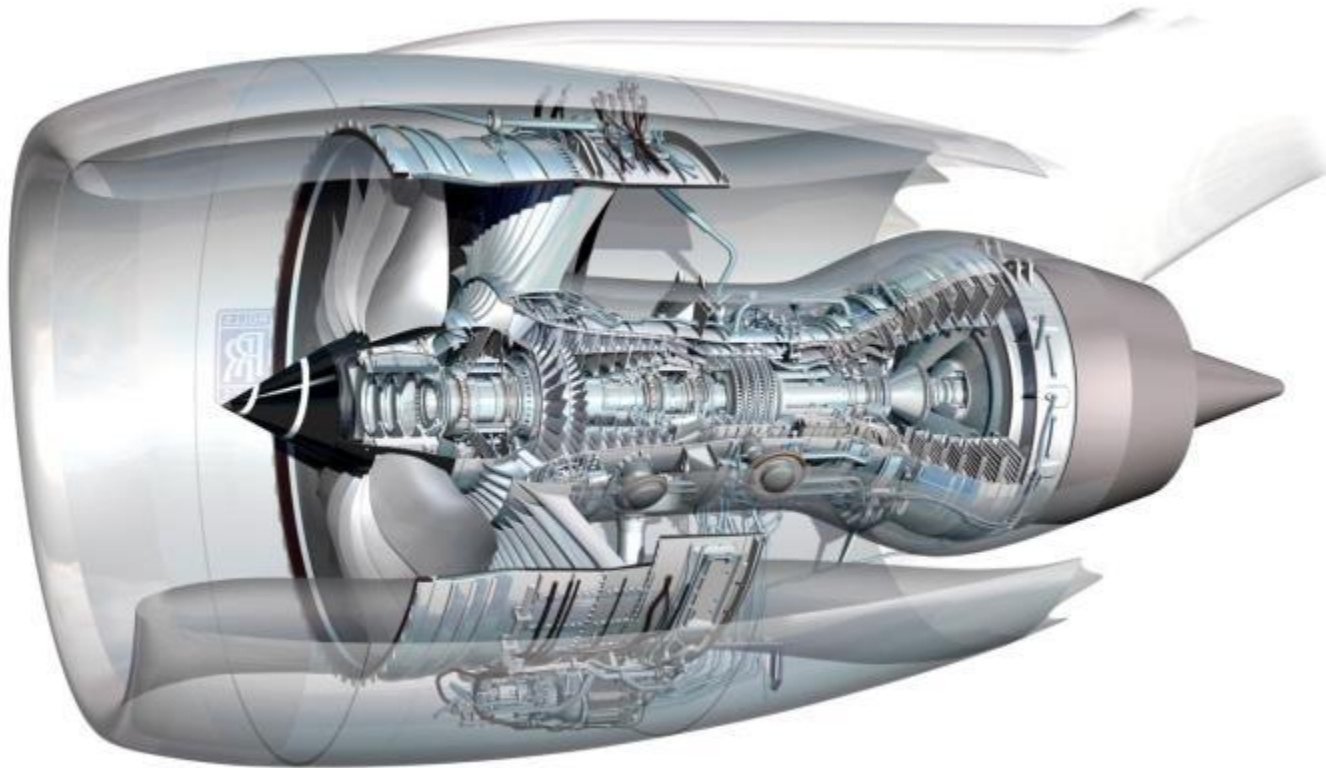
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Introduction

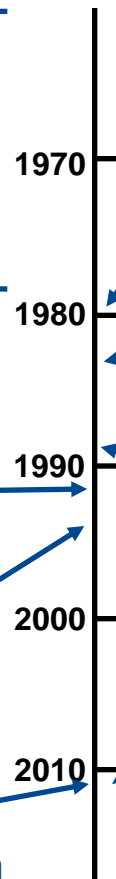
- An introductory bit of history
- How volcanic ash damages gas turbine engines
- Quantifying the damage – what is and isn't known
- Where do we go from here?



Volcanic Ash & Aviation – A Short History

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



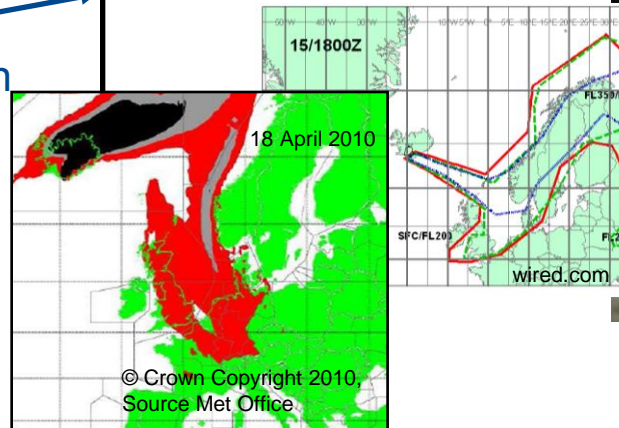
Mt St Helens 1980 & a L100 (C-130) – T56 engines

Galunggung 1982 & BA009 – B747 with RB211-524s

Mt Redoubt 1989 & KLM867 – B747 with CF-6s

Eyjafjallajokull 2010 eruption

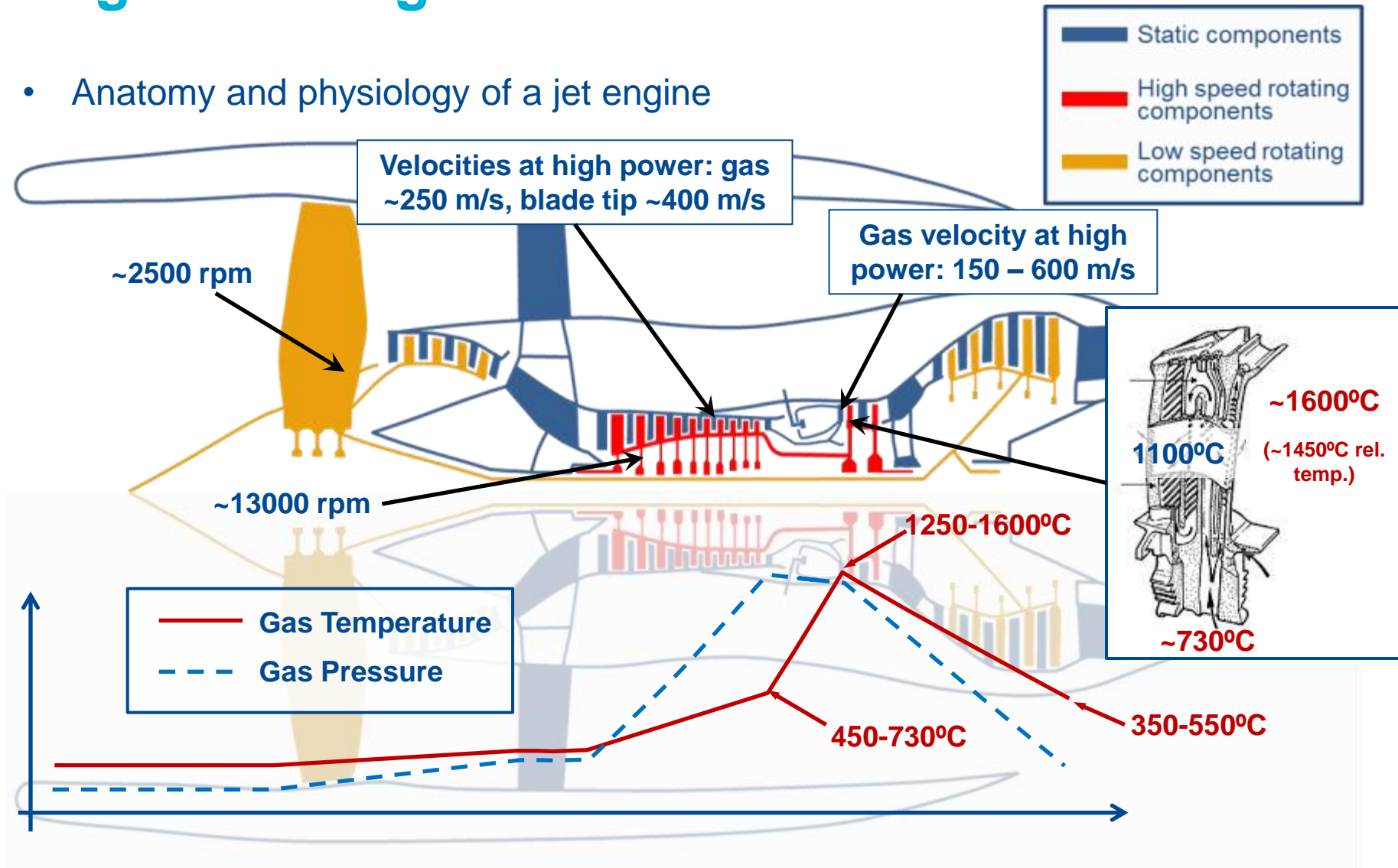
- ICAO sets up VAACs & principle of 'AVOID, AVOID, AVOID' established
- 15th April much of Western Europe's airspace shuts down
- UK CAA attempts to get flights going by discussing possible safe concentration level



Engine Damage Mechanisms

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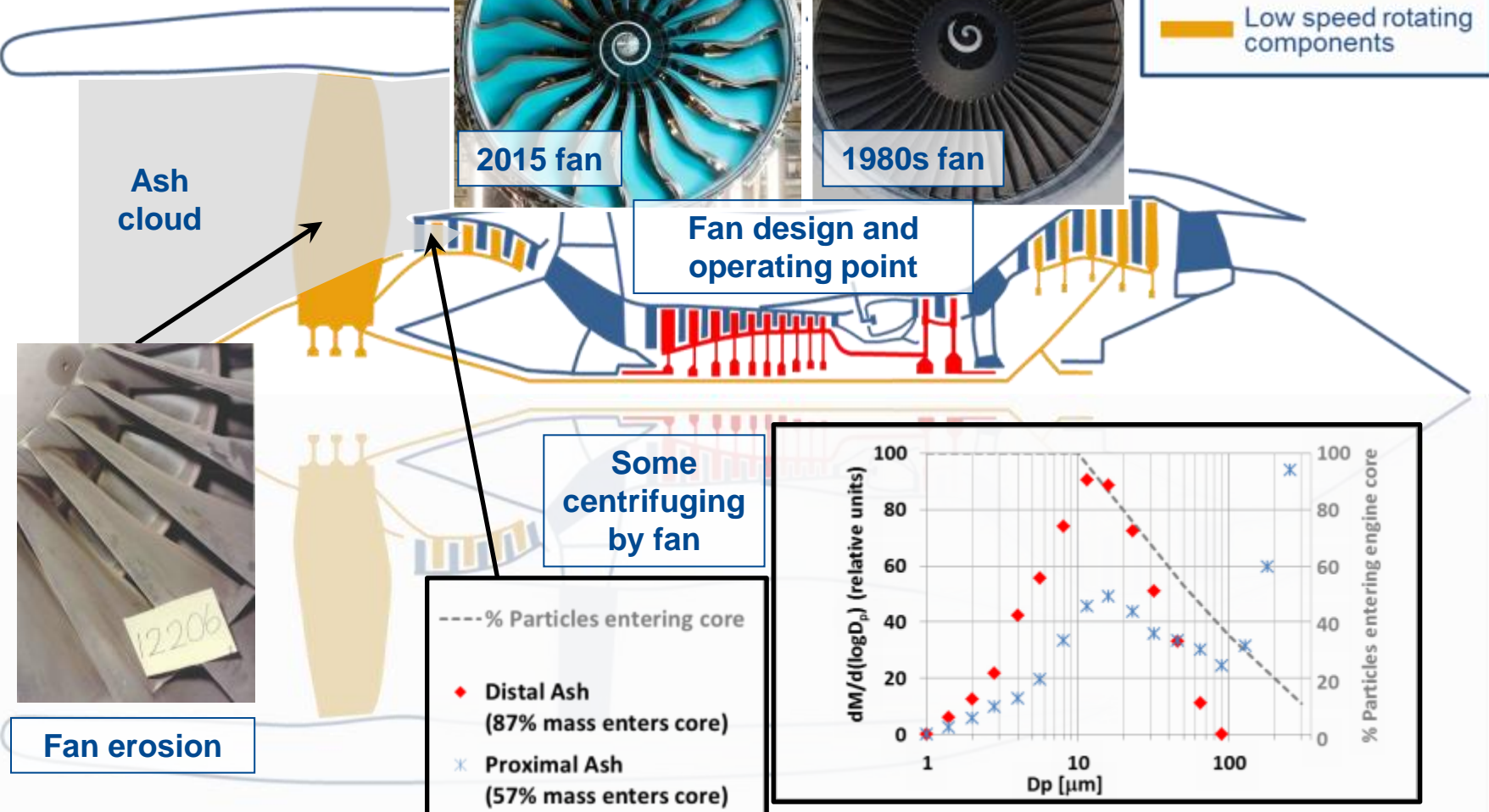
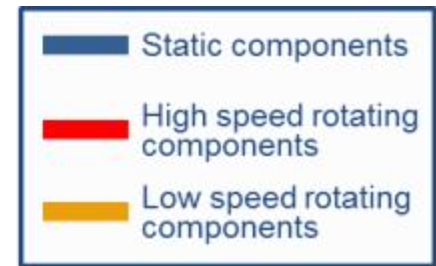
- Anatomy and physiology of a jet engine



Engine Damage Mechanisms

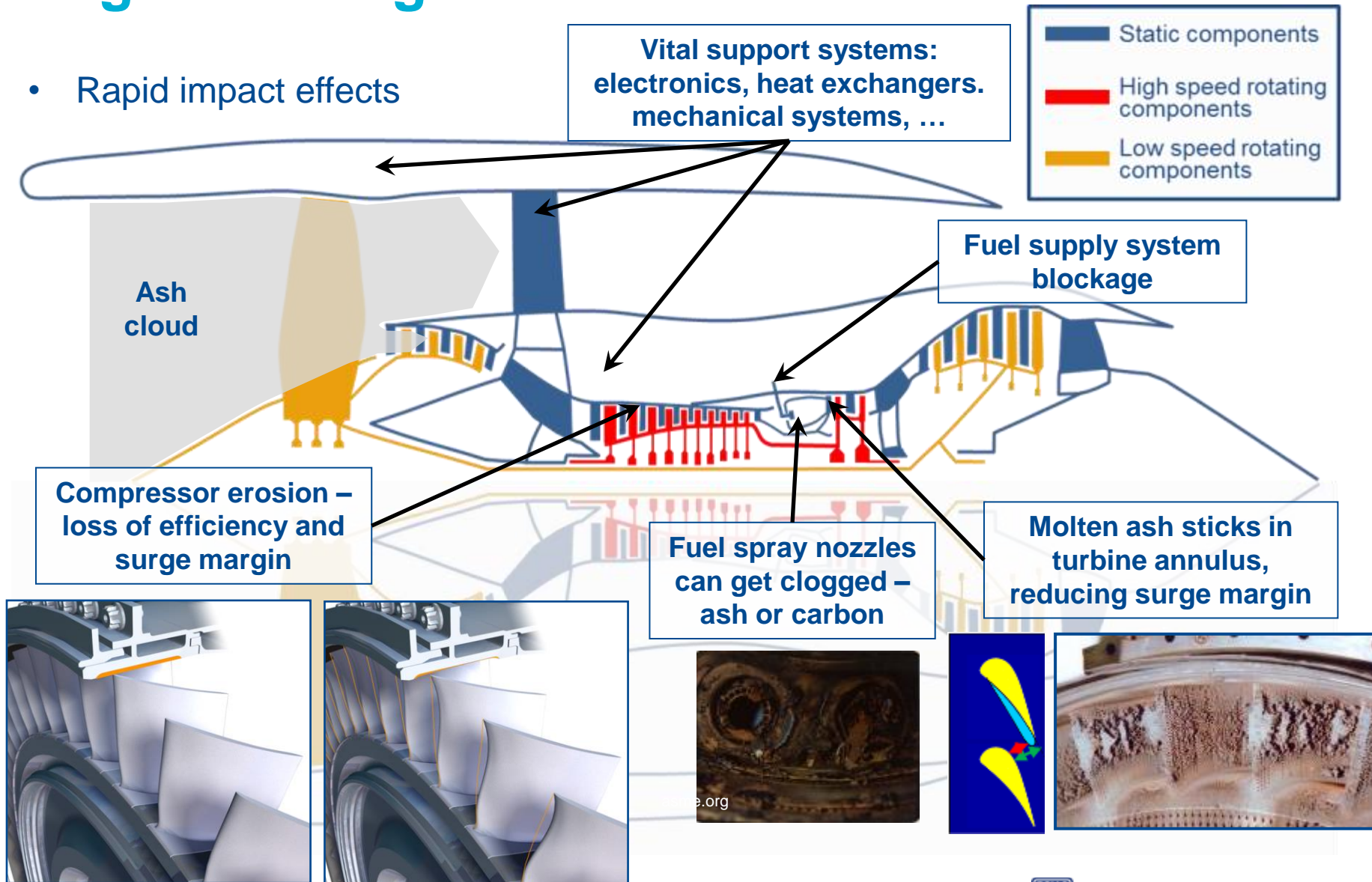
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- Fan effects



Engine Damage Mechanisms

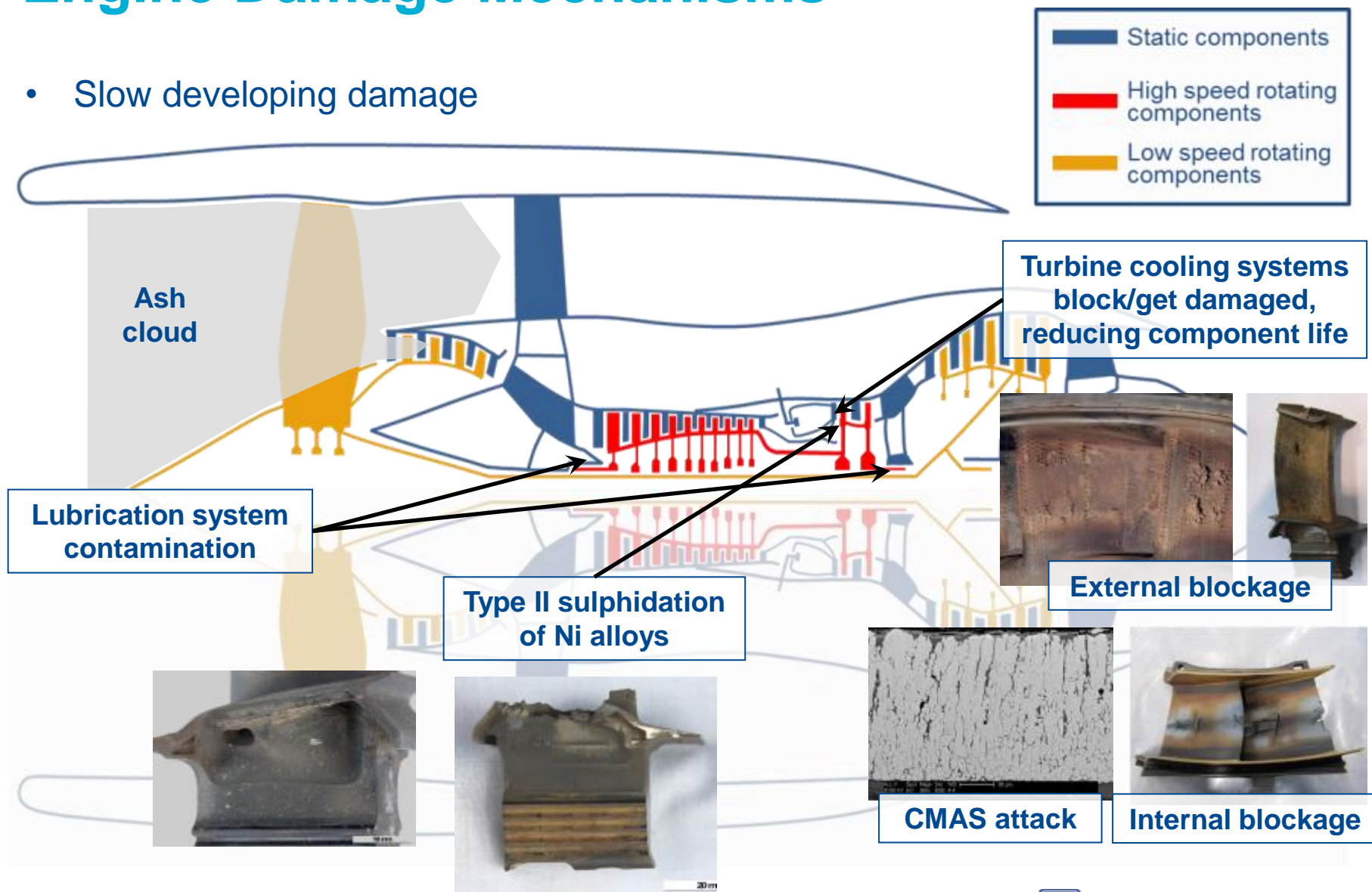
- Rapid impact effects



Engine Damage Mechanisms

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- Slow developing damage



But How Much Ash Can Engines Tolerate?

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- Up until 2010 engine quantitative susceptibility was poorly understood

- Eyjafjallajokull changed all that



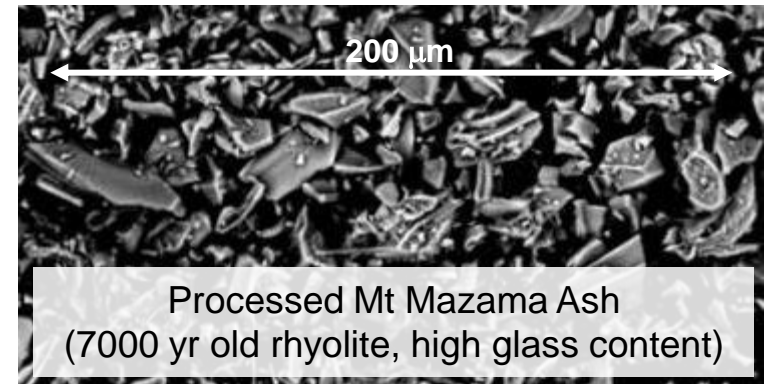
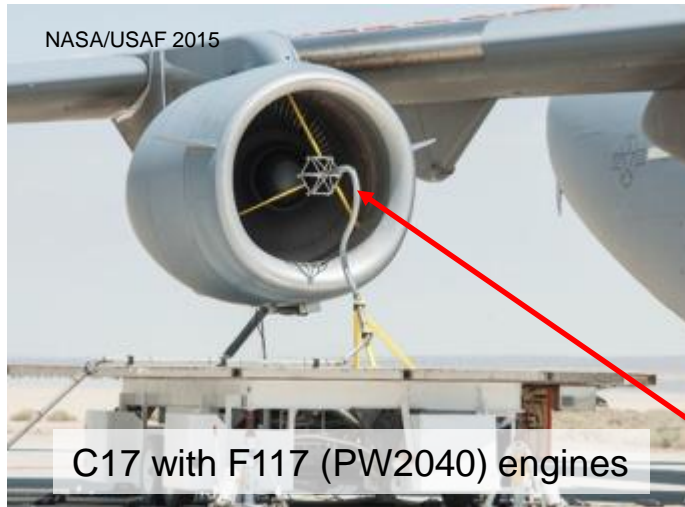
- Sources of data to understand more:

Actual Aircraft Encounters	Analogous Sand/Dust Experience	Laboratory Research	Engine Testing
1982 BA009, 1985 Soputan, 1989 KLM867, 2000 NASA DC-8, 2010 E15 experience, 2014 Kelut, 2014 Fogo, etc....	Desert operation - RR civil fleet, 2015 Doha sandstorm, Military experience in Iraq & Afghanistan, V-22 events, etc....	Calspan HSTS, NEWAC, VERTIGO & PROVIDA projects, University based sand/dust/coal ash research, Military research...	Calspan tests, GE tests, Military sand/dust testing, VIPR-III test.

- Plus attempts to understand fundamental scientific principles

VIPR-III July/August 2015

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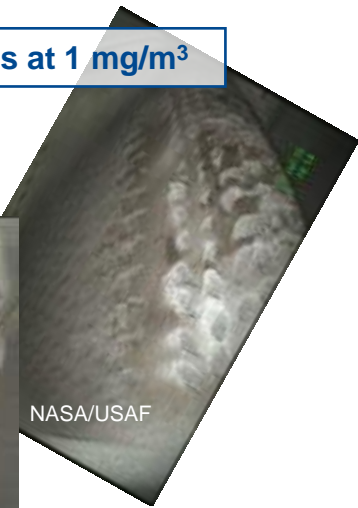


- Ash significantly more erosive than the sand previously used with rig
- 427 min at $\sim 1 \text{ mg/m}^3$
 - 3 runs on 3 separate days: 90 min, 68 min, 269 min
- 410 min at 10 mg/m^3 (175 min and 235 min runs)
 - Initial 3 hr run produced $\sim 5 \text{ K}$ rise in EGT, compressor erosion, significant deposit in HP NGVs
 - Additional 4 hr run, core temperatures continued to rise another $\sim 7 \text{ K}$

7 hrs at 1 mg/m^3

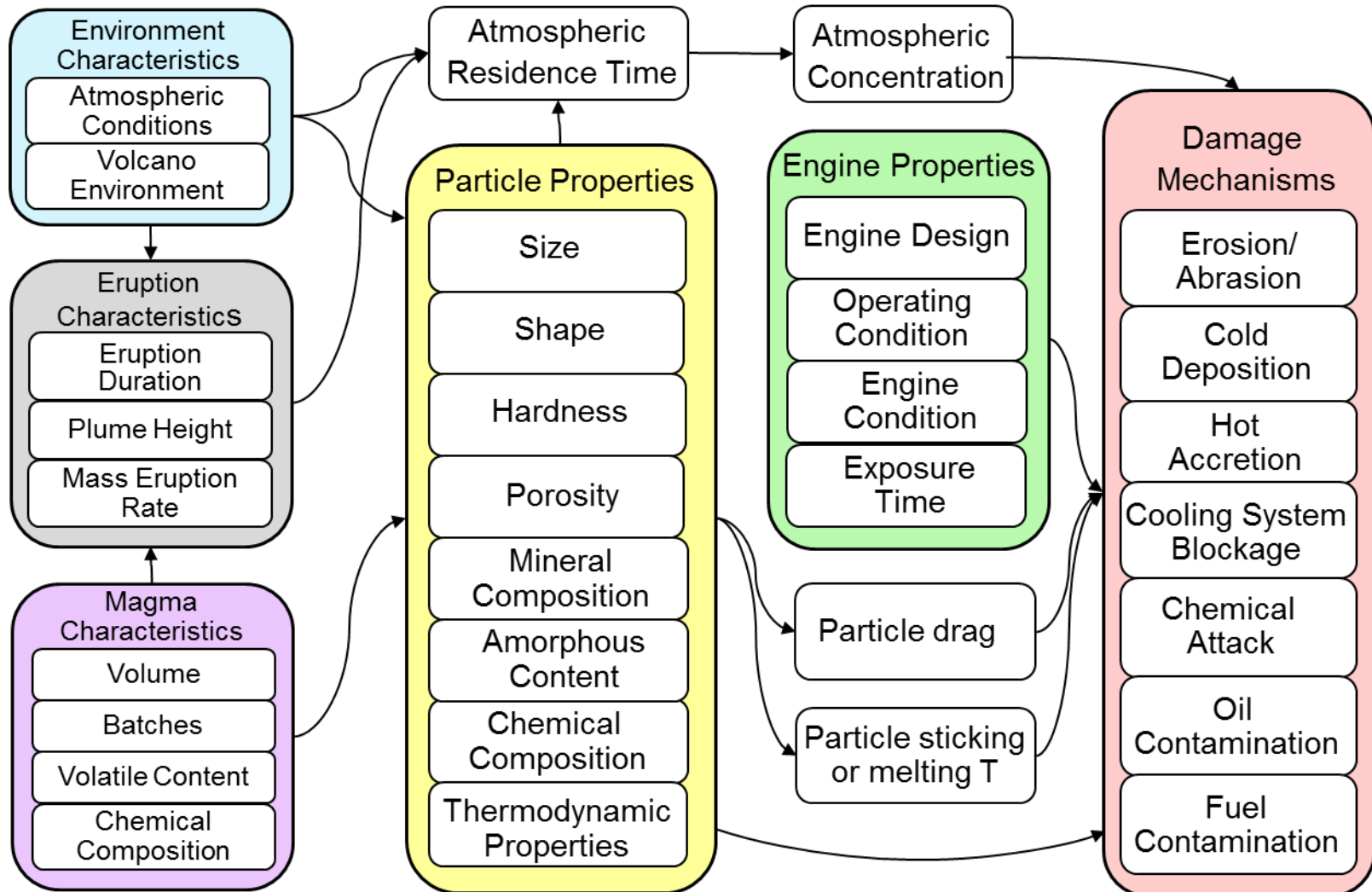


3 hrs at 10 mg/m^3



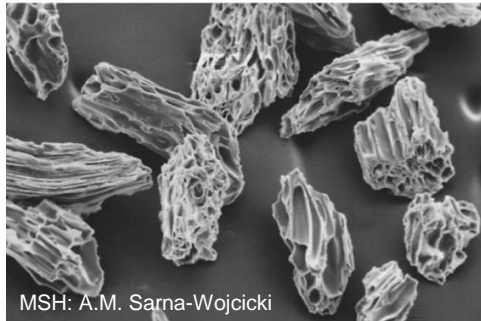
Fundamental Scientific Principles

- Factors that influence damage mechanisms...

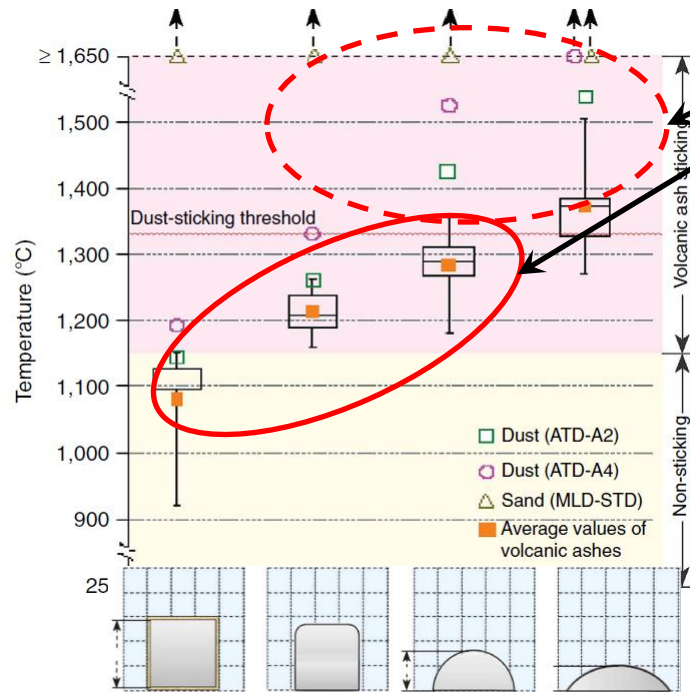


Sand, Dust and Ash – Similar Problems?

- Volcanic ash
 - Sharp crystals, lithics and glass



- Sand and dust
 - Weathered crystalline material



Data indicates range of accretion temperatures

- Compare test sands/dusts: 1350°C – >1600°C
- With extensive range of ash types: <1000°C – 1300°C



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 |

However USAF studies indicate that some dusts melt and stick within the range of temperatures for ash

Phelps, Krisak – AFRL, 2016



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Sand, Dust and Ash – Similar Problems?

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- Volcanic ash deposited on a turbine inlet guide vane



3-6 mins at
100-2000 mg/m³



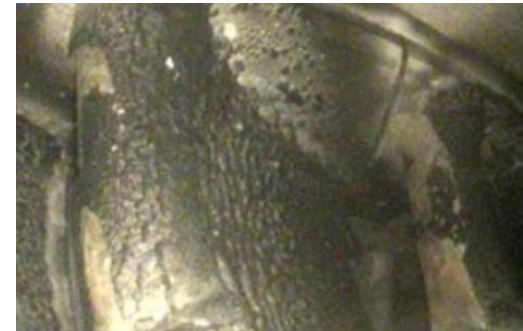
175 mins at
10 mg/m³



NASA/USAF 2015

427 mins at
~1 mg/m³

- Sand/dust deposited on a turbine inlet guide vane



1-2 mins at
1000-3000 mg/m³



~20 mins at
~4 mg/m³

Quantifying Damage

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- Three categories of damage:
- Flight safety implications – could result in loss of controllable thrust

e.g. Blocked fuel delivery system



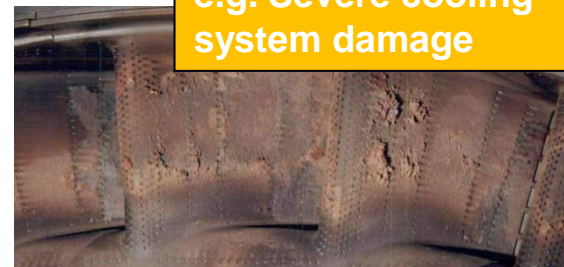
e.g. Molten ash sticks in turbine annulus, choking engine

- 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



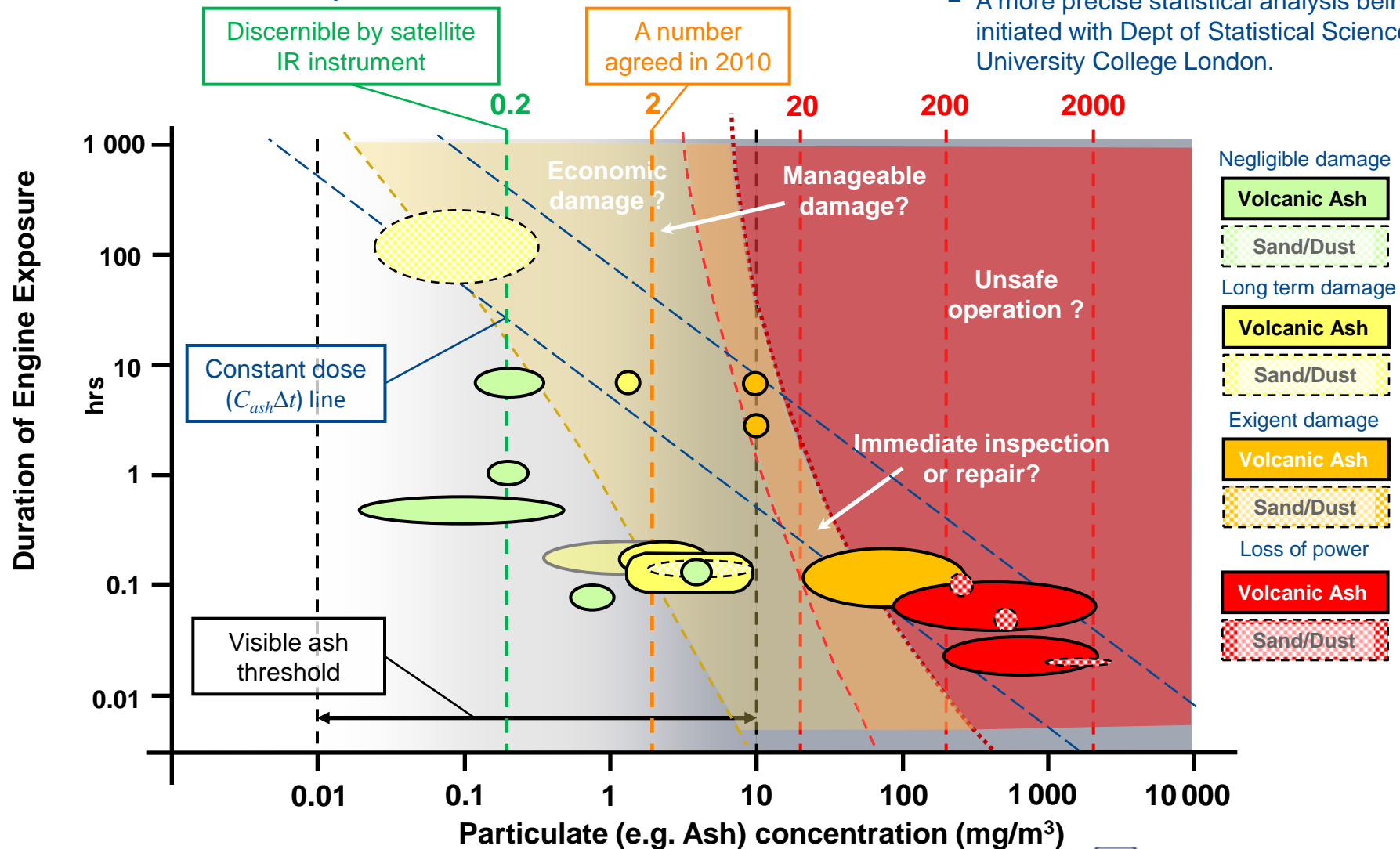
e.g. Ni alloy sulphidation



Quantifying Damage

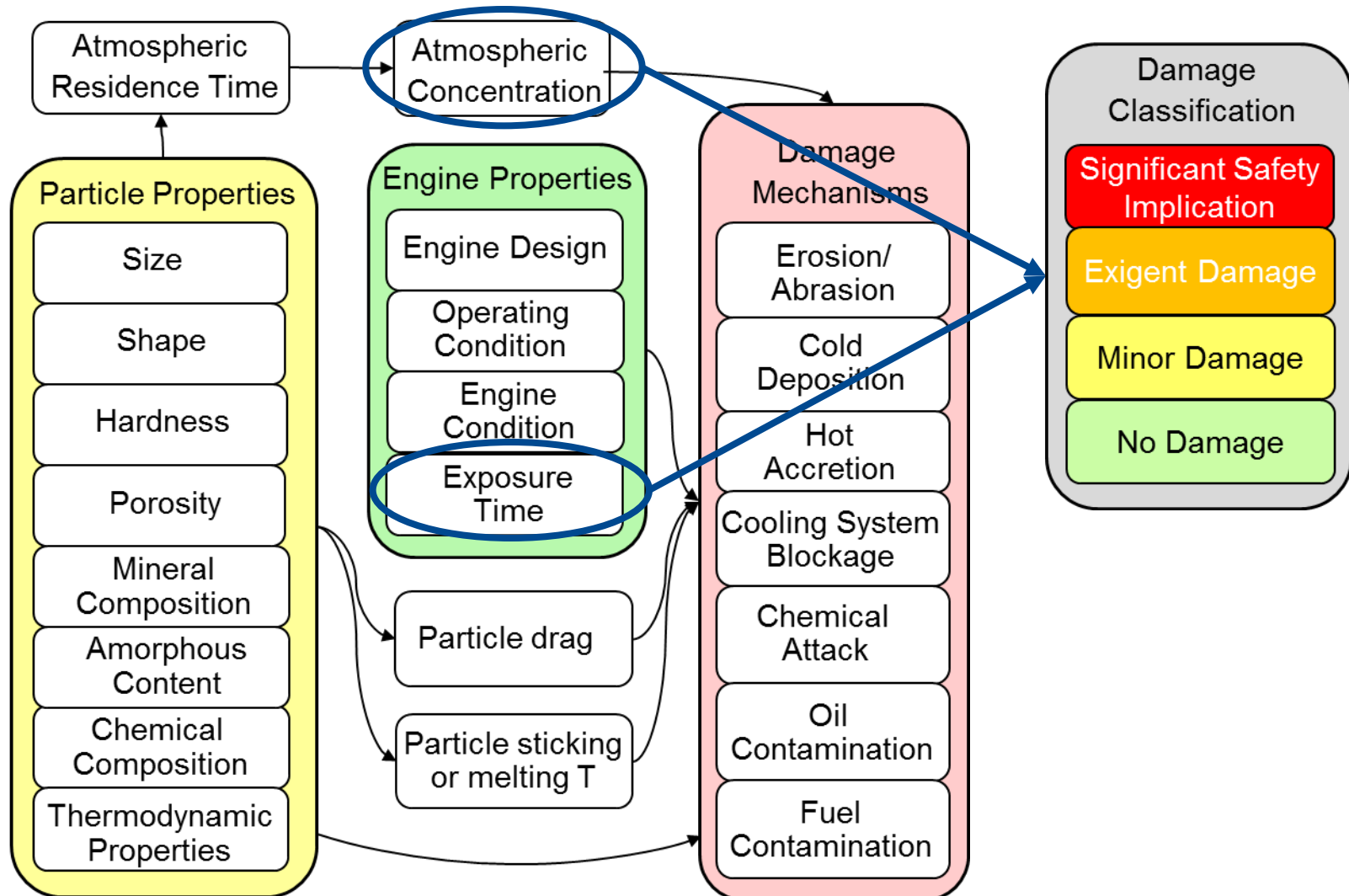
Duration of Exposure v Ash Concentration chart

- An engineer's curve drawing exercise
- A more precise statistical analysis being initiated with Dept of Statistical Science, University College London.



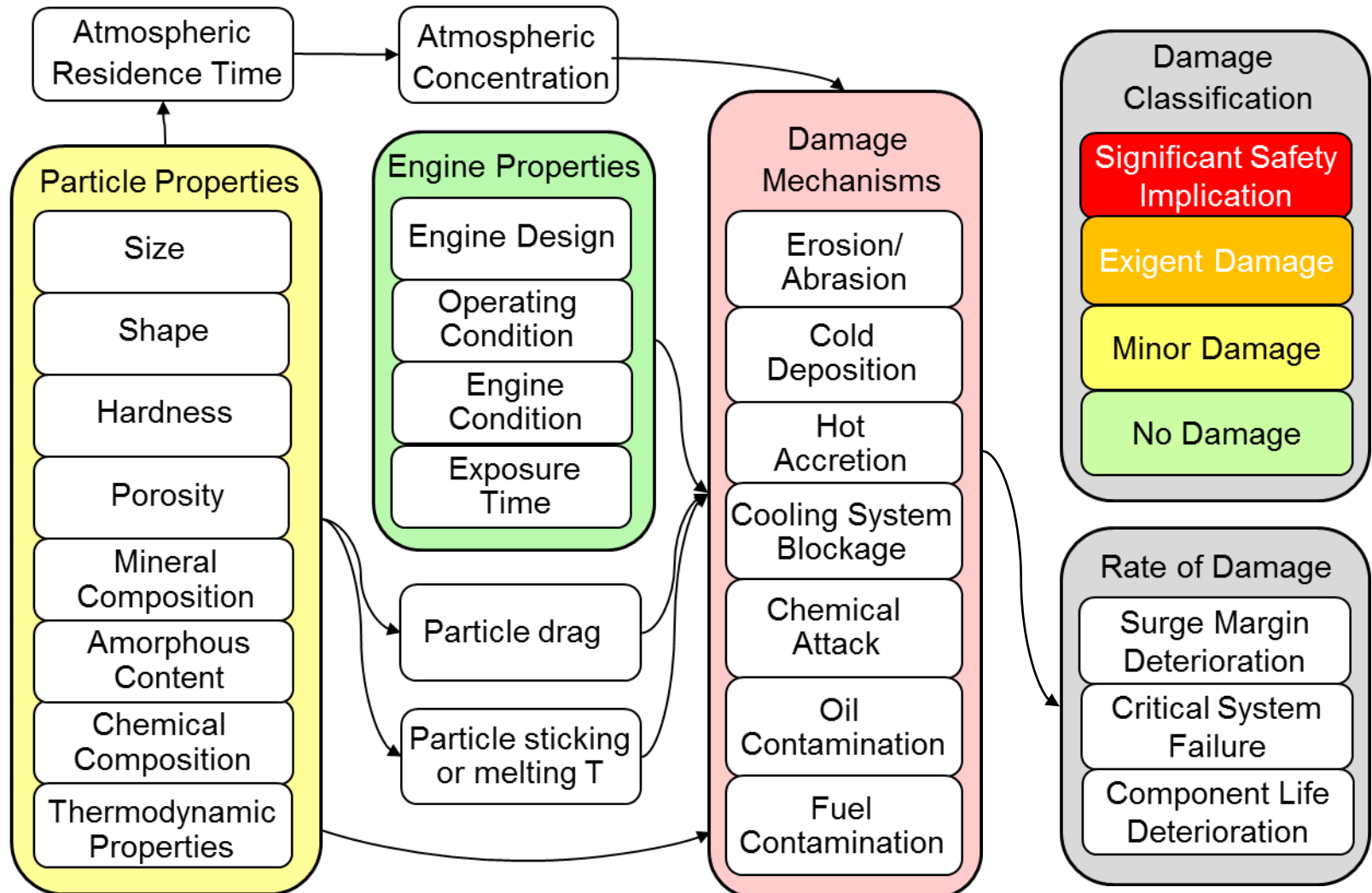
Quantifying Damage

- DEvAC chart really only gives an indication of the damage classification...



Quantifying Damage

- Many operators, civil and military, will need to know more...



Quantifying Damage

- EASA Regulations 2013-2015
- CS-E Amendment 4 (March 2015) – CS-E 1050



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

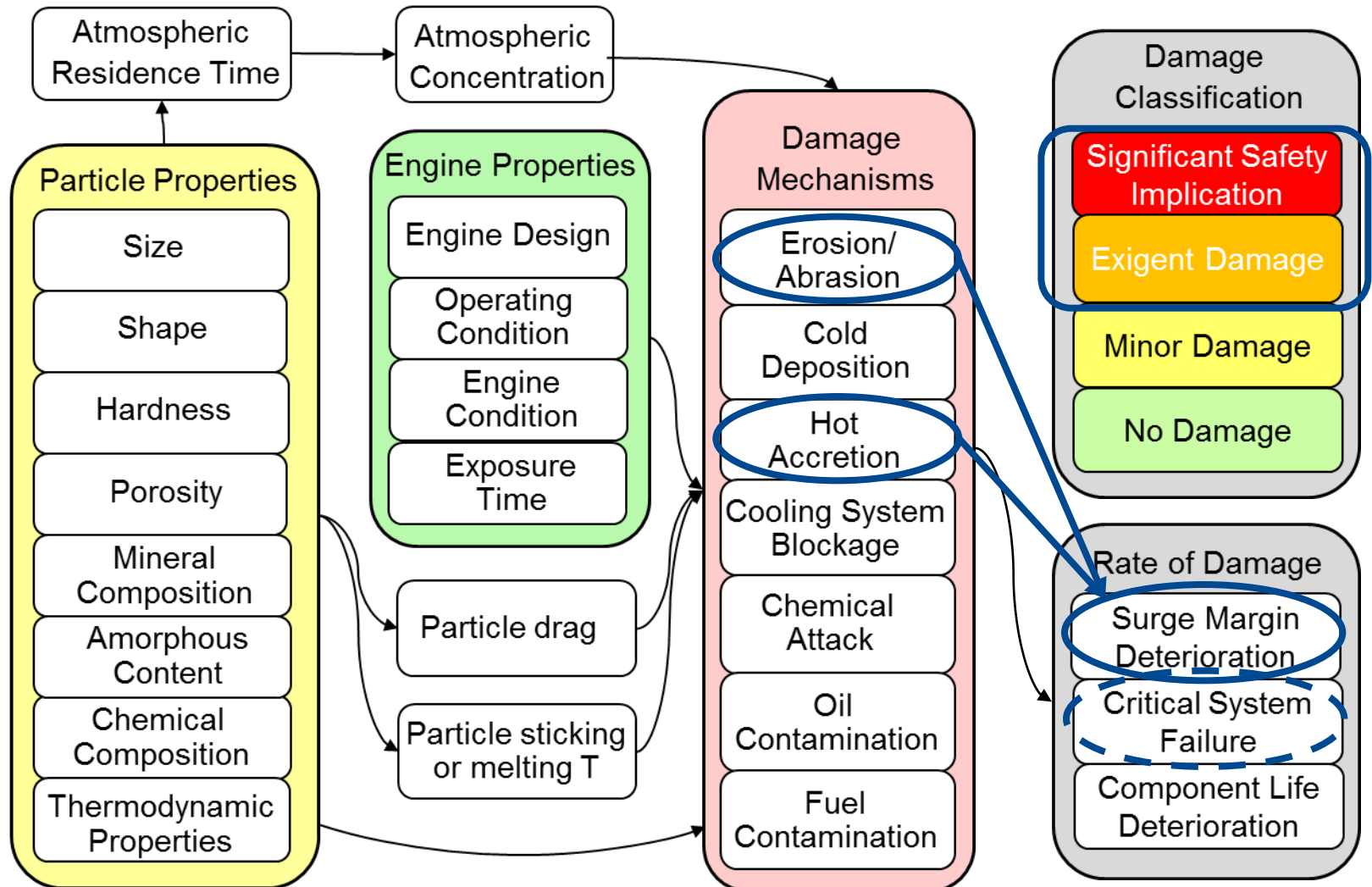
- (a) The susceptibility of turbine Engine features to the effects of volcanic cloud hazards must be established.
- (b) Information necessary for safe operation must be provided in the relevant documentation.

- Oct 2014 – EASA guidance on CS-25 1593 and CS-E 1050

- ☐ Purpose is to provide data to support operators' SRAs
 - Still apply principle: *"Volcanic ash encounters shall be avoided (do not operate in visible + discernable ash)"*
 - Operators need to know susceptibility to volcanic ash to understand operational risk
- ☐ Requires manufacturers to investigate and understand the hazards associated with exposure to the harmful effects of volcanic clouds
- ☐ A statement to avoid visible or discernible ash is not acceptable for compliance – such a statement is an operational recommendation not a susceptibility
- ☐ Engine testing required if susceptibility declared to be between 4 mg/m³ to 1000 mg/m³
 - No need to test if susceptibility set at <4 mg/m³ (and presumably >1000 mg/m³ 😊)
- ☐ Applies to new and changed products

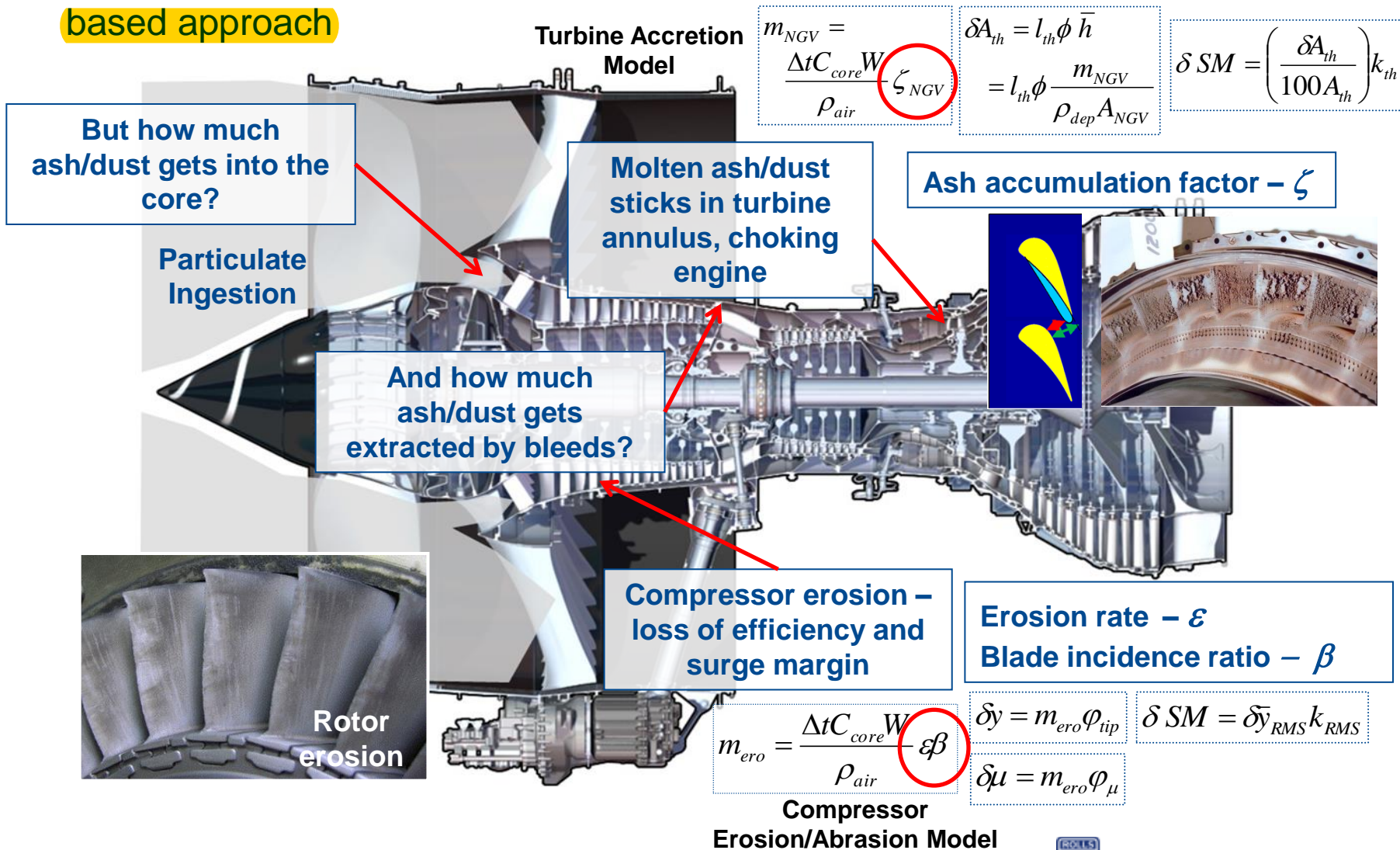
Quantifying Damage

- Complying with EASA regulations – CS-E 1050



Quantifying Damage

- How long does it take to surge an engine – simple engineering correlation based approach



Fan Effects, Abrasion and Hot Accretion

- Since 2011 - A cottage industry approach, using small amounts of money...

Fan Effects



EC funded PhD
study 2014-2017

Abrasion/Erosion

Substantial existing data
from sand/dust studies



Some NEWAC studies
2010-2011

No new studies since
2011, just evidence from
VIPR-III

Hot Accretion



Small laboratory scale rigs using some industry money,
but mainly research grants or university funds

- What have these studies shown?
- Ash accumulation factor (ζ) tends to increase with:
 - Increasing gas and surface temperature
 - Larger particle sizes
 - Greater proportion of non-silica components
 - Greater impingement angle
 - The amount of material already deposited
 - Increasing concentration (i.e. same total mass over shorter time periods)

Hot Accretion

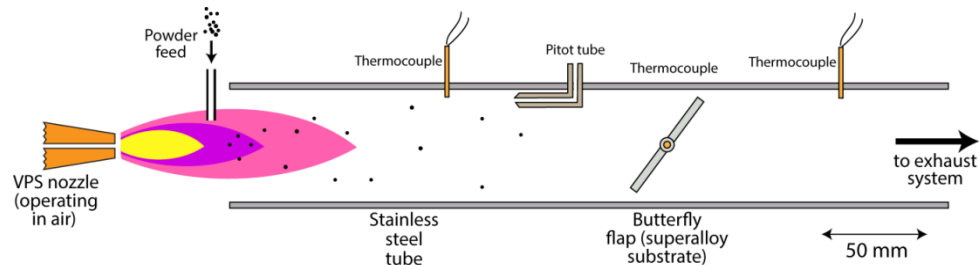
A PROVIDA Study



UNIVERSITY OF
CAMBRIDGE

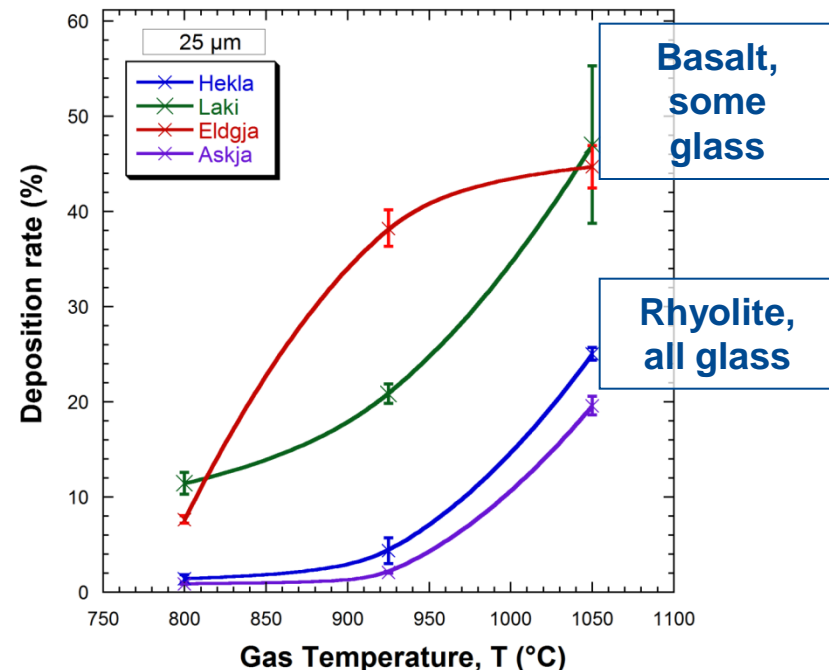
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- University of Cambridge
 - J. Dean, C. Taltavull, P. Earp & T. W. Clyne



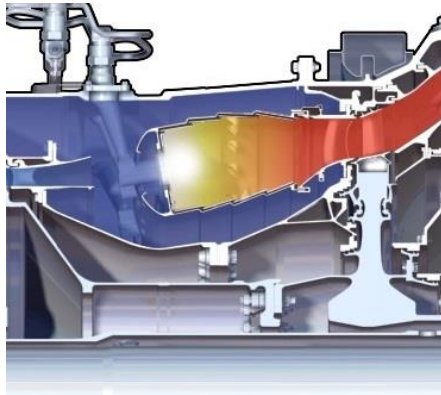
- Deposition rates:

Ash Sample	Type	% Glass
Hekla	Rhyolite	100
Laki	Basalt	70
Eldgja	Basalt	23
Askja	Rhyolite	100



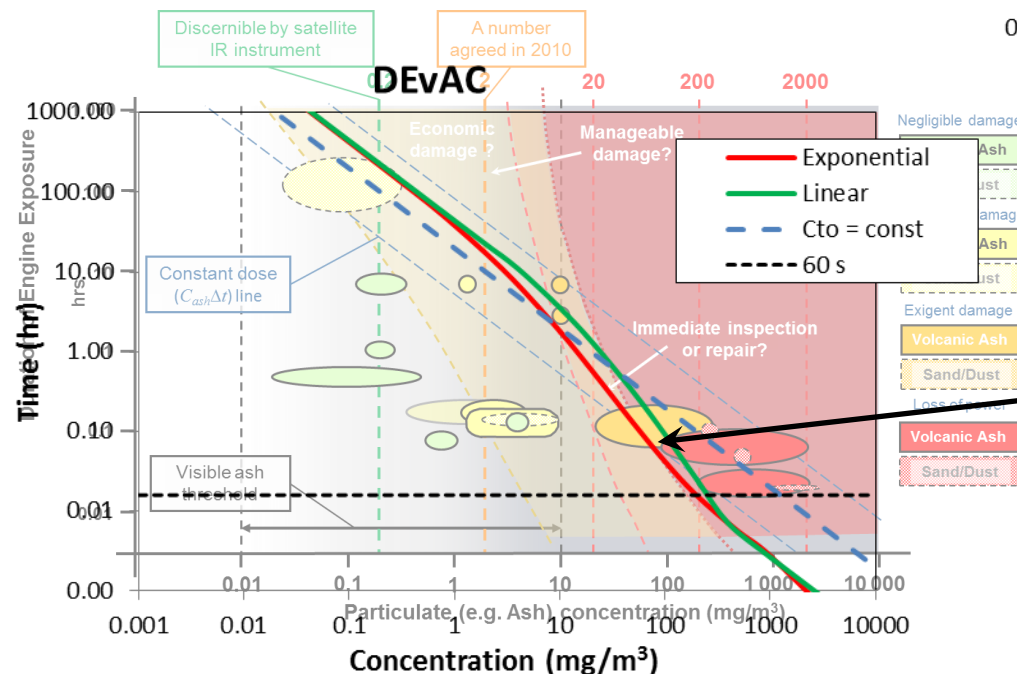
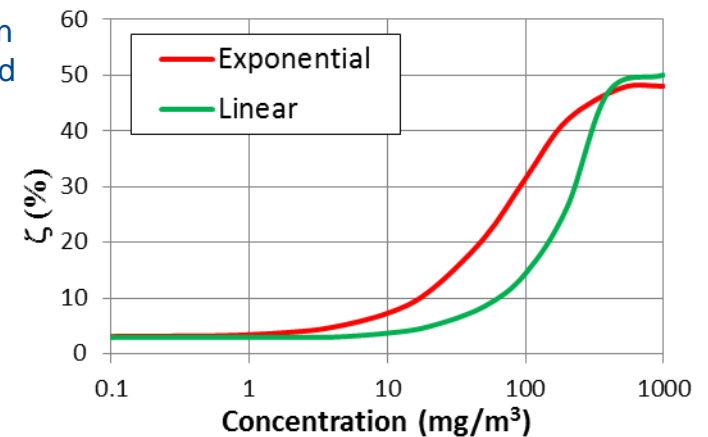
Hot Accretion

- Effect of $\zeta = f(C_{ash})$ on rate of turbine accretion



- Study looking at aggregation in the combustor is being initiated between a group from the VERTIGO Partners:
University of Geneva
LMU Munich
University of Oslo
Rolls-Royce UK

Accumulation Factor (ζ)



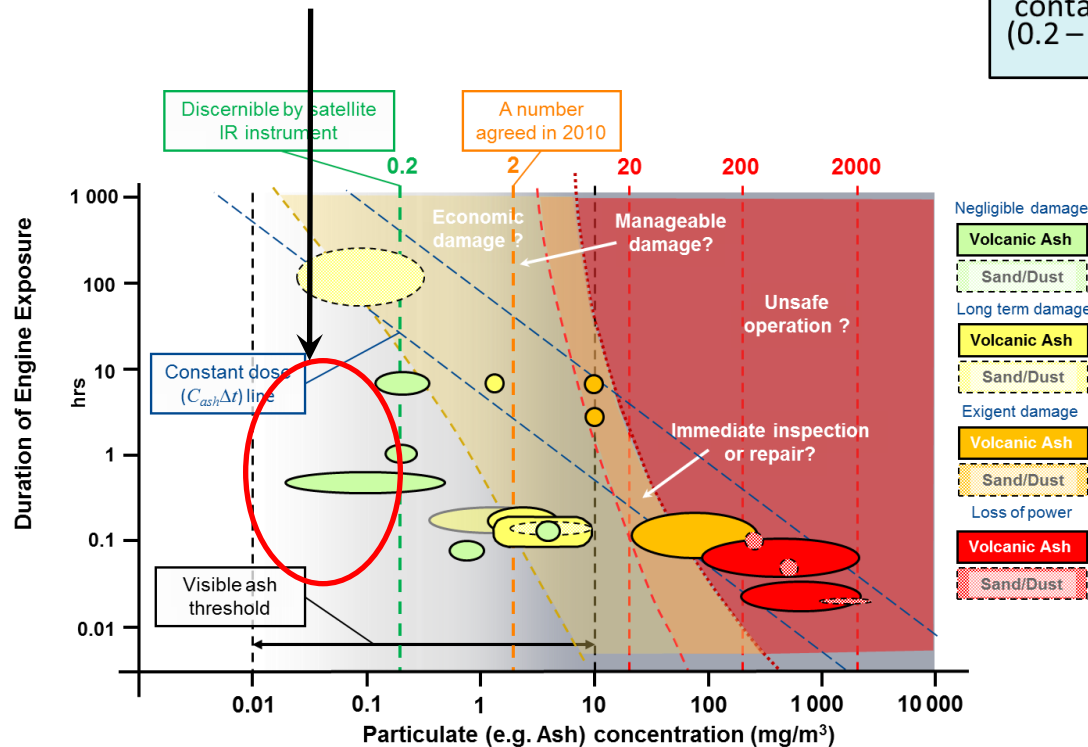
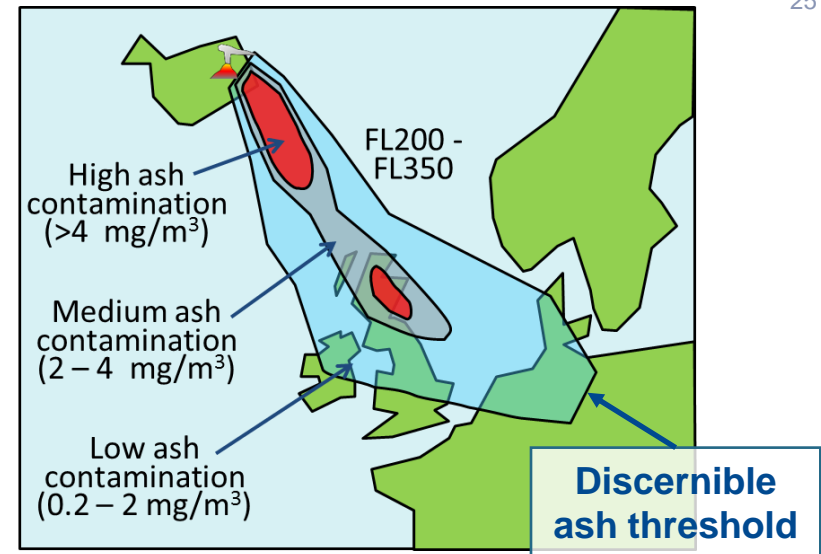
Possible explanation for non-linear behaviour: particle aggregation in combustor

Conclusions (1)

- Since 2010 a substantial improvement in our understanding of engine damage from volcanic ash has been achieved
- But there are still substantial gaps in the knowledge
- Should we be trying to fill the gaps?
- Does the benefit to aviation justify the cost?
- Is there an operational and cost benefit from knowing more?

Conclusions (2)

- Hypothetical scenario from 2010-2015:
- But EASA has adopted the principle of simply avoiding discernible and visible ash



- Is there any incentive to understand engine and airframe susceptibility at concentrations $>0.2 \text{ mg/m}^3$?
- Are concentration charts still relevant?