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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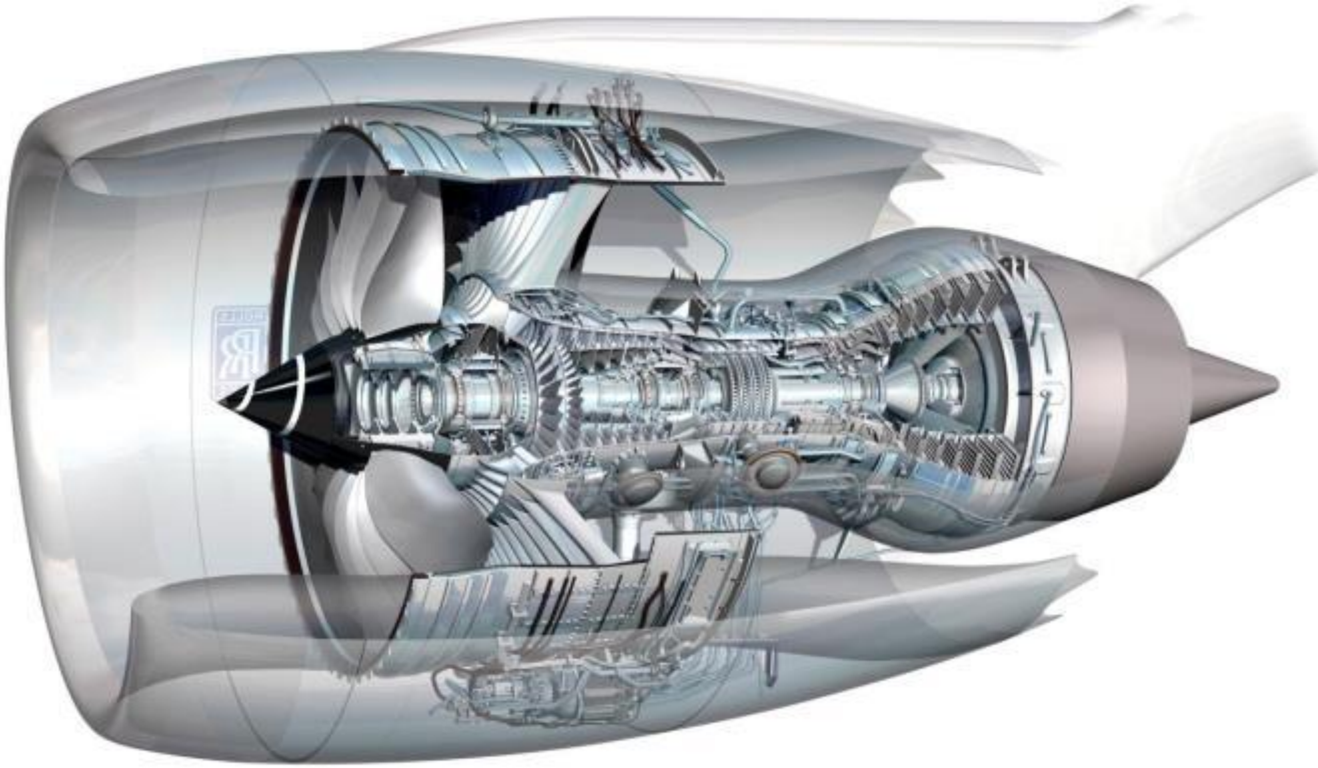
Introduction

- 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

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

- 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

1970

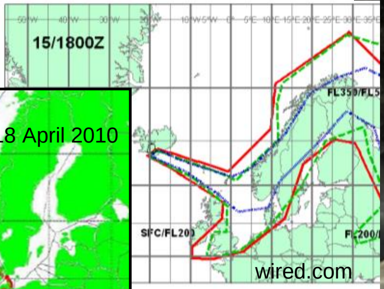
1980

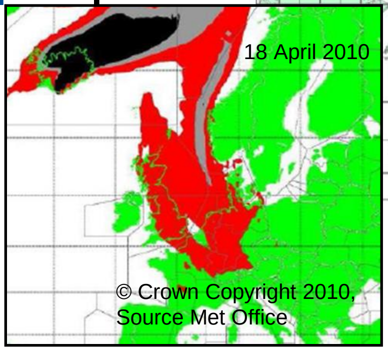
1990

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 eruption





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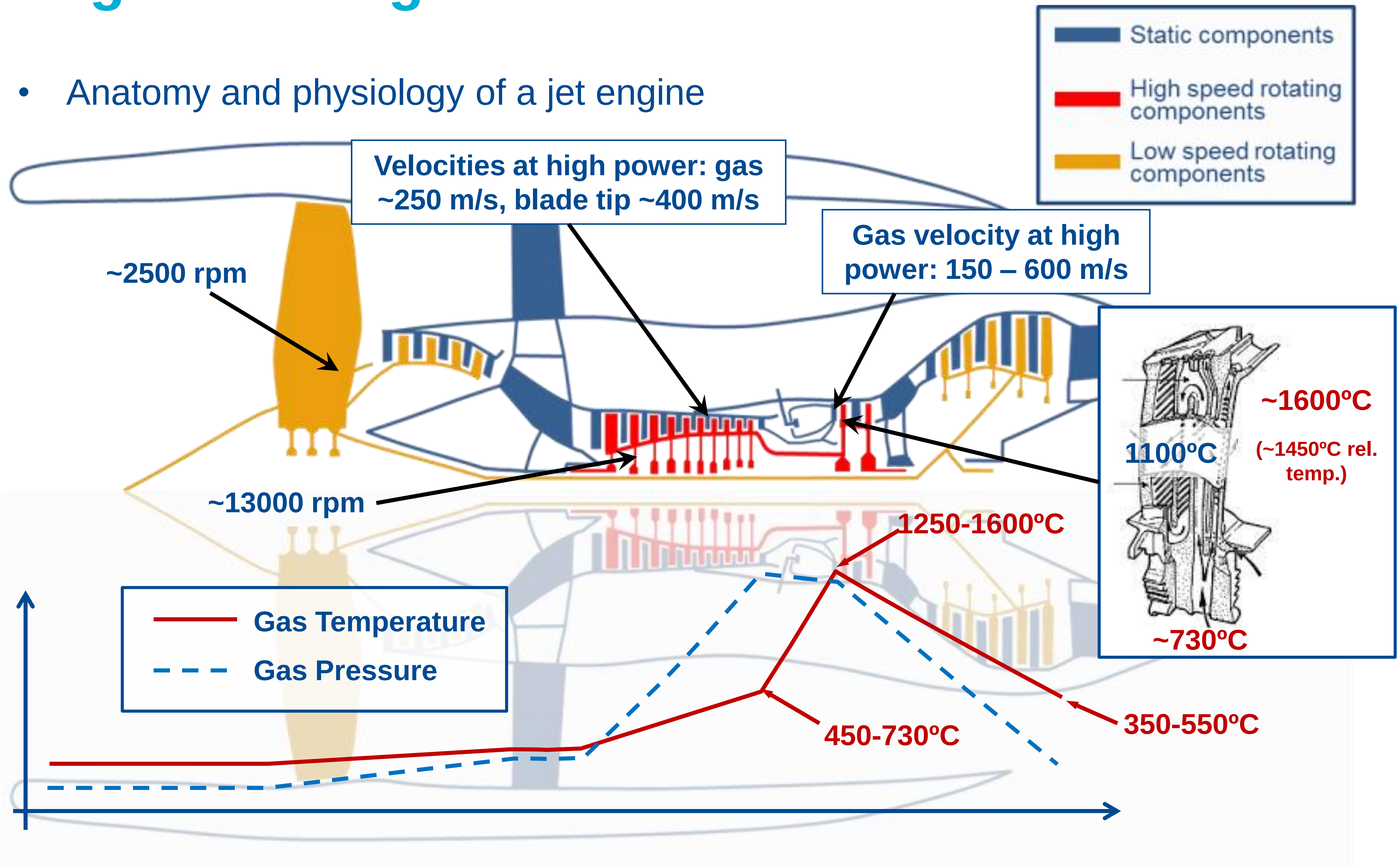
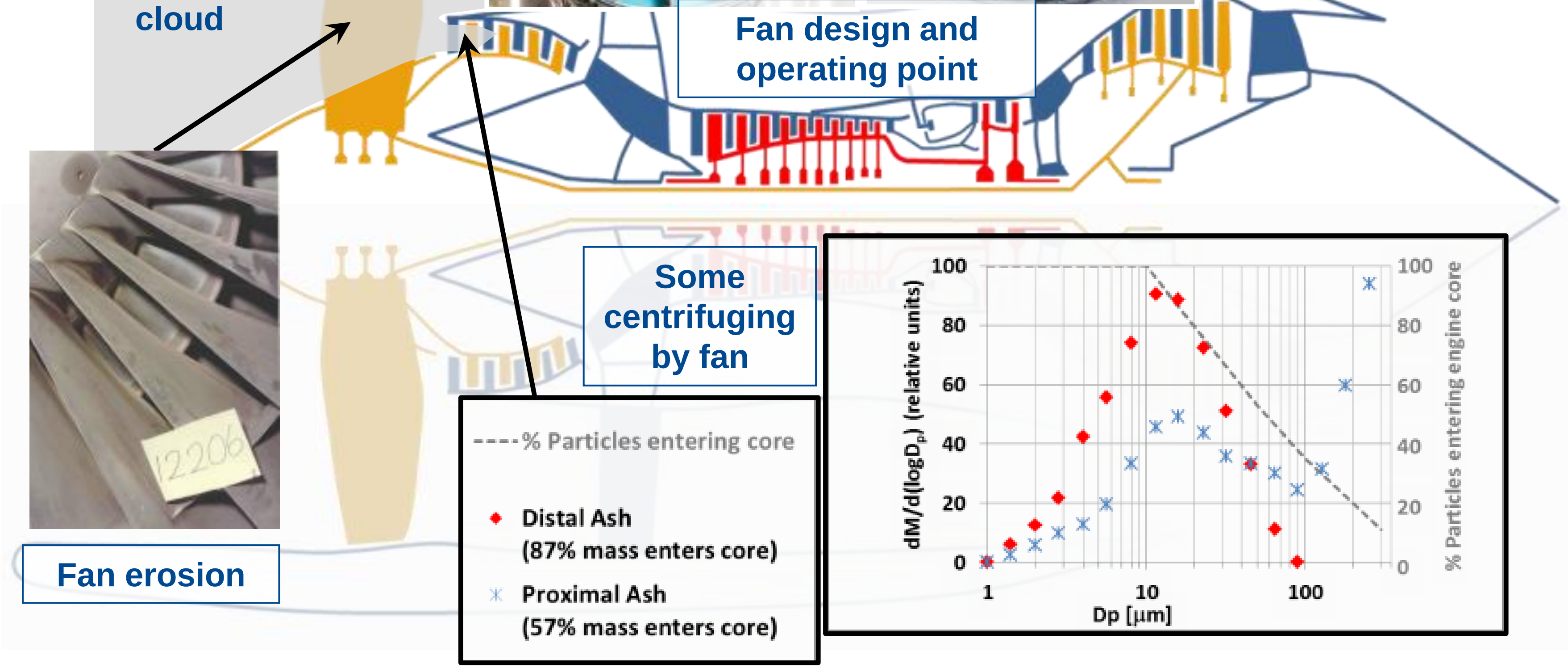
Engine Damage Mechanisms

- Anatomy and physiology of a jet engine



Engine Damage Mechanisms

- Fan effects



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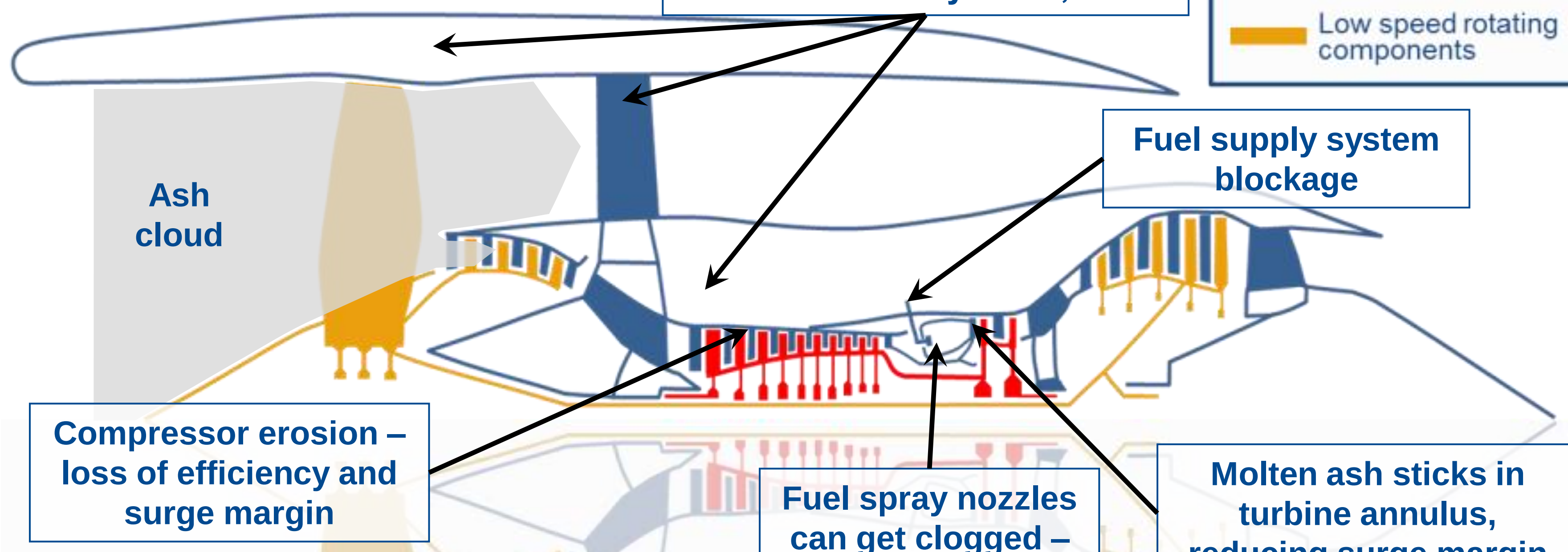
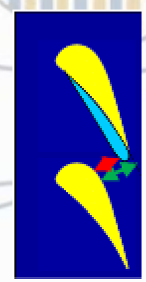
Engine Damage Mechanisms

- Rapid impact effects





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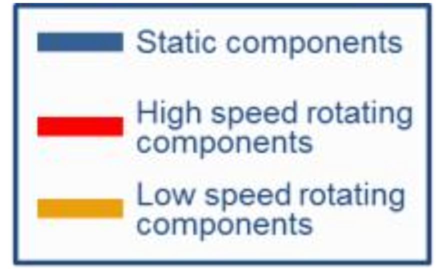
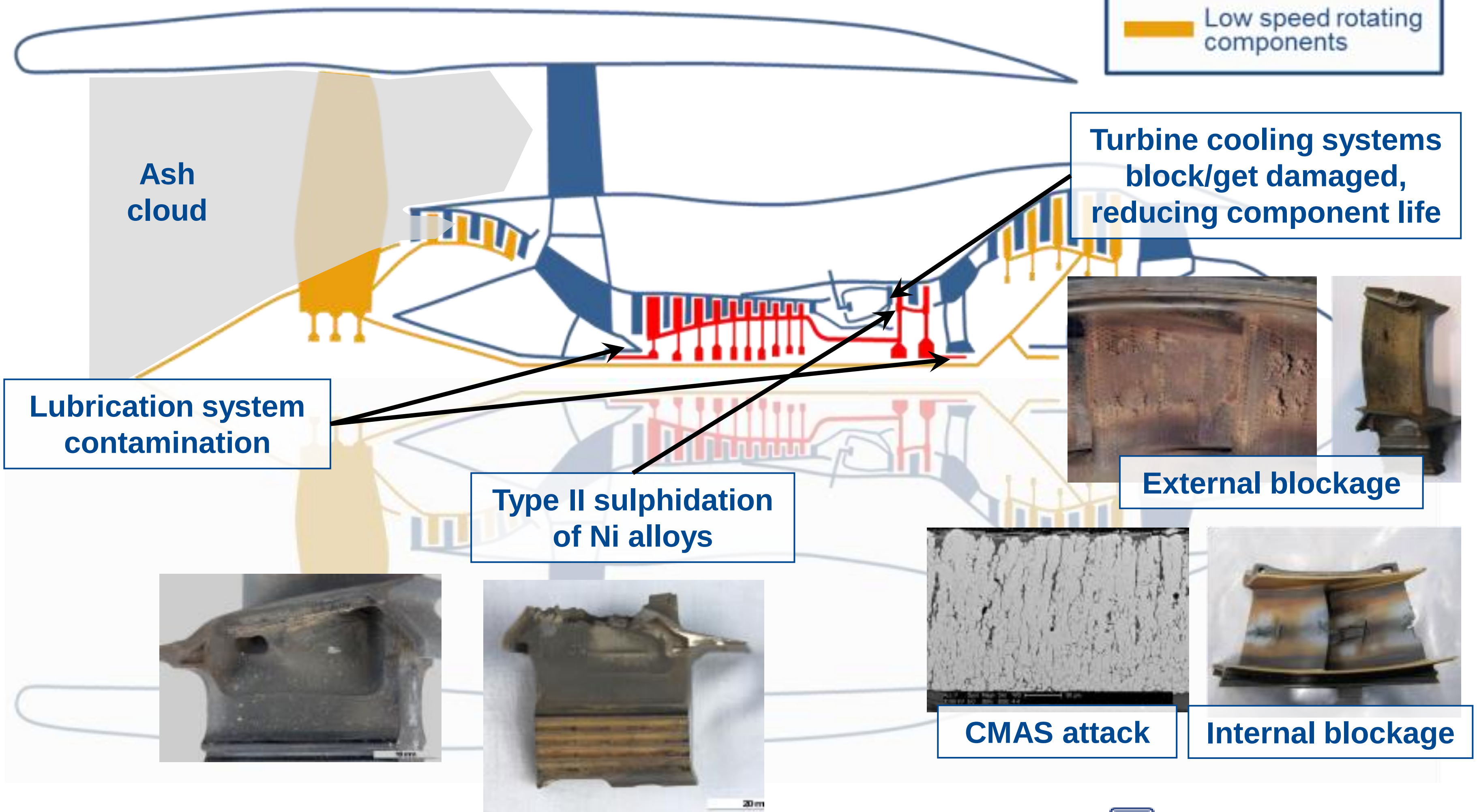
Engine Damage Mechanisms

- Slow developing damage





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But How Much Ash Can Engines Tolerate?

- 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 rsearch, Military research…	Calspan tests, GE tests, Military sand/dust testing, VIPR-III test.

- Plus attempts to understand fundamental scientific principles

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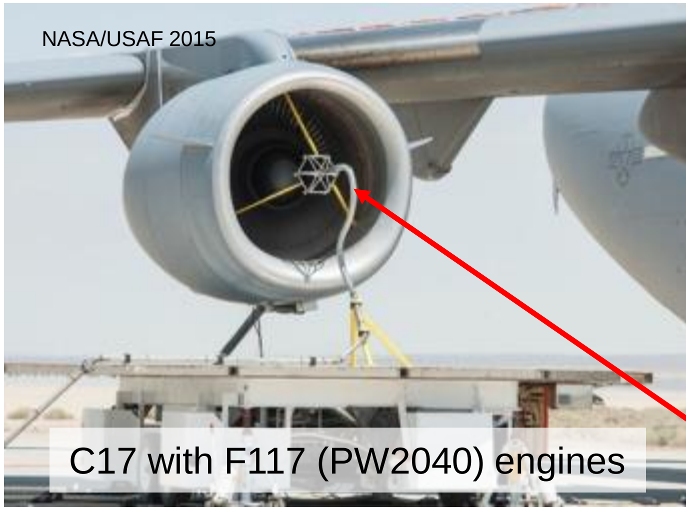
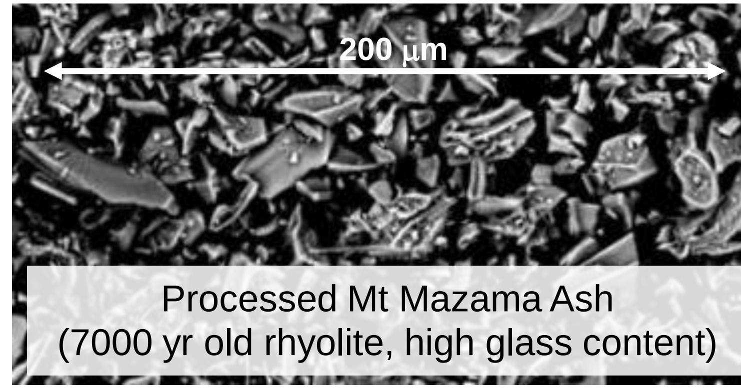
VIPR-III July/August 2015



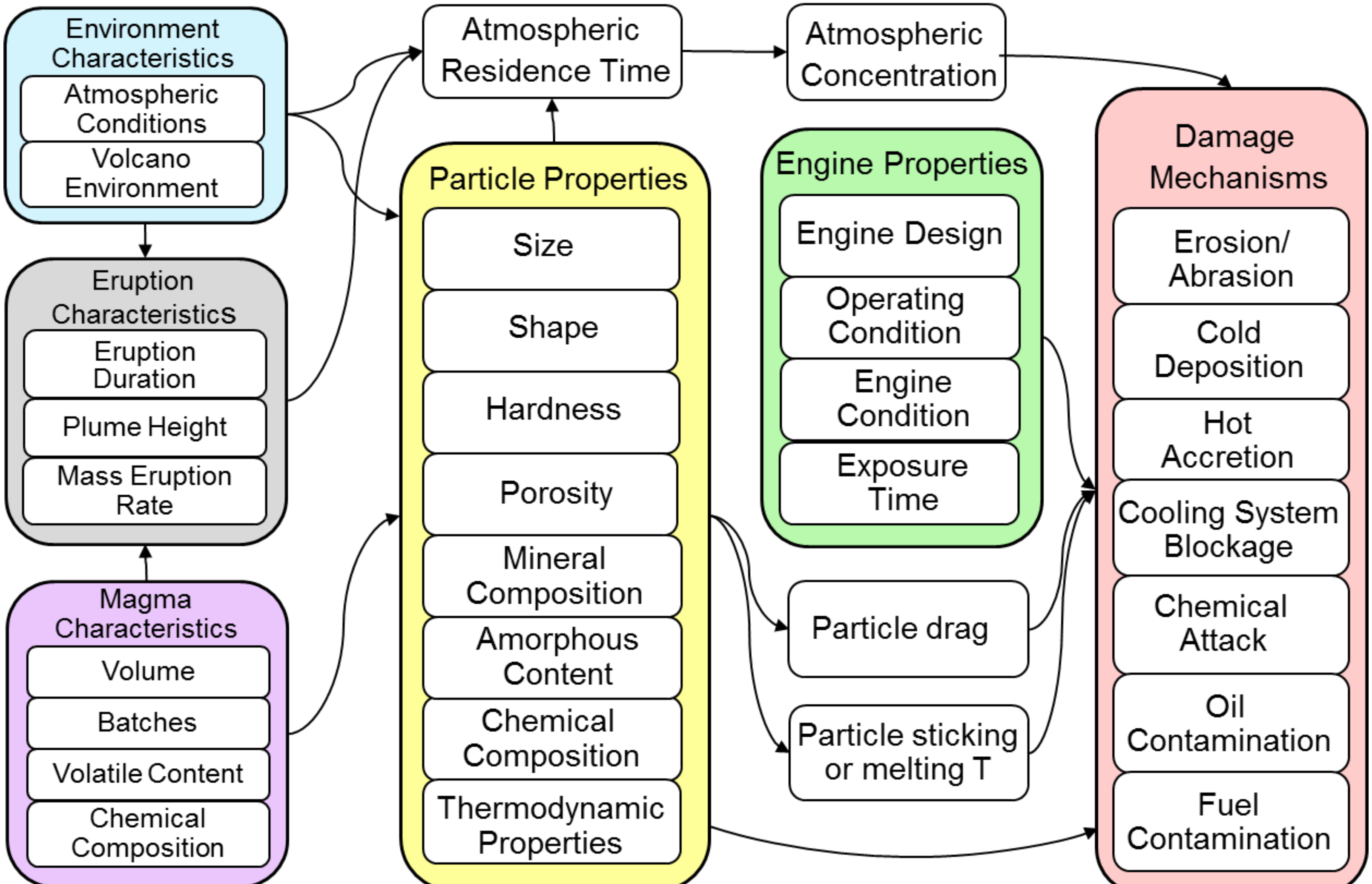


- Ash significantly more erosive than the sand previously used with rig

- 427 min at ~1 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 ~5 K rise in EGT, compressor erosion, significant deposit in HP NGVs
  - Additional 4 hr run, core temperatures continued to rise another ~7 K

Fundamental Scientific Principles

- Factors that influence damage mechanisms…



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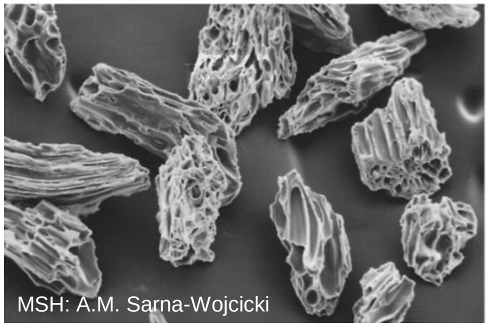
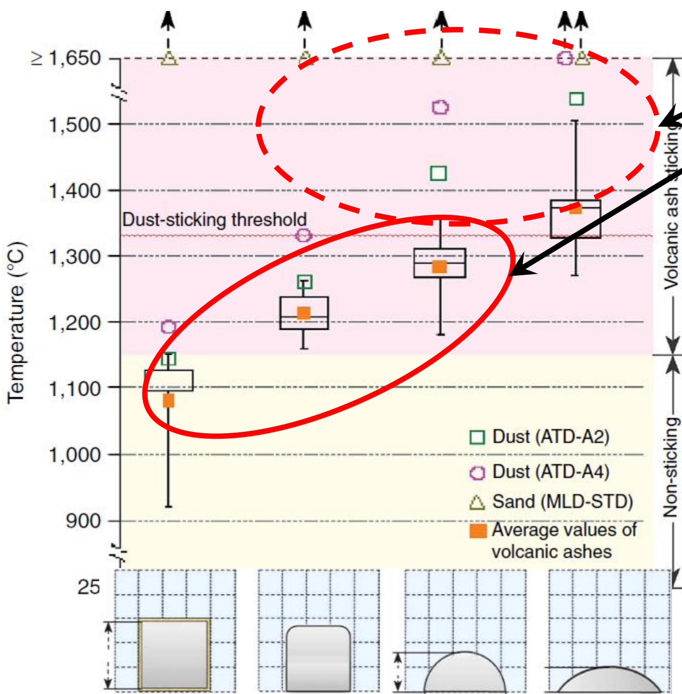
Sand, Dust and Ash – Similar Problems?

- Volcanic ash
  - Sharp crystals, lithics and glass



- Sand and dust
  - Weathered crystalline material



Data indicates range of accretion temperatures
- Compare test sands/dusts: 1350ºC – >1600ºC
- With extensive range of ash types: <1000ºC – 1300ºC

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

Song et al. – LMU Munich 2016

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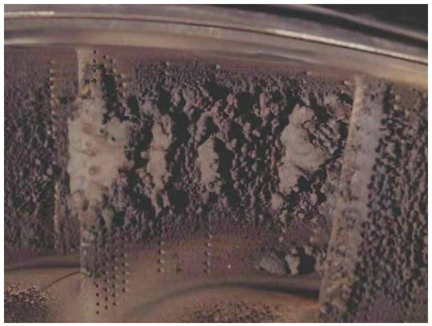
Sand, Dust and Ash – Similar Problems?

- Volcanic ash deposited on a turbine inlet guide vane

175 mins at 10 mg/m³

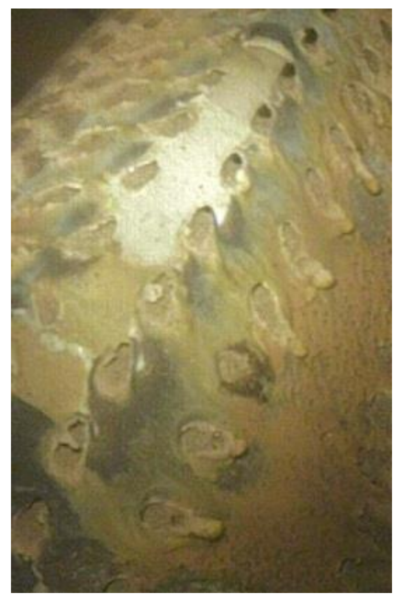


3-6 mins at 100-2000 mg/m³

427 mins at ~1 mg/m³

- Sand/dust deposited on a turbine inlet guide vane

1-2 mins at 1000-3000 mg/m³

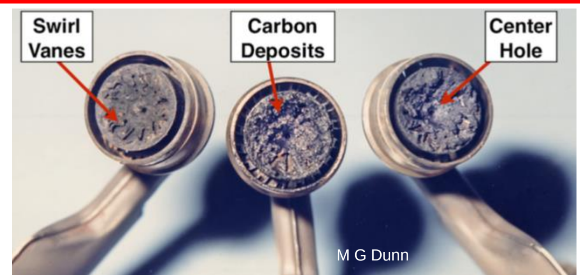


~20 mins at ~4 mg/m³

Quantifying Damage

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

e.g. Blocked fuel delivery system

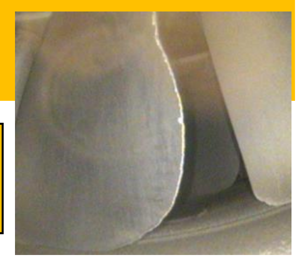


e.g. Molten ash sticks in turbine annulus, choking engine

- Exigent damage – immediate maintenance action required

e.g. Severe 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

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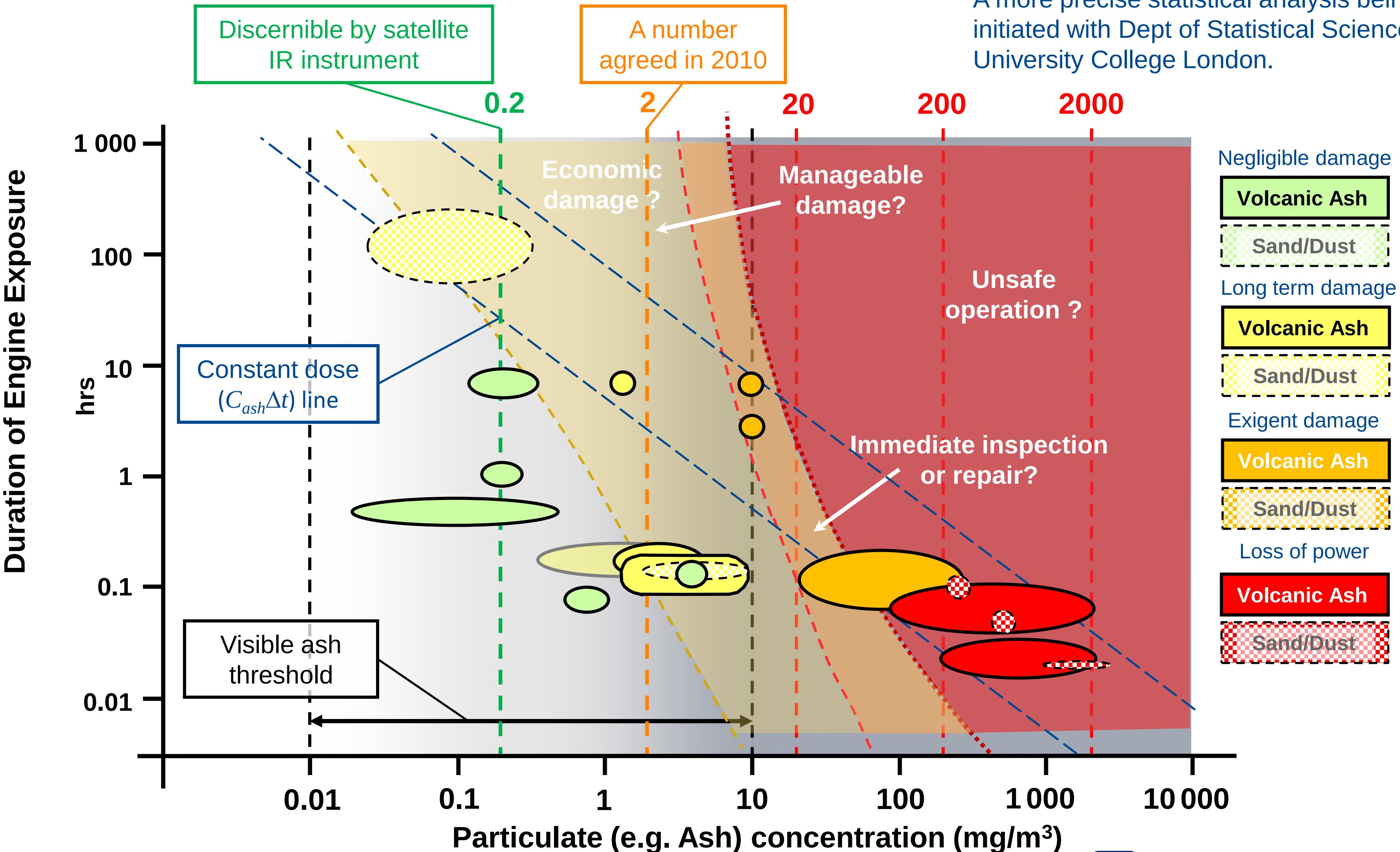
Quantifying Damage

- 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.



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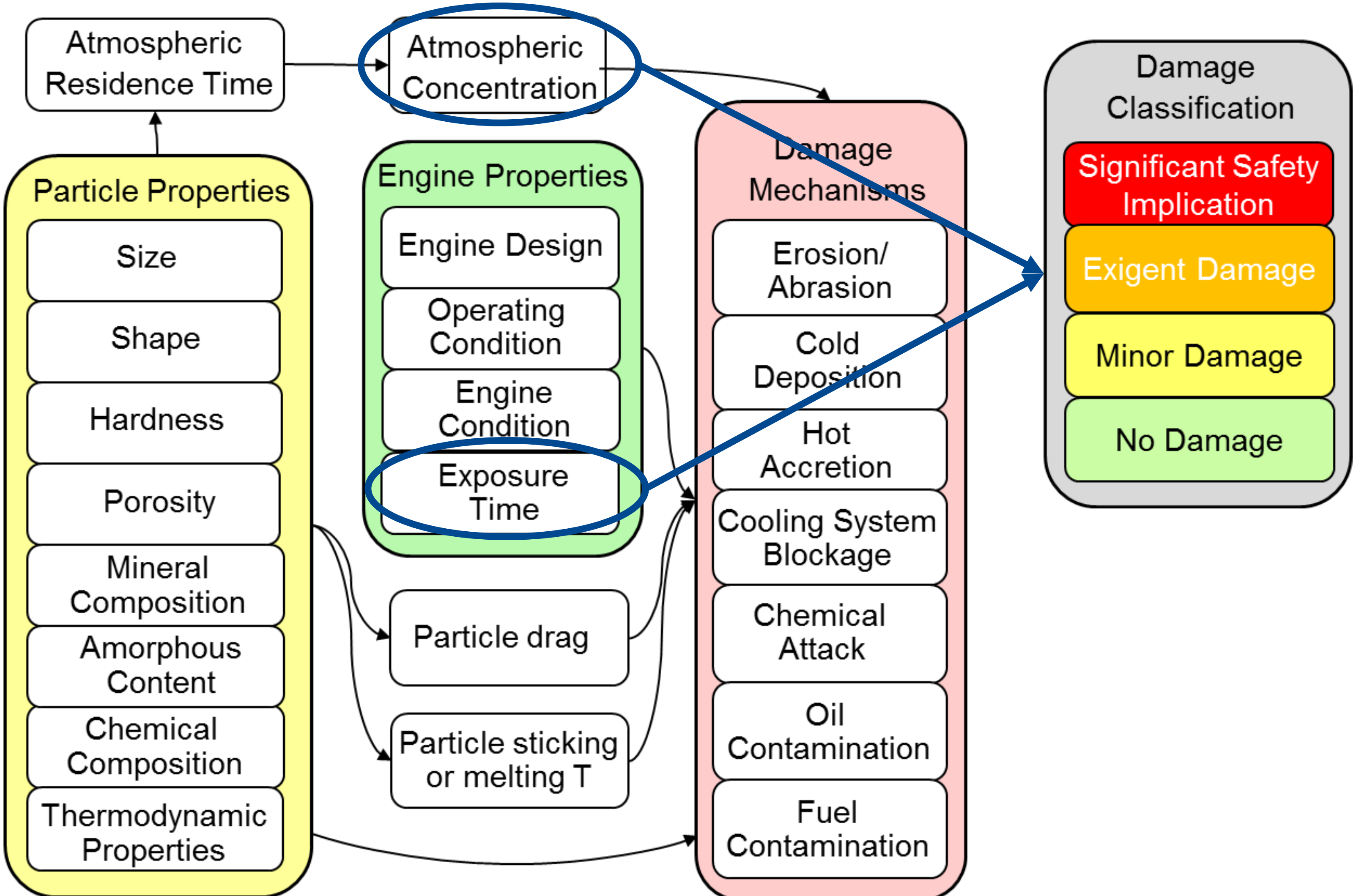
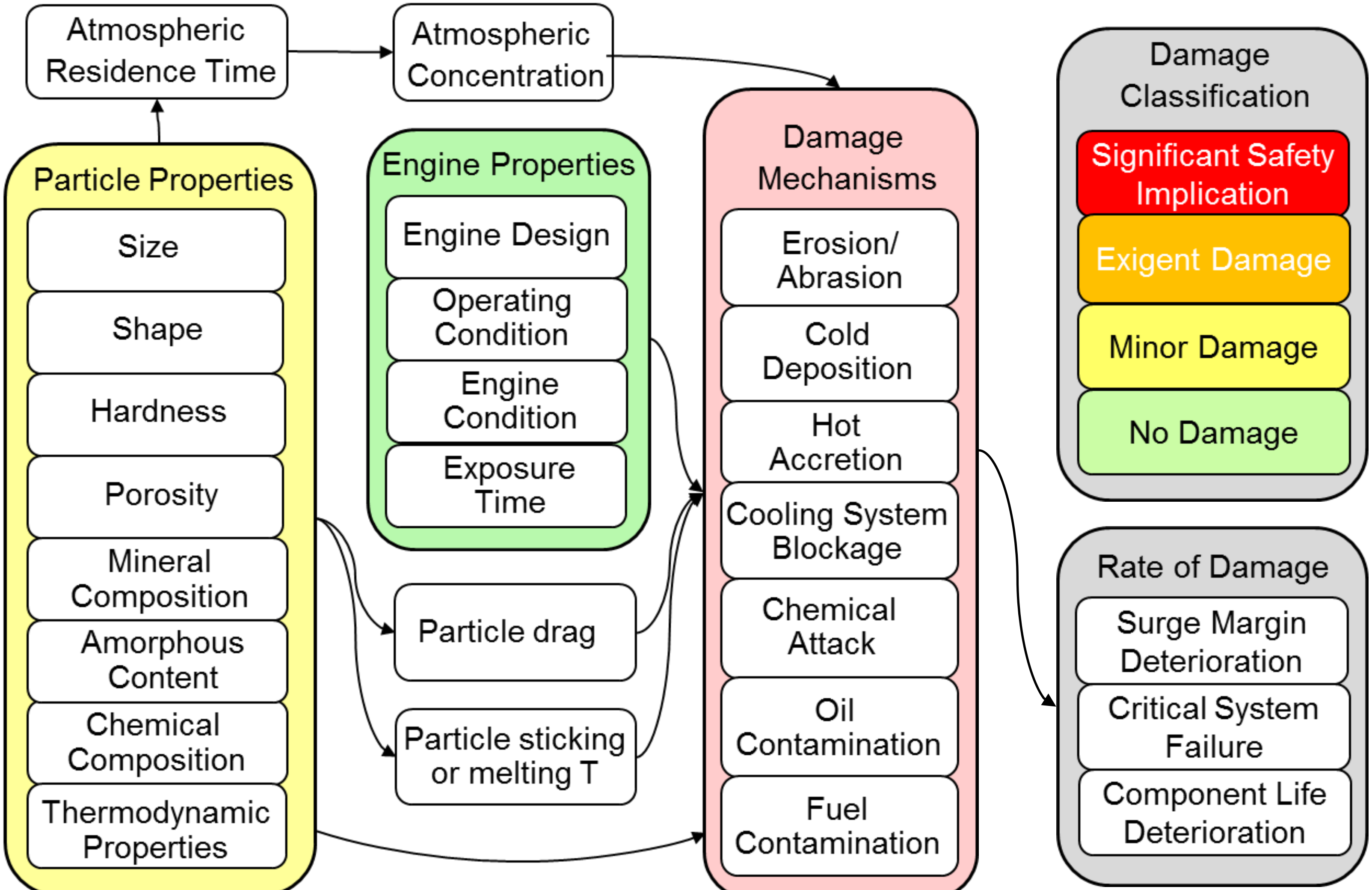
Quantifying Damage

- 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

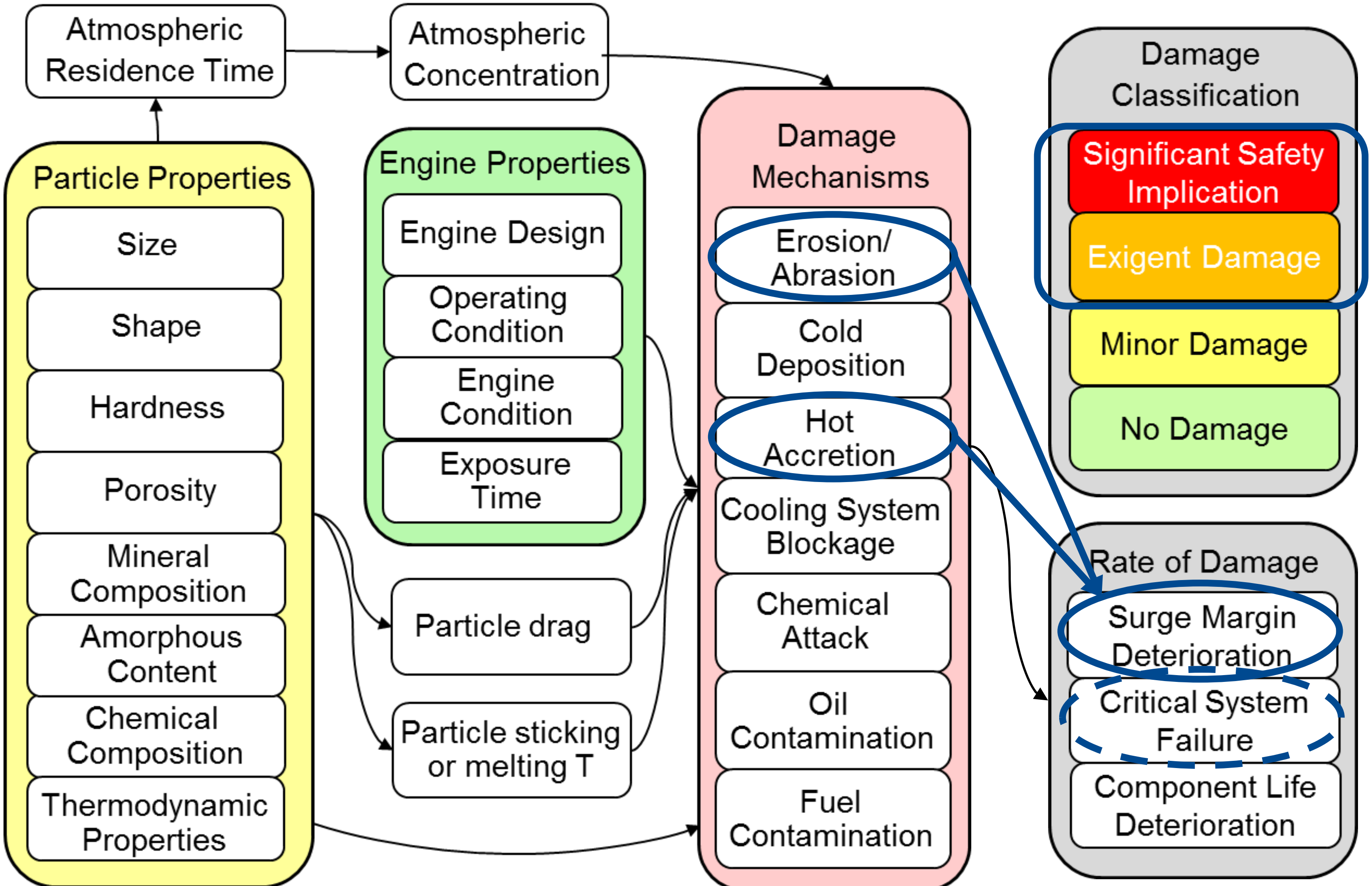
CS-E 1050 Exposure to volcanic cloud hazards (See AMC E 1050)
(a) The susceptibility of turbine Engine features to the effects of volcanic cloud hazards must be established.
(b) Information necessary for safe operation must be provided in the relevant documentation.

- 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/m^3 to 1000 mg/m^3
  - ➢ No need to test if susceptibility set at <4 mg/m^3 (and presumably >1000 mg/m^3 ☺)
- ❑ Applies to new and changed products

Quantifying Damage

- Complying with EASA regulations – CS-E 1050



Quantifying Damage

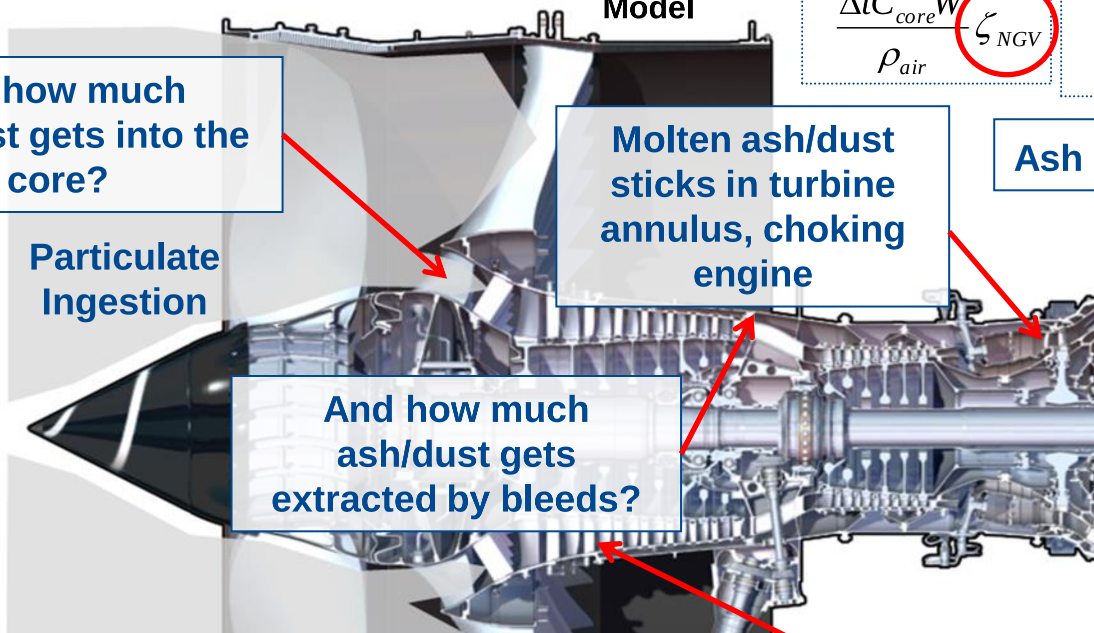
- How long does it take to surge an engine – simple engineering correlation based approach

Turbine Accretion Model

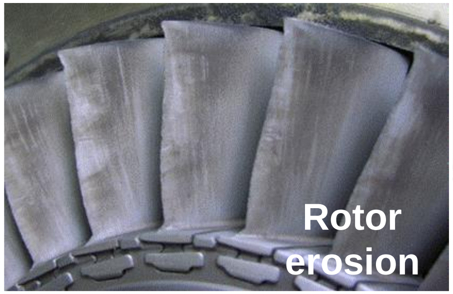
$$m_{NGV} = \frac{\Delta t C_{core} W}{\rho_{air}} \zeta_{NGV}$$

$$\delta A_{th} = l_{th} \phi \, \bar{h} = l_{th} \phi \frac{m_{NGV}}{\rho_{dep} A_{NGV}}$$

$$\delta\, SM = \left(\frac{\delta A_{th}}{100 A_{th}} \right) k_{th}$$



Ash accumulation factor – ζ



Erosion rate – ε

Blade incidence ratio – β

$$m_{ero} = \frac{\Delta t C_{core} W}{\rho_{air}} \varepsilon \beta$$

$$\delta y = m_{ero} \varphi_{tip}$$

$$\delta\, SM = \delta y_{RMS} k_{RMS}$$

$$\delta \mu = m_{ero} \varphi_{\mu}$$

Compressor Erosion/Abrasion Model

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

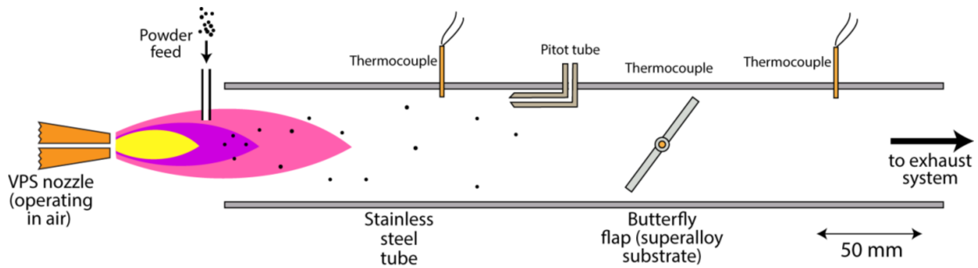
- What have these studies shown?
- Ash accumulation factor (ζ) tends to increase with:
  - Increasing gas and surface temperature
  - Larger particle sizes
  - Greater proportion of non-silica components
  - Greater impingement angle
  - The amount of material already deposited
  - Increasing concentration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

Hot Accretion

A PROVIDA Study

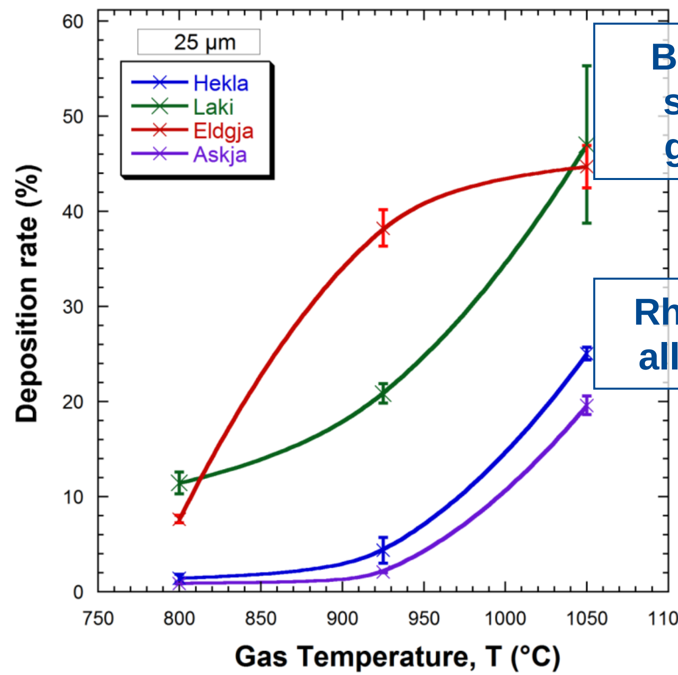
UNIVERSITY OF CAMBRIDGE

- 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



Basalt, some glass

Rhyolite, all glass

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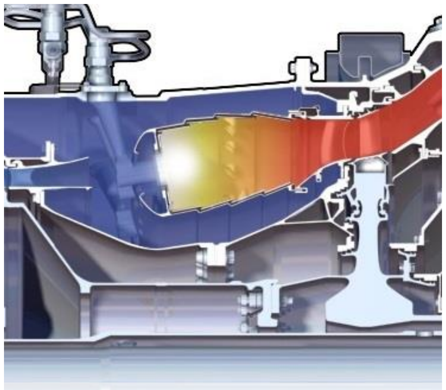
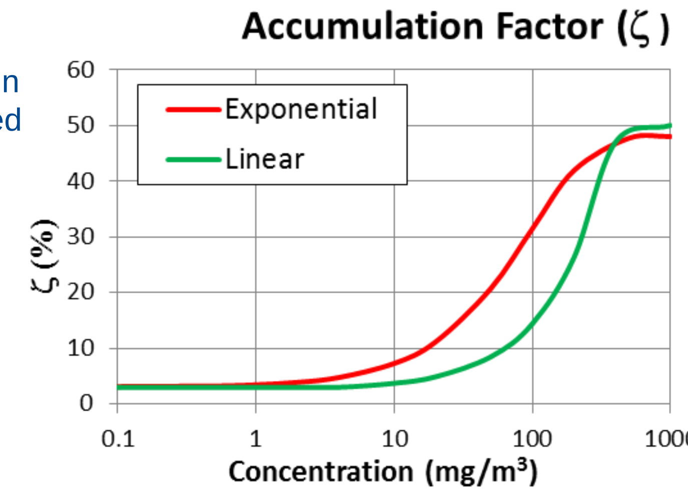
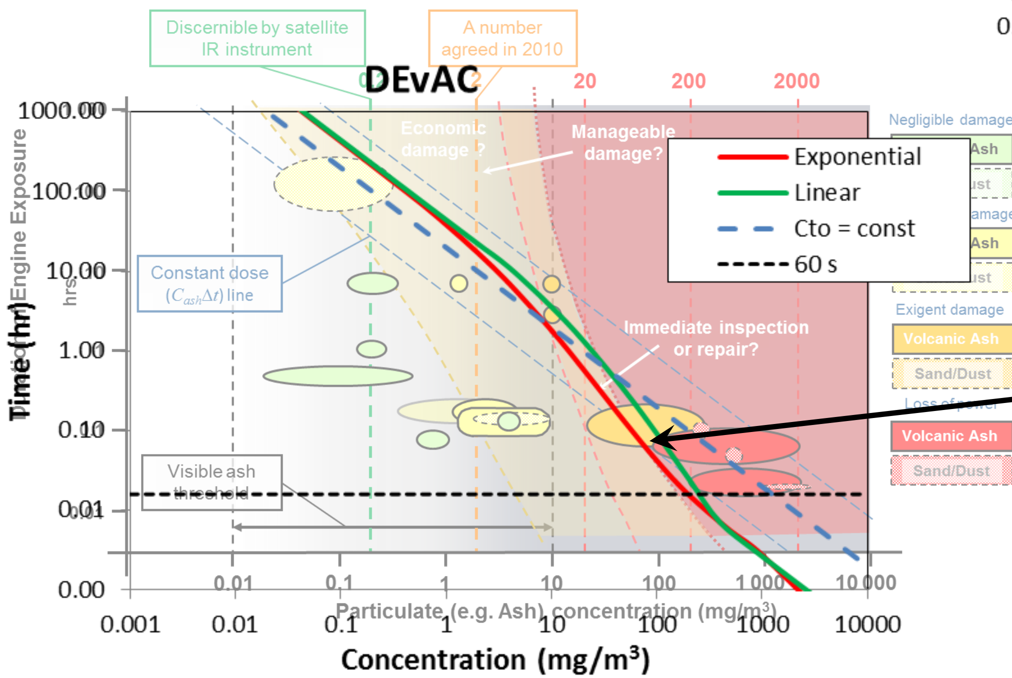
Hot Accretion

- 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





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

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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?

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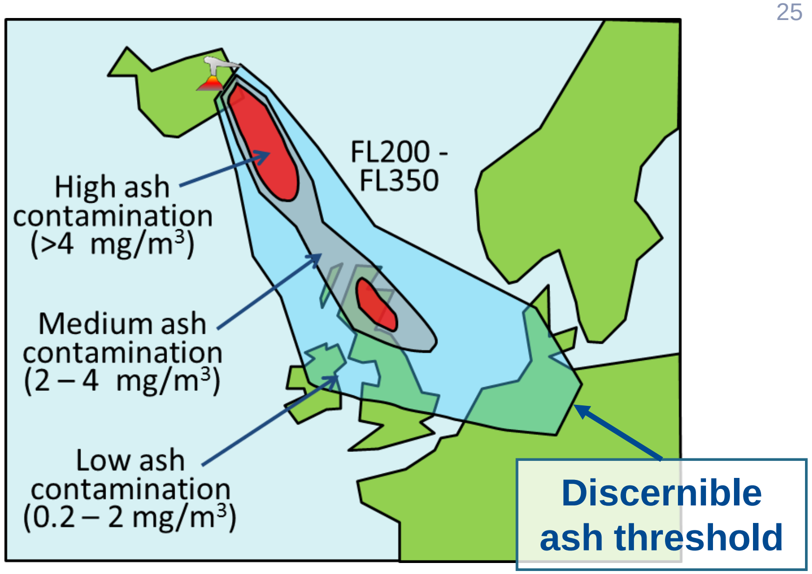
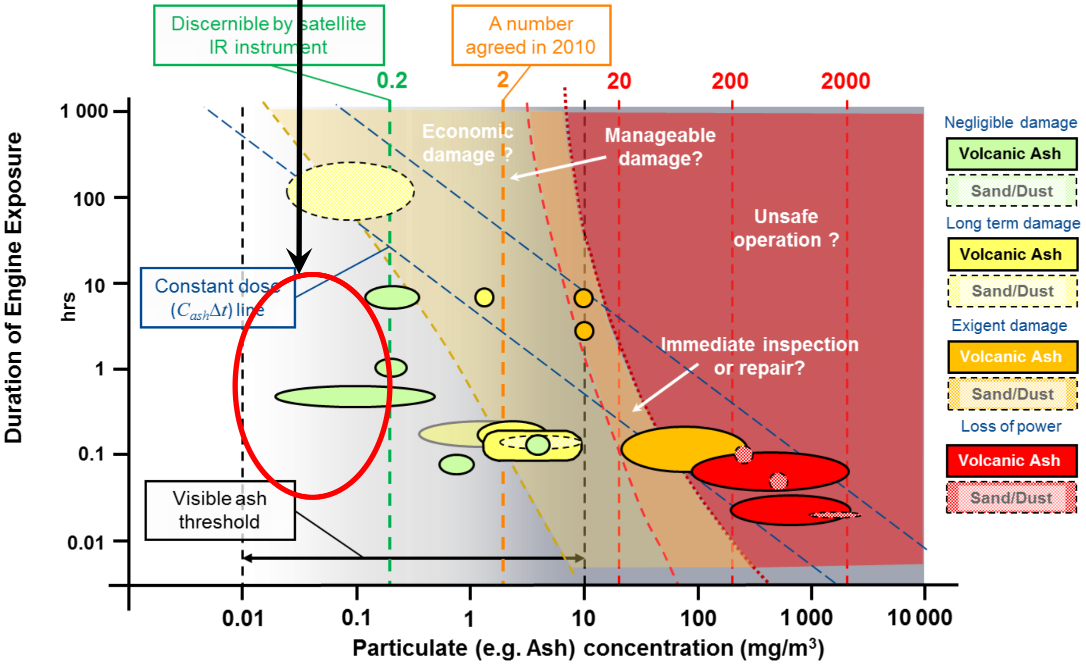
Conclusions (2)

- 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 mg/m³?
- Are concentration charts still relevant?

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