



The Hazard of Volcanic Ash Ingestion

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NASA Glenn Research Center

- Engines are highly reliable....however
- Engine malfunctions contributing to accidents and incidents do occur
- Ground-based testing may not identify problems occurring in-flight
- EHM is limited due to the harsh environment operational conditions
- Malfunction examples include
 - uncontained rotor failures
 - in-flight engine shutdowns
 - restricted thrust response
- Examples of underlying causes include
 - environmental effects such as volcanic ash and ice ingestion
 - turbomachinery damage
 - controls and accessory faults

**Engine Failure
Incident - June 2, 2006**



**Propulsion System Malfunction combined with
Inappropriate Crew Response Accidents**

- **Engine tests provide rare and much needed opportunities to demonstrate propulsion health management technology**

VIPR Overview



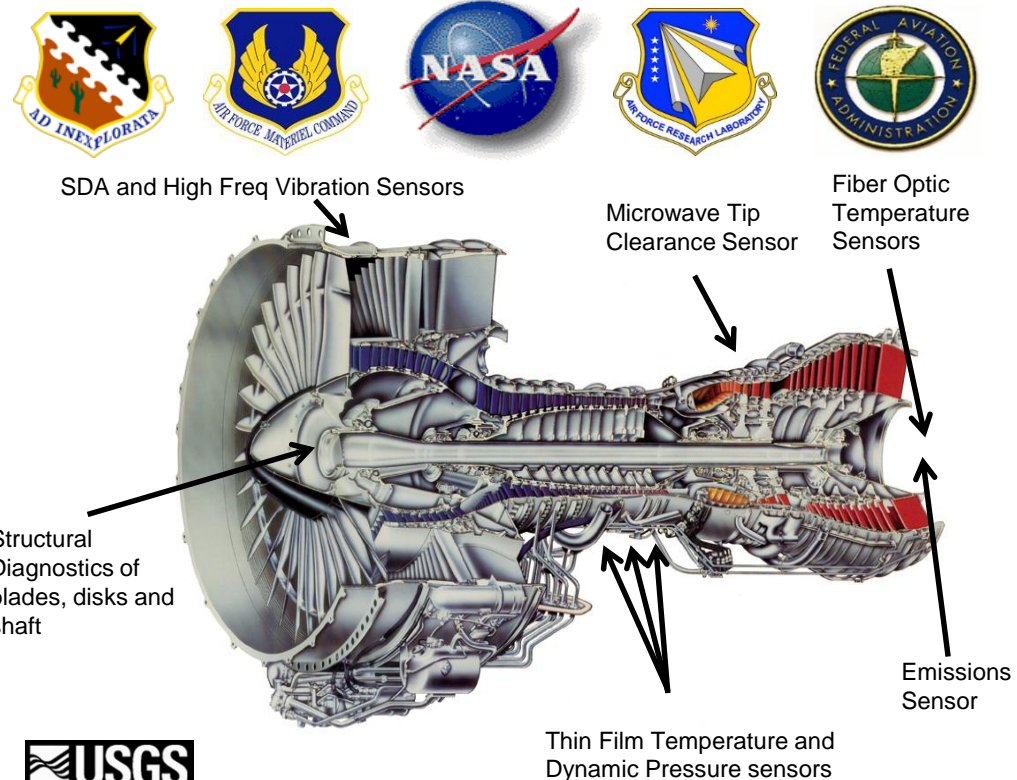
Vehicle Integrated Propulsion Research (VIPR) engine tests to support the R&D of Engine Health Management (EHM) Technologies to augment Aviation Safety

Engine testing is a necessary and challenging component of EHM technology development

Partnerships make it possible.

Partnerships:

- NASA
- Air Force
- Federal Aviation Administration
- Pratt & Whitney
- GE
- Rolls-Royce
- United States Geological Survey
- Boeing



Model-based gas path diagnostic architecture
Prognostic Decision Making
Acoustic Sensor Array



Pratt & Whitney
A United Technologies Company



Ground Testing Overview



VIPR 1 (DECEMBER 2011): PERIPHERAL SENSORS

- SUCCESSFULLY INTEGRATED EXPERIMENTAL TECHNOLOGIES
- SELF DIAGNOSTIC ACCELEROMETER
- MODEL BASED DIAGNOSTICS
- EMISSIONS SENSORS

VIPR 2 (JULY 2013): INTEGRATED CORE SENSORS

- SUCCESSFULLY INTEGRATED EXPERIMENTAL TECHNOLOGIES
 - MICROWAVE BLADE TIP CLEARANCE SENSOR
 - THIN FILM PRESSURE SENSORS
- DETECTED & CHARACTERIZED INDUCED FAULT IMPACTS



VIPR 3 (2015): INTEGRATED ADVANCED & MATURED SENSORS

- INDUCED VOLCANIC ASH INGESTION - RAPID ENGINE DEGRADATION
- DETERMINED CAPABILITY OF ADVANCED DETECTION
- CHARACTERIZED ENGINE PERFORMANCE [*DIAGNOSTIC & PROGNOSTIC*]
- IDENTIFIED FAULT MODALITIES

Since the beginning of air travel, volcanic ash has been a hazard to flight



- From 1952 to 2009, according to a recent study¹, there have been:
 - 129 incidents of planes flying into ash clouds
 - 79 with airframe or engine damage, i.e. about 2 per year since 1976, and
 - 9 with total engine shutdown during flight
- Some most significant encounters:
 - A Boeing 747 flying into an ash cloud at Galunggung Volcano, Indonesia, October 8, 1982, losing power to all four engines, dropping from 36,000 to 14,000 feet before restarting; and
 - A Boeing 747 flying into the ash cloud from Redoubt volcano, Alaska, December 15, 1989, losing power to all engines.



Inspection of KLM Jet in Anchorage following encounter at Redoubt volcano, December, 1989

Photo from Wikimedia Commons

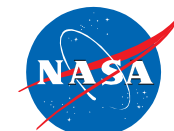


¹Guffanti et al., 2010, U.S. Geological Survey Data series 545
<http://pubs.usgs.gov/ds/545/>

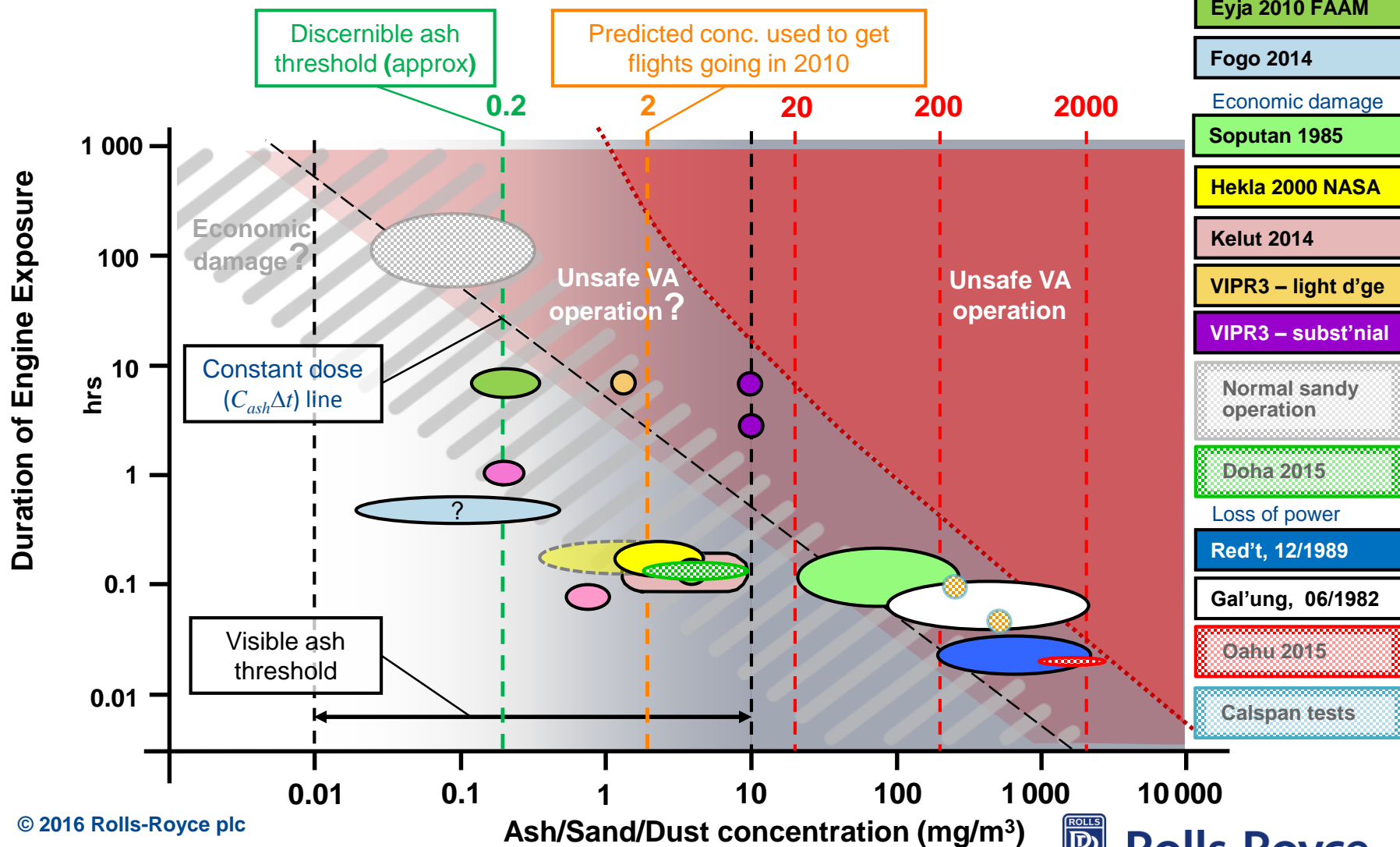
From L. Mastin et al., Properties of Volcanic Ash used in VIPR III Engine Experiments, Aircraft Airworthiness and Sustainment, Grapevine, Texas, March 2016.

What Can Engines Tolerate?

Chart Provided Courtesy of Rolls-Royce plc



- The DEvAC chart – with latest 2014-2015 data



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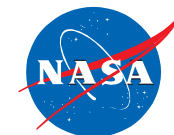
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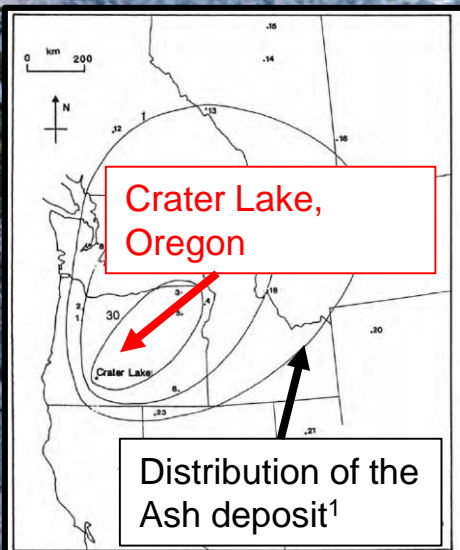
Rolls-Royce

For the engine tests, the USGS chose Mazama Ash

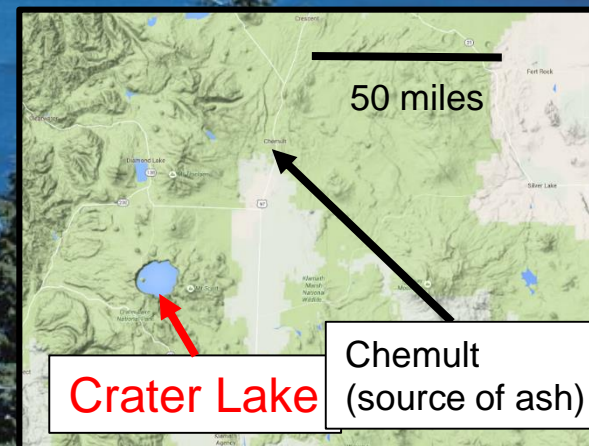


- This ash comes from southwestern Oregon
- It was produced 7,900 years ago during the eruption that created Crater Lake, shown in this photo
- It is the largest eruption in the Western U.S. in the past 10,000 years
- The ash used in the VIPR tests was quarried from Chemult, Oregon, about 50 miles northeast of Crater Lake

Crater Lake, Oregon



¹Young, S. R. (1990), Ph.D. Dissertation, University of Lancaster, England, UK.



From L. Mastin et al., Properties of Volcanic Ash used in VIPR III Engine Experiments, Aircraft Airworthiness and Sustainment, Grapevine, Texas, March 2016.

The viscosity of volcanic glass can vary by orders of magnitude



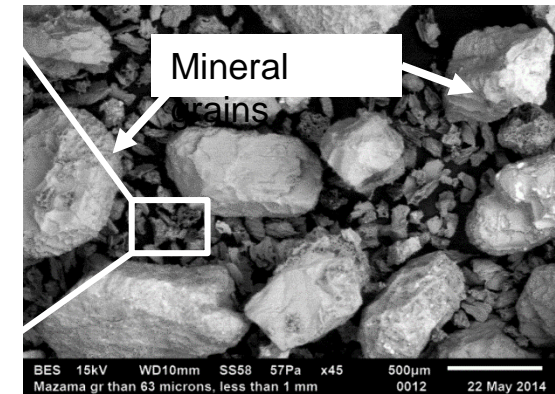
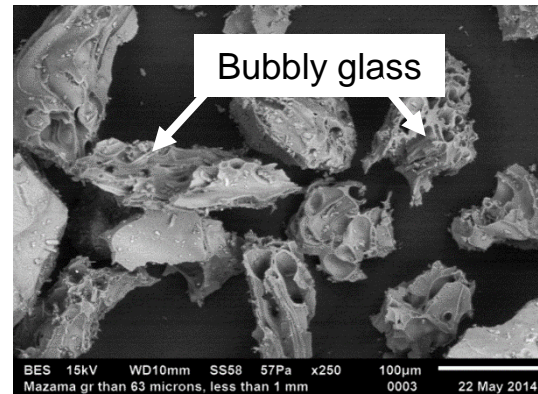
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Texture and Structure



- The *natural deposit* contained about
 - 10% mineral grains
 - 90% bubbly glass
- The *milled and processed ash* contained no mineral grains that we could find
- We think that most mineral grains were separated out during processing
- The final product was a powder with size range from about 5 to 100 microns

Natural ash fragments from deposit



Milled and processed ash

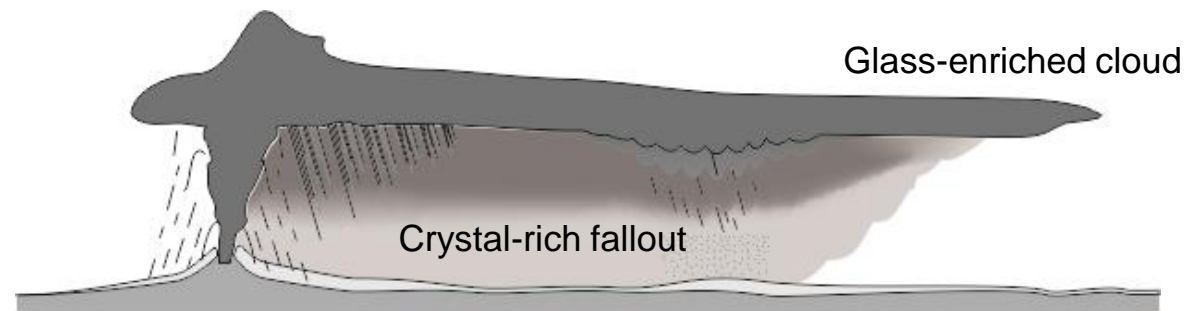


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Resemblance to ash in distal clouds



- In real ash clouds crystals fall out first, leaving distal clouds enriched in glass.
- Distal clouds typically contain ash particles tens of microns in size or smaller.
- In these respects, the test ash resembles natural ash in clouds



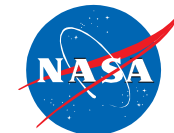
Particle size Meters to
microns
Distance 0 km

Microns to tens of
microns
1,000 km

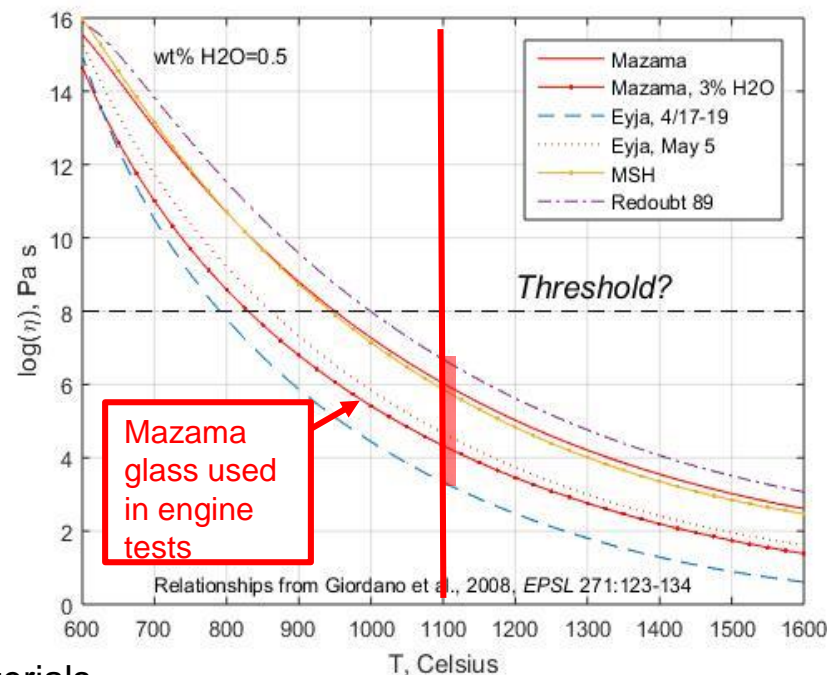


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Glass viscosity



- The right-side plot shows the viscosity of this glass relative to other volcanic glasses that have been involved in ash-aircraft encounters
- This viscosity of the test glass is within the range for these other volcanic glasses
- At an operating temperature of 1100° Celsius, viscosities of all these glasses are well below the threshold of about 10⁸ Pascal seconds, below which ash should soften and coat engine parts.
- We are therefore confident that softening occurred during testing.

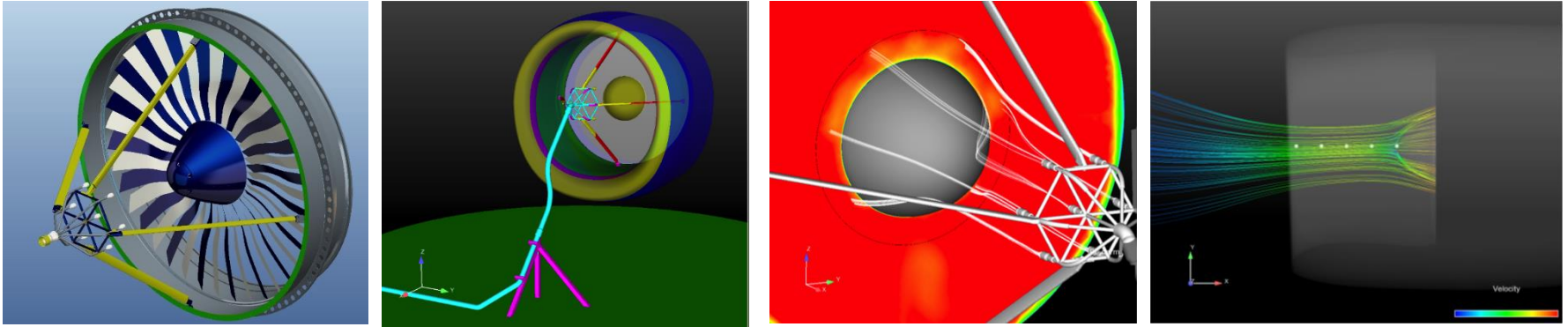


- No single type of ash is representative of all volcanic materials
- Ash viscosity, the primary factor that determines softening within an engine, can vary over several orders of magnitude.
- The Mazama Ash, used in the VIPR-III engine tests, lies within the range of viscosity of volcanic materials known to have been involved in past aircraft encounters.



From L. Mastin et al., Properties of Volcanic Ash used in VIPR III Engine Experiments, Aircraft Airworthiness and Sustainment, Grapevine, Texas, March 2016.

Modeling and Analysis Confirm Controlled Flow into the Core Stream



- The ash did flow into the core stream
- Ash flow was controllable
- The engine ran unabated by the SPIDER/VADR installed in the inlet

VIPR3 VAE Test Execution Sequence



Test Execution Sequence:

July 14: Engine water wash conducted to remove any dirt or fouling from engine turbomachinery prior to commencing ash ingesting testing

July 22: Calibration run conducted to establish baseline engine performance level

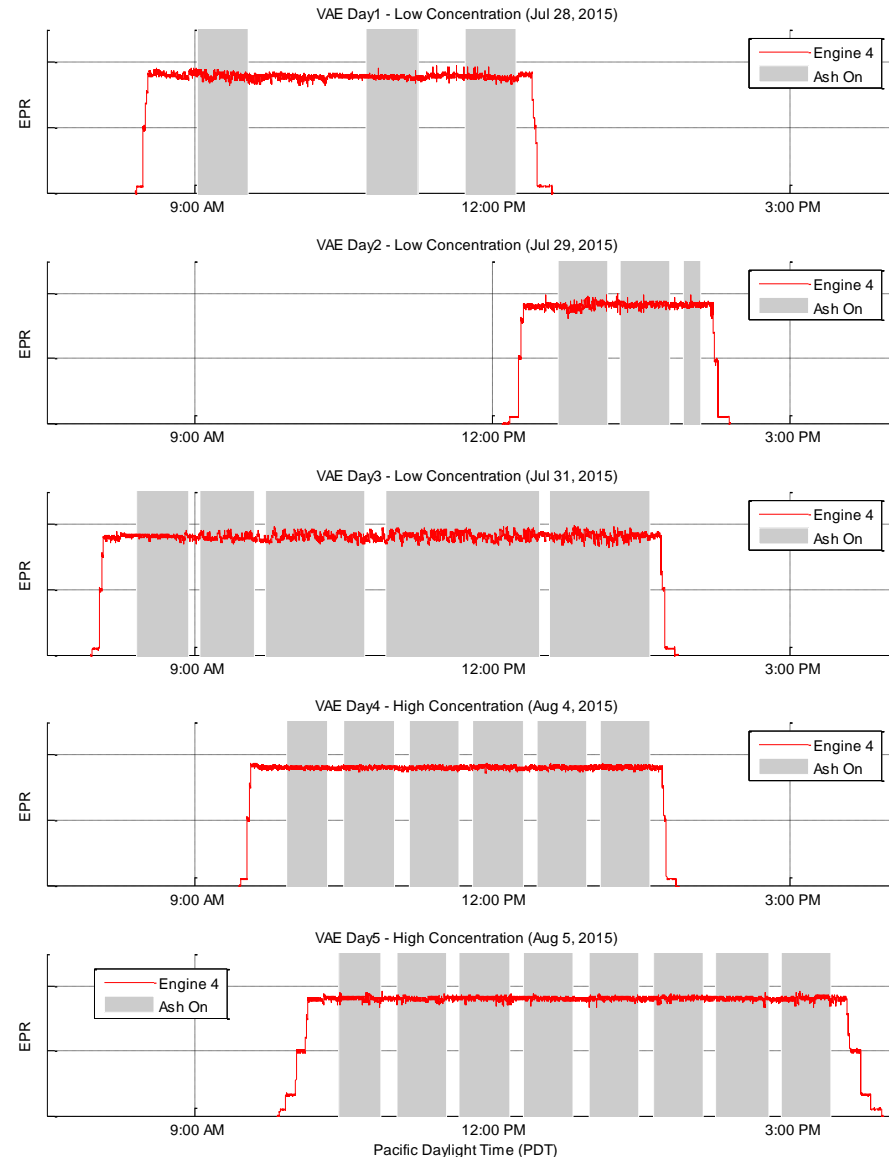
July 23: SPIDER and Ash spray nozzle array installation and checkout test

July 28 – Aug 5: Five (5) days of ash ingestion testing conducted



Run duration and amount of ash ingested in engine over 5 days of ash ingestion testing

Run #	Date	Target Concentration (mg/m ³)	Daily Ash Ingested Run Time (min)	Daily Ash Ingested Mass (kg)
1	28-Jul-15	1	90	0.730
2	29-Jul-15	1	68	0.549
3	31-Jul-15	1	269	2.156
4	04-Aug-15	10	175	11.017
5	05-Aug-15	10	235	14.465

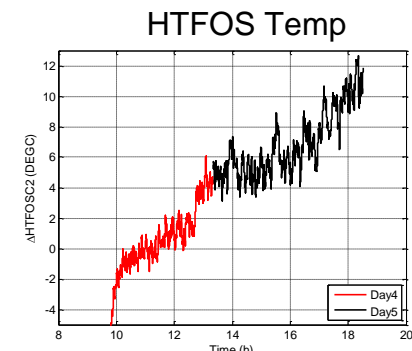
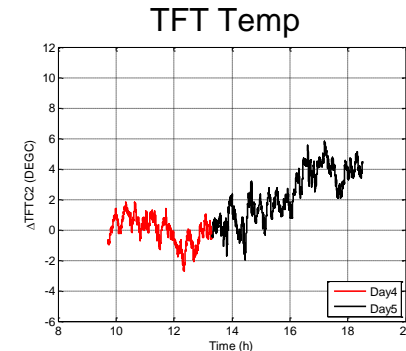
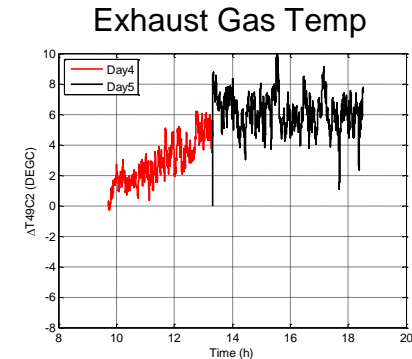
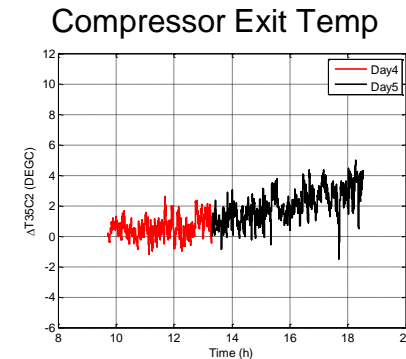
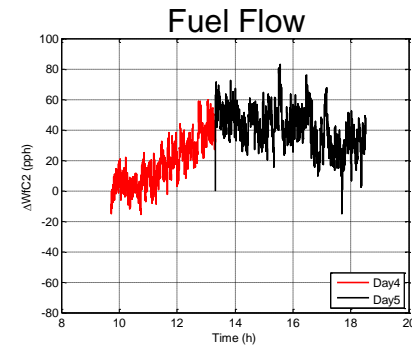
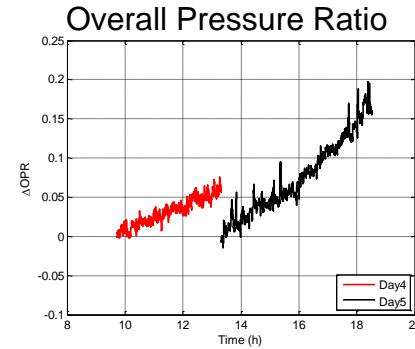


Gas Path Measurement Data – Volcanic Ash Test Runs



RESULTS AND SIGNIFICANCE (Preliminary)

- Five (5) days of volcanic ash ingestion testing
 - Days 1, 2, and 3 ran low concentration ash ingestion
 - Days 4 and 5 ran higher concentration ash ingestion
- No significant engine performance variations were observed during low concentration ash runs
- On high ash concentration run days, discernable performance trend changes were observed in overall pressure ratio (OPR), fuel flow, compressor exit temperature, and exhaust gas temperature.
- Advanced sensor data tracks performance changes observed elsewhere in engine
 - High Temperature Fiber Optic Sensor (HTFOS) trends with exhaust gas temperature
 - Thin Film Thermocouple (TFT) trends with compressor exit temperature



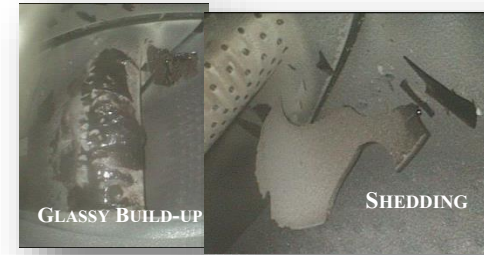
VAE Performance Trend Shifts – Day 4 & 5

Results

Vehicle Integrated Propulsion Research (VIPR) III



E15 Volcanic ash cloud in Iceland
April 2010



GLASSY BUILD-UP

SHEDDING

FOCUS: "ASH (*NON-VISIBLE/VISIBLE SPECTRUM*) THRESHOLD DECISION-POINT DEBATE"

- EVALUATED FLIGHT DECISION POINT CONCENTRATIONS RATES OF **LOW (1 MG/M3)** & **HIGH (10 MG/M3)**
 - US GOVERNMENT & MANUFACTURERS TEAM - SUMMER 2015, EDWARDS AFB
- **PREDICTED ENGINE DEGRADATION** WITHIN **1HR @ LOW**; & **RED-LINE BREACH** (*ENGINEER- SET -MARGIN THRESHOLD*) @ **3HR HIGH**

RESULTS: **VERIFIED COMPRESSOR BLADE EROSION**

TURBINE MOLTEN ASH GLASSY BUILD-UP

ASH SHEDDING

ENGINE PERFORMANCE DEGRADATION @10HR

14HR CUMULATIVE TEST NO RED-LINE BREACH

WHAT'S NEXT: DATA ANALYSIS; ENGINE ANALYTICAL CONDITION INSPECTION ...*BEYOND VIPR III*

BOTTOM LINE:

- 1ST CONTROLLED VOLCANIC ASH EXPOSURE EXPERIMENT CONSISTENT WITH FLIGHT SAFETY POLICY
- MATURED KEY TURBINE ENGINE TECHNOLOGIES RELEVANT TO AEROSPACE COMMUNITY

VIPR 1, 2 and 3 Summary

Testing complete: highly successful



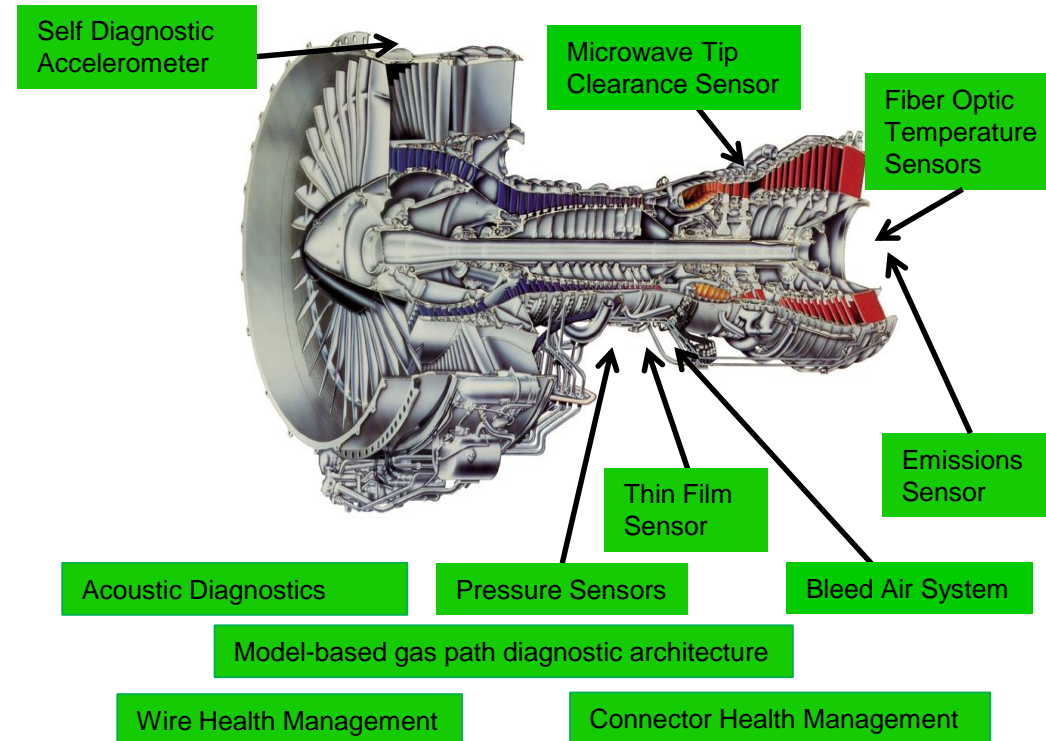
Test Objectives:

Demonstrate capability of advanced health management technologies for detecting and diagnosing incipient engine faults before they become a safety impact and to minimize loss of capability

Approach:

Perform on wing engine ground tests

- Normal engine operations
- Seeded mechanical faults
- Seeded gas path faults
- Accelerated engine life degradation through volcanic ash ingestion testing



VIPR 2 Test completed in July 2013

VIPR 3 Test completed in August 2015