National Aeronautics and Space Administration

Vehicle Integrated Propulsion Research (VIPR) III Volcanic Ash Ingestion Testing

AVT-272 Specialists Meeting on “Impact of Ash Clouds on Military Operations”

May 15-17, 2017

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www.nasa.gov

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Engine Health Management

- 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

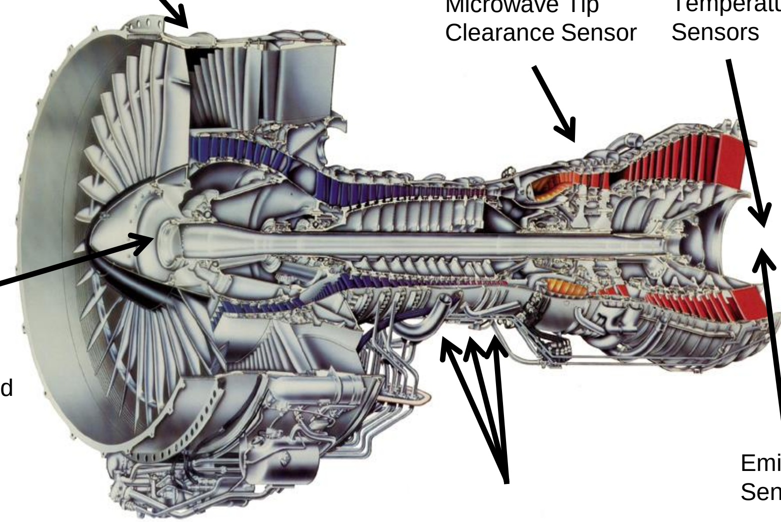
Vehicle Integrated Propulsion Research (VIPR) engine tests to support the R&D of Engine Health Management (EHM) Technologies to augment Aviation Safety

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

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Ground Testing Overview

VIPR 1 (December 2011): Peripheral Sensors

- Successfully integrated experimental technologies
- Self Diagnostic Accelerometer
- Model Based Diagnostics
- Emissions Sensors

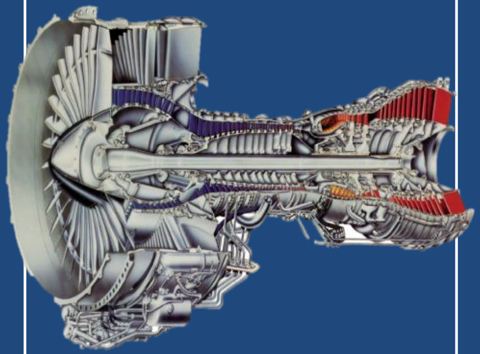
VIPR 2 (July 2013): Integrated Core Sensors

- 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

VIPR Technology

NASA Team Technologies Demonstrated	Synopsis **12 Research areas**	BENEFITS
SENSOR SUITE 1 Accelerometer 2 Microwave Tip & Clearance Sensor 3 Fiber Optic Temperature Sensors 4 Thin Film Temperature Sensor 5 Pressure Sensors 6 Acoustic Signature Microphones 7 Self-Tuning Eng Model Diagnostics 8 High Temperature Fiber Optic Sensor CREW SAFETY BLEED AIR SYSTEM VOLCANIC ASH INGESTION Schlieren Imaging Particle Detection Probe		Advanced Health Management Advanced Diagnostics Safety Reliability Enabling Prognosis & Prognostics For Life Management Improved asset availability Improved Fuel Efficiency

Volcanic Ash Testing

Characterize engine degradation effects due to simulated exposure to dispersed distal volcanic ash clouds

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

- **From 1952 to 2009, according to a recent study[1], 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

USGS
science for a changing world

[1]Guffanti 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.

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What Can Engines Tolerate?

- The DEvAC chart – with latest 2014-2015 data

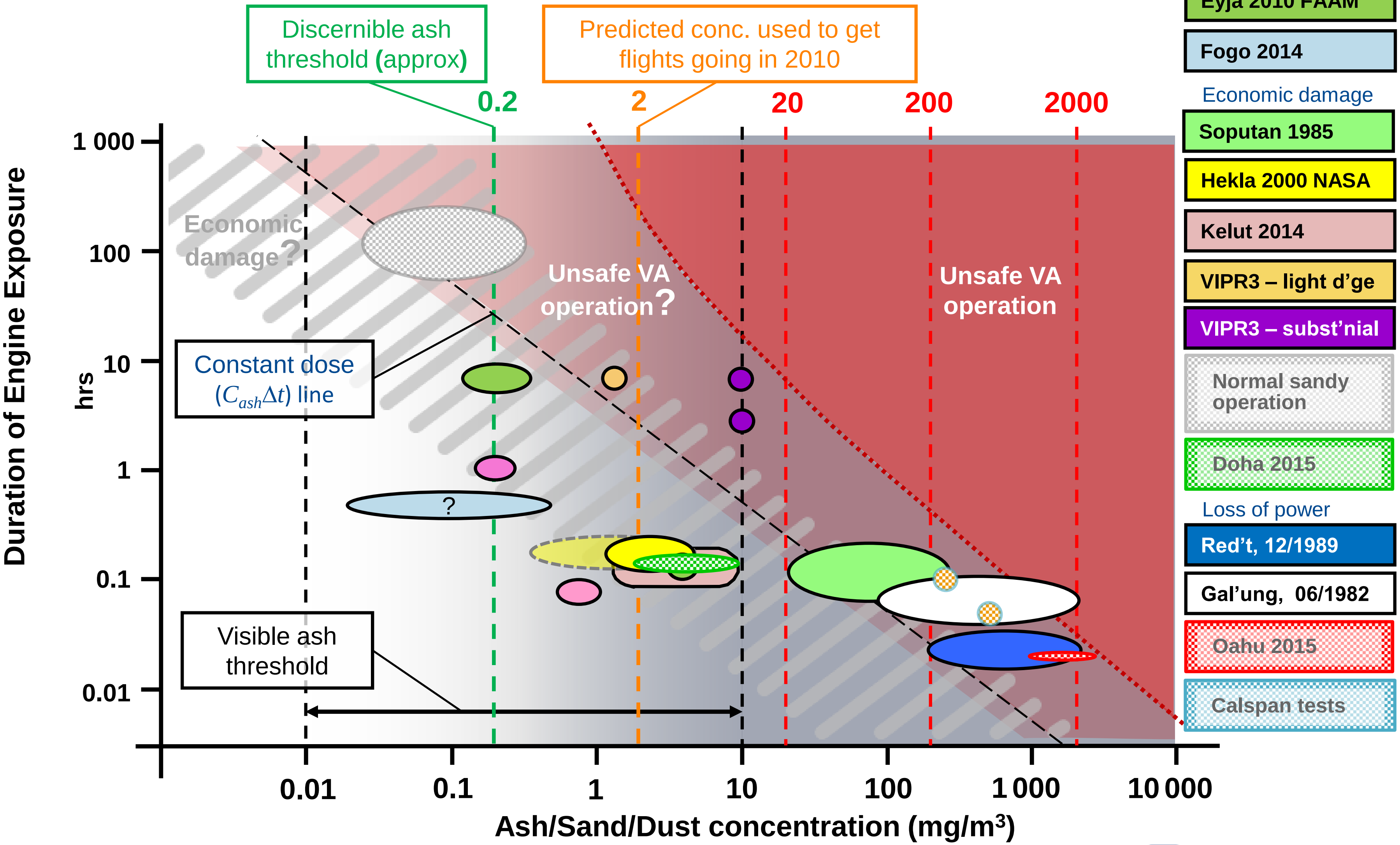

Chart Provided Courtesy of Rolls-Royce plc

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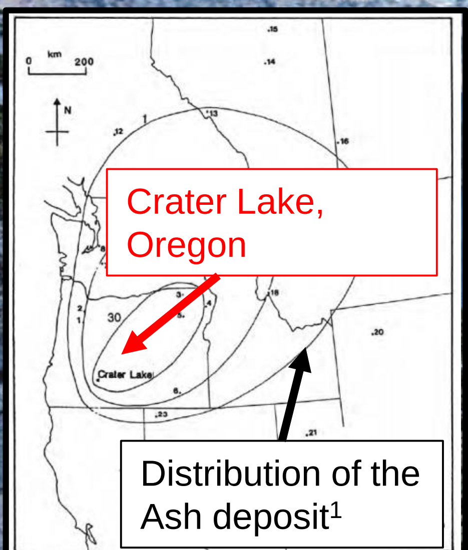
For the engine tests, the USGS chose Mazama Ash

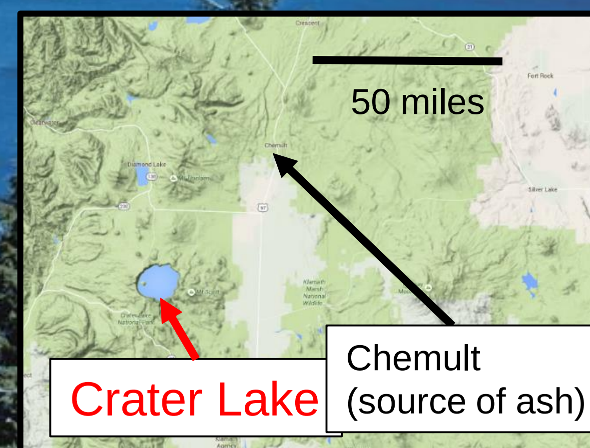
- **This ash comes from southwestern Oregon**
- **It was produced 7,900 years ago during the eruption that created Crater Lake, shown in this photo**
- **It is the largest eruption in the Western U.S. in the past 10,000 years**
- **The ash used in the VIPR tests was quarried from Chemult, Oregon, about 50 miles northeast of Crater Lake**
- **Rationale for its selection and method of processing are presented in slides 10-14.**

Crater Lake, Oregon



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

Painting by Paul Rockwood



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

Viscosity (Pascal Seconds) at 1,100° Celsius

10^2 — 10^8

50% — *SiO_2 in glass* — *75%*

Eyja, April 2010

Redoubt, 1989

Kilauea, Hawaii

- Viscosity of volcanic glass generally correlates with SiO_2 content, which can range from about 50 to 75 weight percent in volcanic glasses.
- Low-silica melts, like those in Hawaii, are low in viscosity and generally not explosive.
- High-silica melts, like Mount St. Helens, are viscous and explosive.
- Eruptions at Eyjafjallajökull, Mount. St. Helens, and Redoubt all involved aircraft encounters. And the viscosity of their glass ranged over about five orders of magnitude

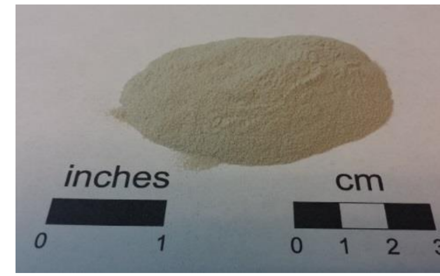
Mount St. Helens

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

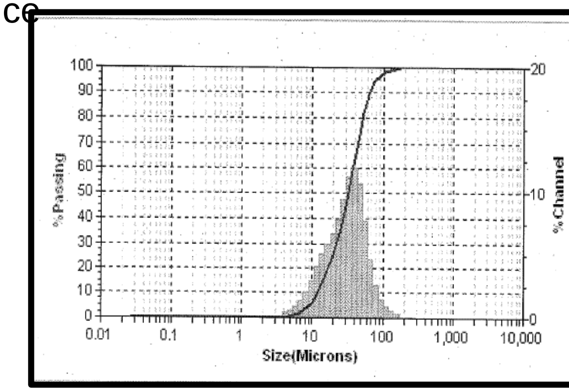
Processing the pumice

- **Ash was processed by Powder Technology Incorporated of Arden Hills, Minnesota. Processing was paid for by Rolls Royce/Liberty Works**
- **Processing included:**
  - Drying
  - Milling
  - Cyclone separation
- **The final product was a powder with size range from about 5 to 100 microns**

Unmilled pumice



Milled ash



Size of milled final ash

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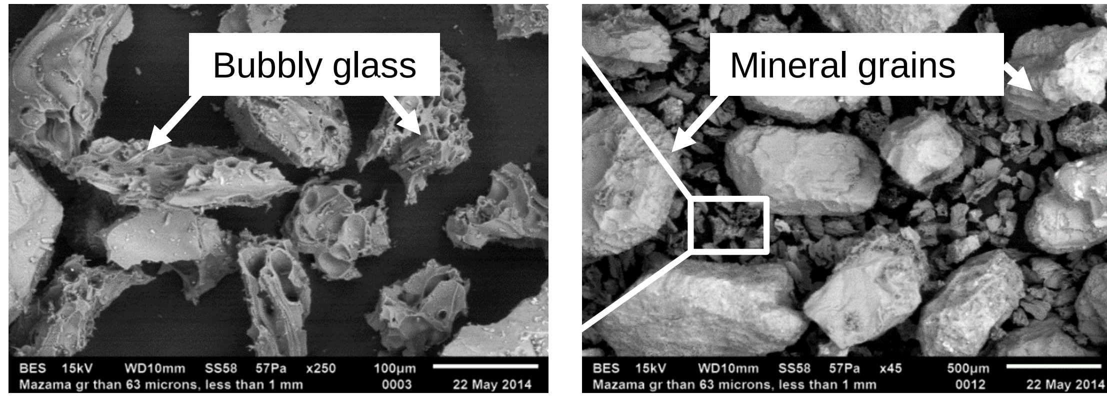
From L. Mastin et al., Properties of Volcanic Ash used in VIPR III Engine Experiments, Aircraft Airworthiness and Sustainment, Grapevine, Texas, March 2016.

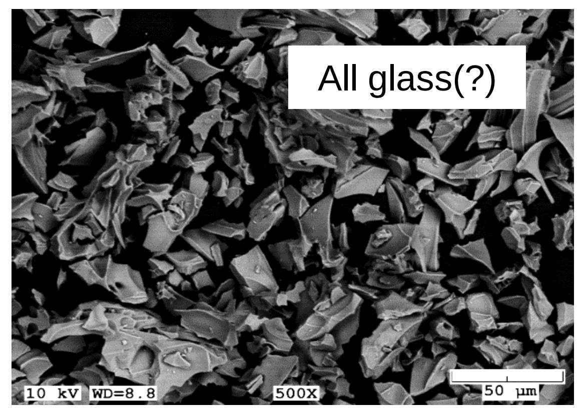
Texture and Structure

- **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**

Natural ash fragments from deposit



Milled and processed ash



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

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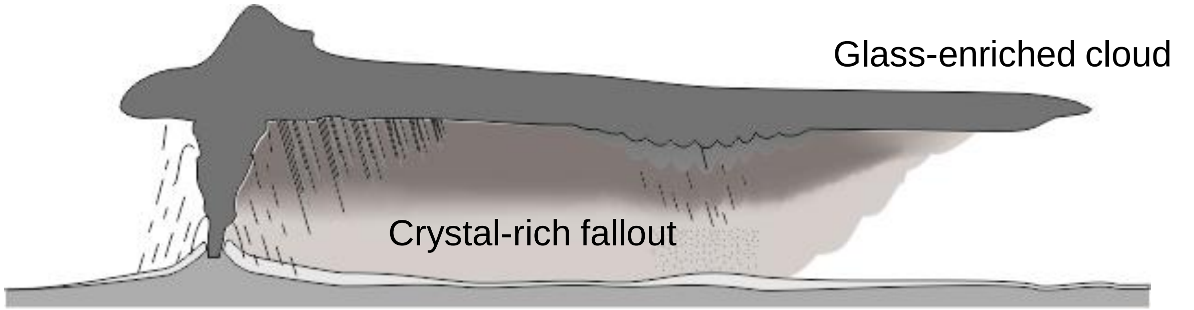
Resemblance to ash in distal clouds

- **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 — Microns to tens of microns

Distance 0 km — 1,000 km

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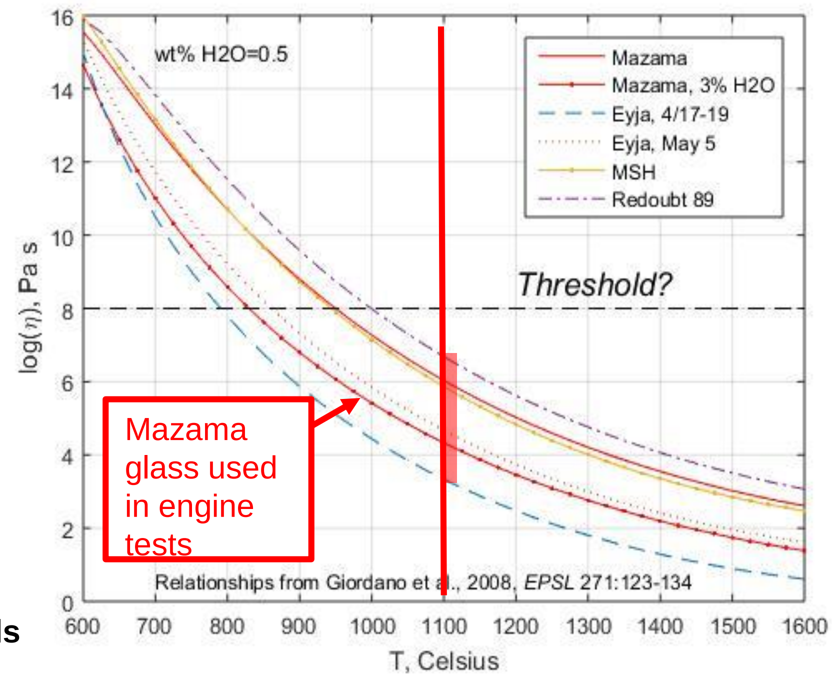
From L. Mastin et al., Properties of Volcanic Ash used in VIPR III Engine Experiments, Aircraft Airworthiness and Sustainment, Grapevine, Texas, March 2016.

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 10^8 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.

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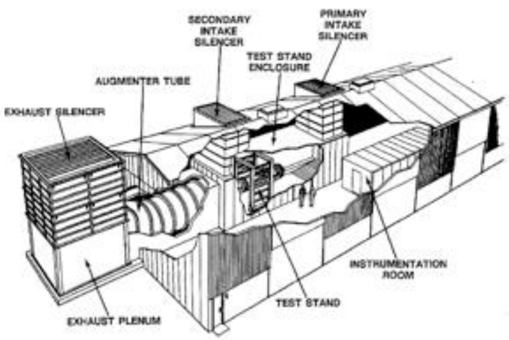
From L. Mastin et al., Properties of Volcanic Ash used in VIPR III Engine Experiments, Aircraft Airworthiness and Sustainment, Grapevine, Texas, March 2016.

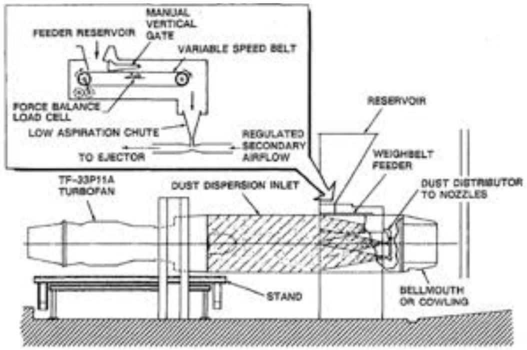
VADR Development - Early Work with Calspan and DNA

- **Volcanic Ash Distribution Rig (VADR)**
- **1980’s-90’s Calspan was contracted to support the Defense Nuclear Agency (DNA; 1971-1996) conducting research on various turbine engines for:**
  - Volcanic ash
  - Nuclear dust effects
- **Facilities were developed/used at both:**
  - Calspan NY
  - Edwards AFB CA
- **This data was not readily available nor time allotted for review prior to conducting NASA Vehicle Integrated Propulsion Research (VIPR)**
- **~25 Papers related to Calpsan/DNA work were found during and post VIPR and in review regarding previous testing**

VADR Development -Calspan Dust Injection vs Edwards AFB Test Cell

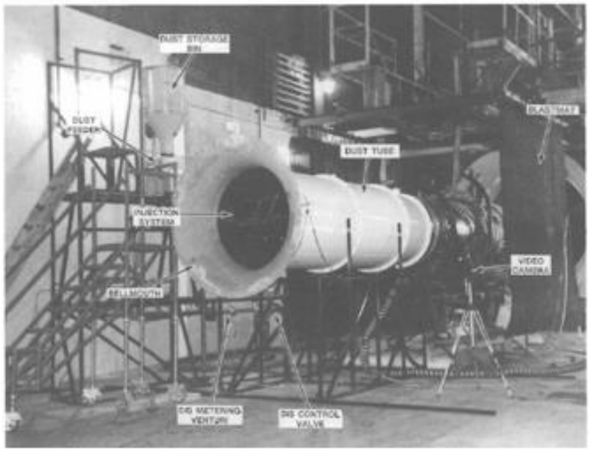
- Fan face concept used bell mouth inlet
- Ingestion rakes were part of bell mouth inlet
- Belt feed technique utilized

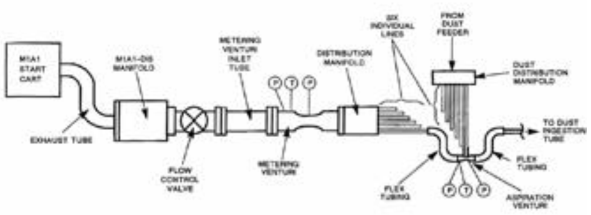




Dunn/Baran/Miatech Images. ASME Large engine research cell, 1996, Operation of Gas Turbine Engines in Volcanic Ash Clouds

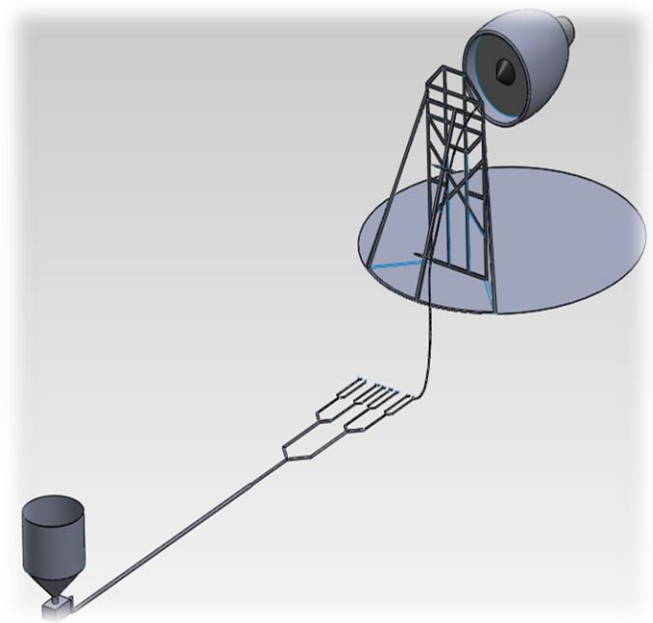
- Auger feed system used in lieu of belt feed
- Similar feed to what was used in VIPR III



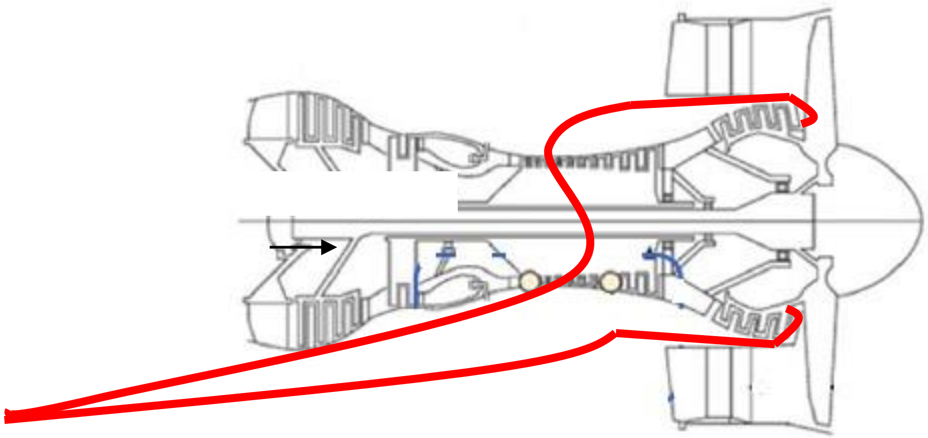


Baran/Dunn. DNA-TR-92-The Response of a YF101-GA-100 Engine to a "Most Probable" Nuclear Dust Environment (U), 1992

VADR Development - Early Considerations VIPR Fan Face Low Pressure Compressor Injection



KSU fan face concept (included ash in the bypass)
- Core loading uncertain
- Possible damage to nacelle and aircraft
- Decoupled engine rig/engine motion
- Possible distortion and stall recovery issues



Booster injection
- Core loading known
- Undesired circumferential variation in ash induced damage
- Difficult to integrate into nacelle

VADR Development - Comments

- **Previous concepts more along the lines of what might be accommodated in test cell environments**

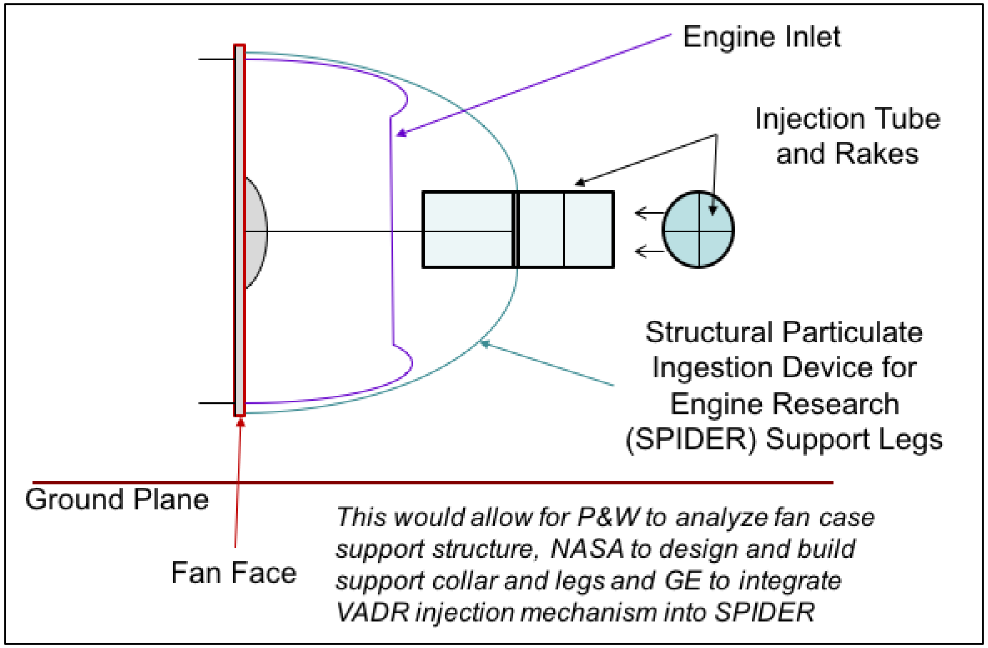
- **Arnold Engineering Development Center (AEDC) was considered but too costly for single test with all other VIPR research**

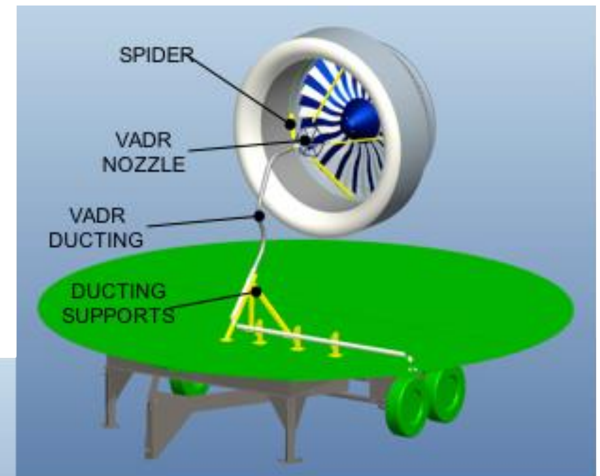
- **Impacts to AEDC and clean up may have been too cumbersome**

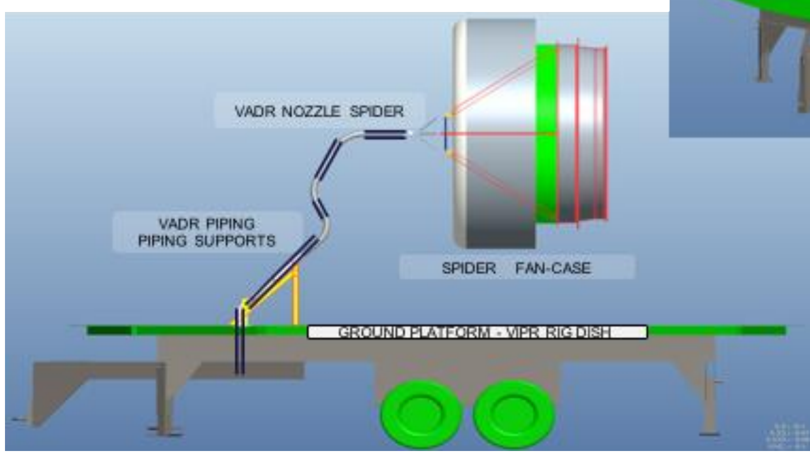
- **VIPR team met at National Museum of the Air Force in late 2013 to discuss possible options for core only controlled ingestion**

- ***Pathway*** **was needed for OEMs and NASA to work seamlessly on VADR components and integration**

VADR Development - Chicken Scratch to Concept







Conceptual Drawings Developed

- 4 Legged SPIDER
- Attached to inner fan case as opposed to outer as first considered
- Plumbing routing considered for integration off platform to VADR control unit

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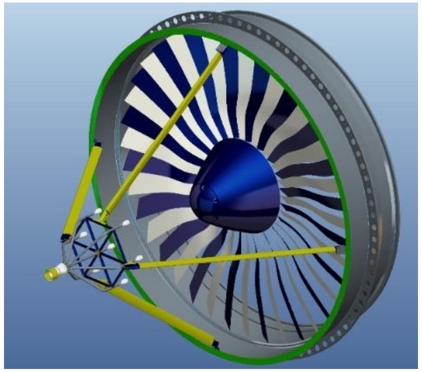
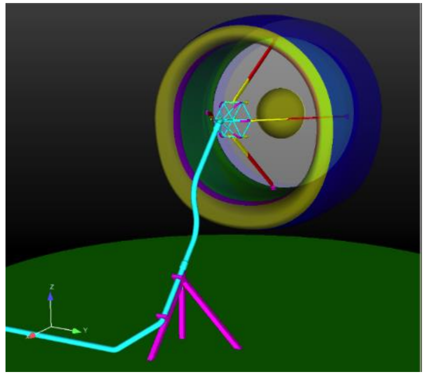
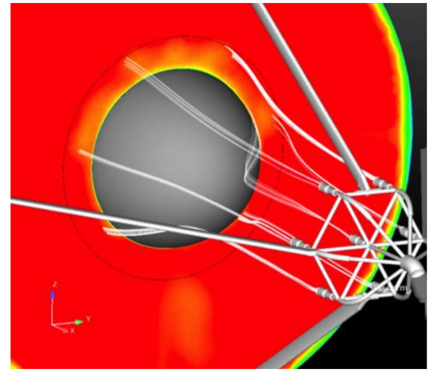
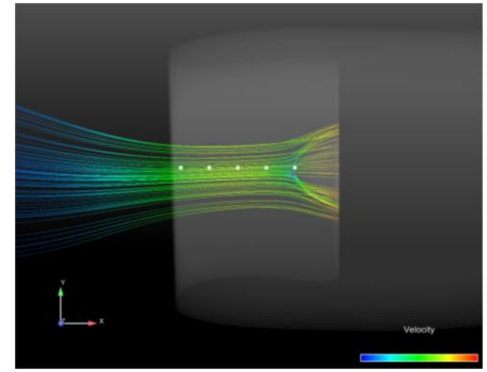
Modeling and Preliminary Analysis Confirm Controlled Flow into the Core Stream



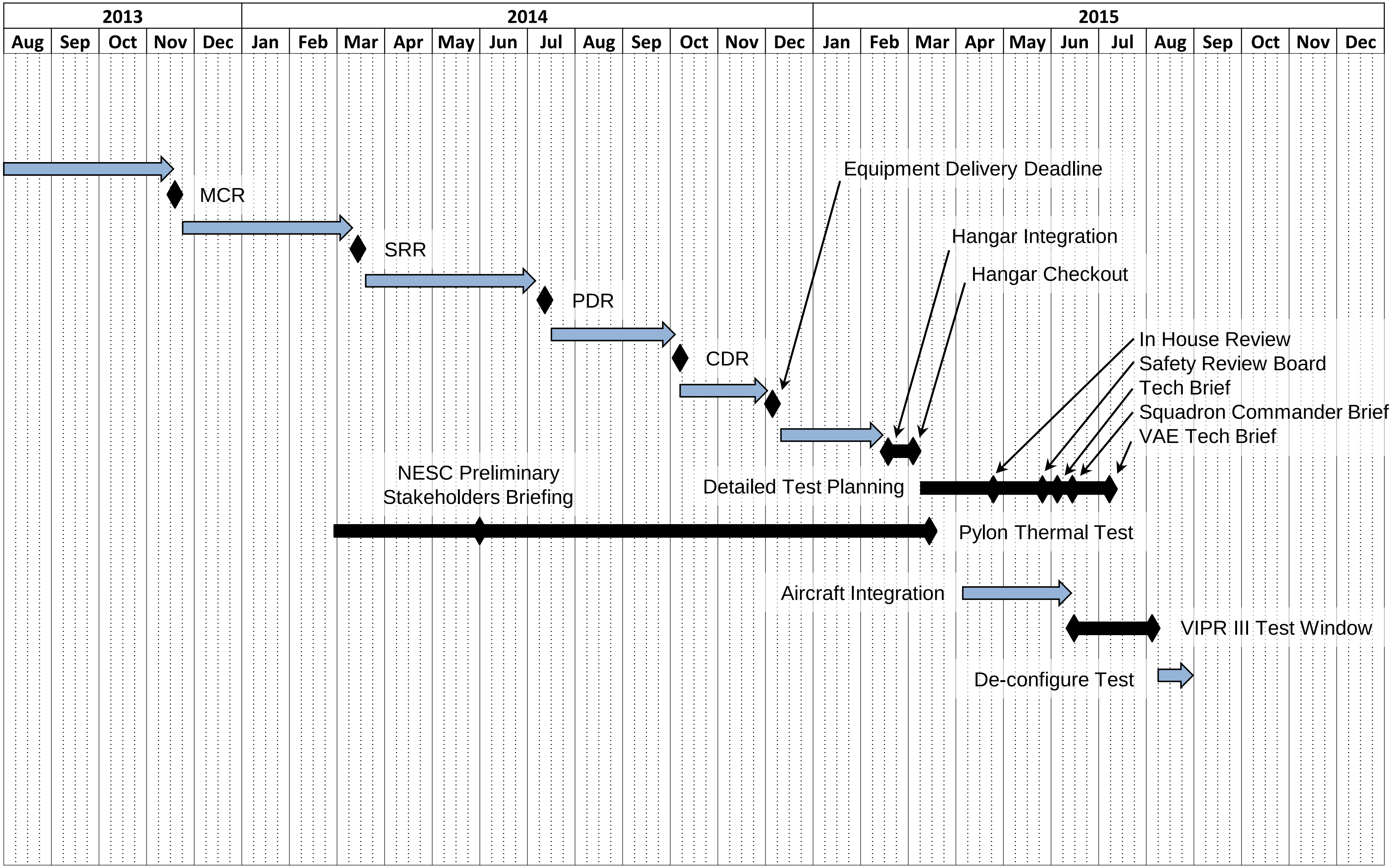




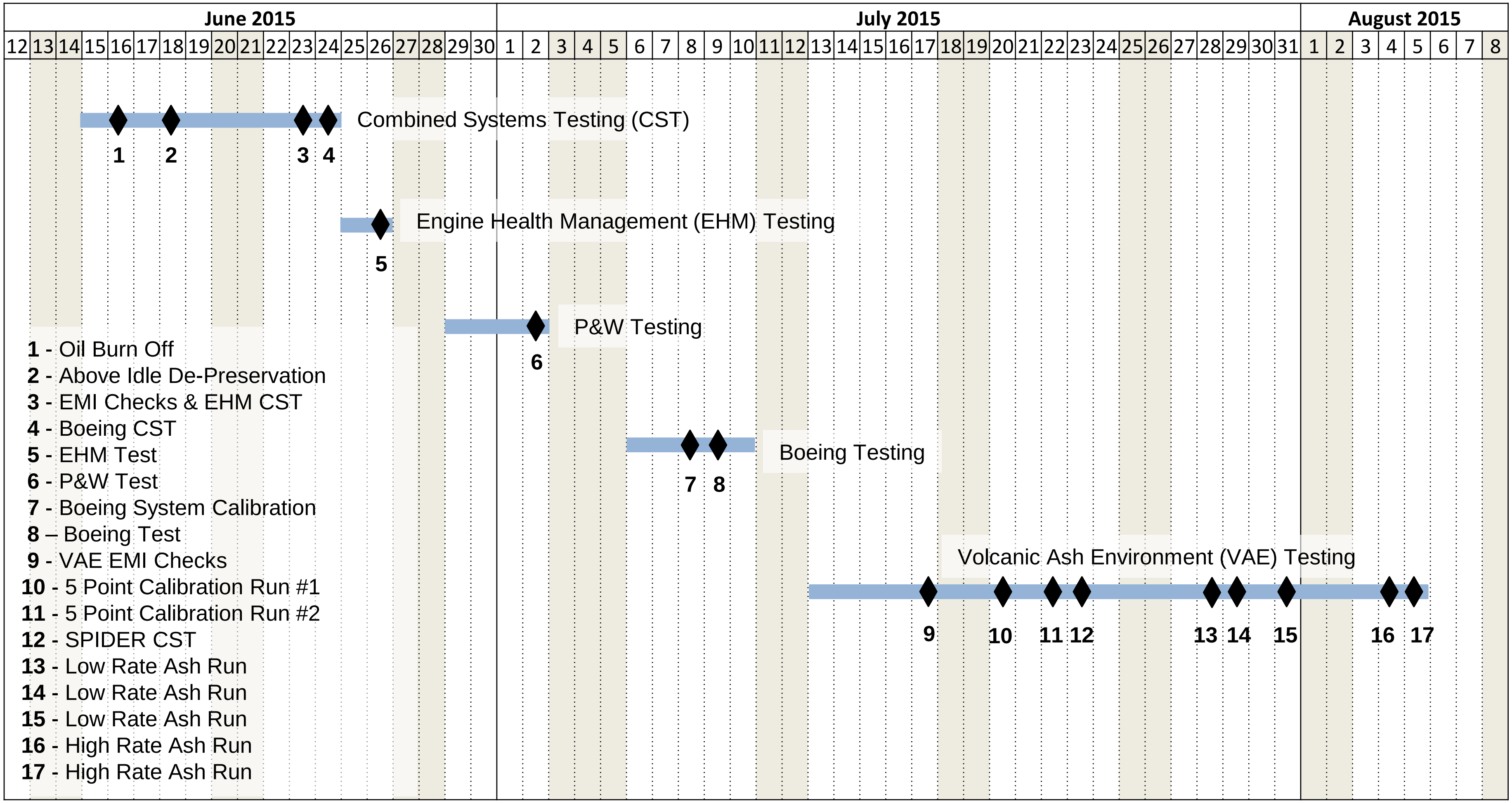


- Good news
  - ✓ The ash will flow into the core stream
  - ✓ Ash flow is controllable
  - ✓ The engine will run unabated by the SPIDER/VADR installed in the inlet
- Not so good news
  - ✓ Found a few structural bumps but overall the concept indicated the idea will work
  - ✓ SPIDER legs went from 4 to 3 legs to ensure upsets in airflow were minimized

VIPR III Execution Flow



On Aircraft Test Execution Flow



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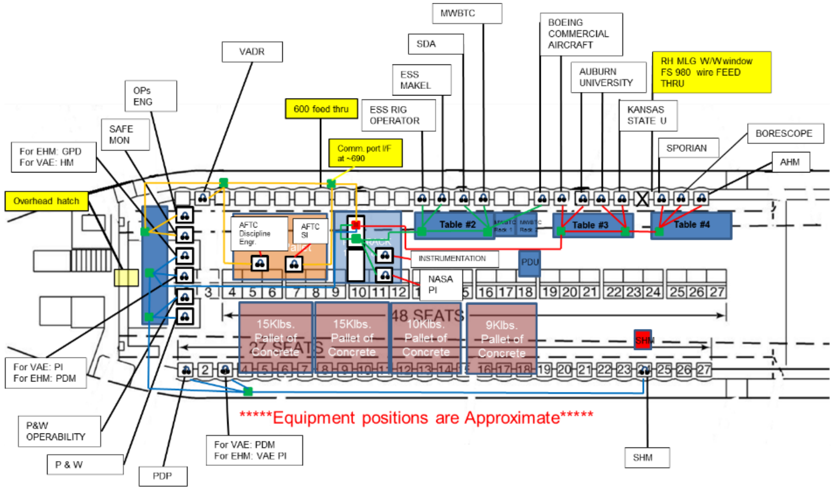
Integration

Hangar Checkout



Aircraft Research Station Layout

Aircraft Research Station Layout (Forward looking Aft)

Aircraft Research Station Layout (Aft Looking Forward)

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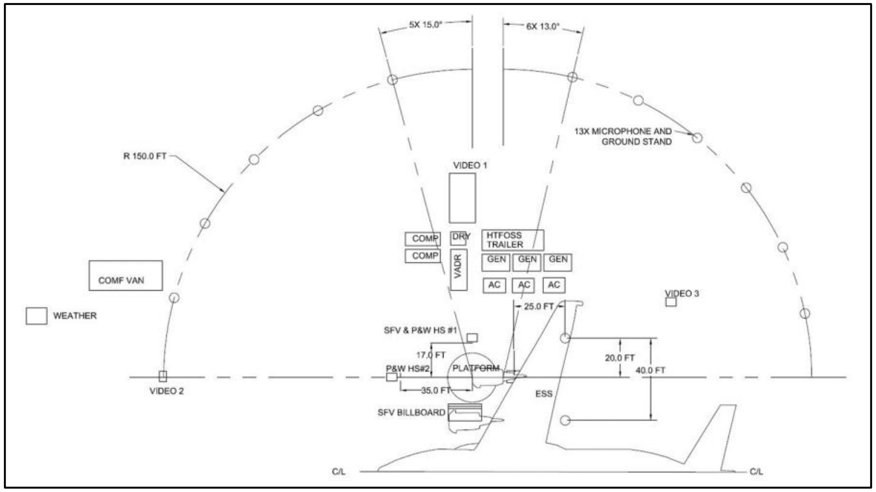
Test Site Integration

Volcanic Ash Ingestion Setup

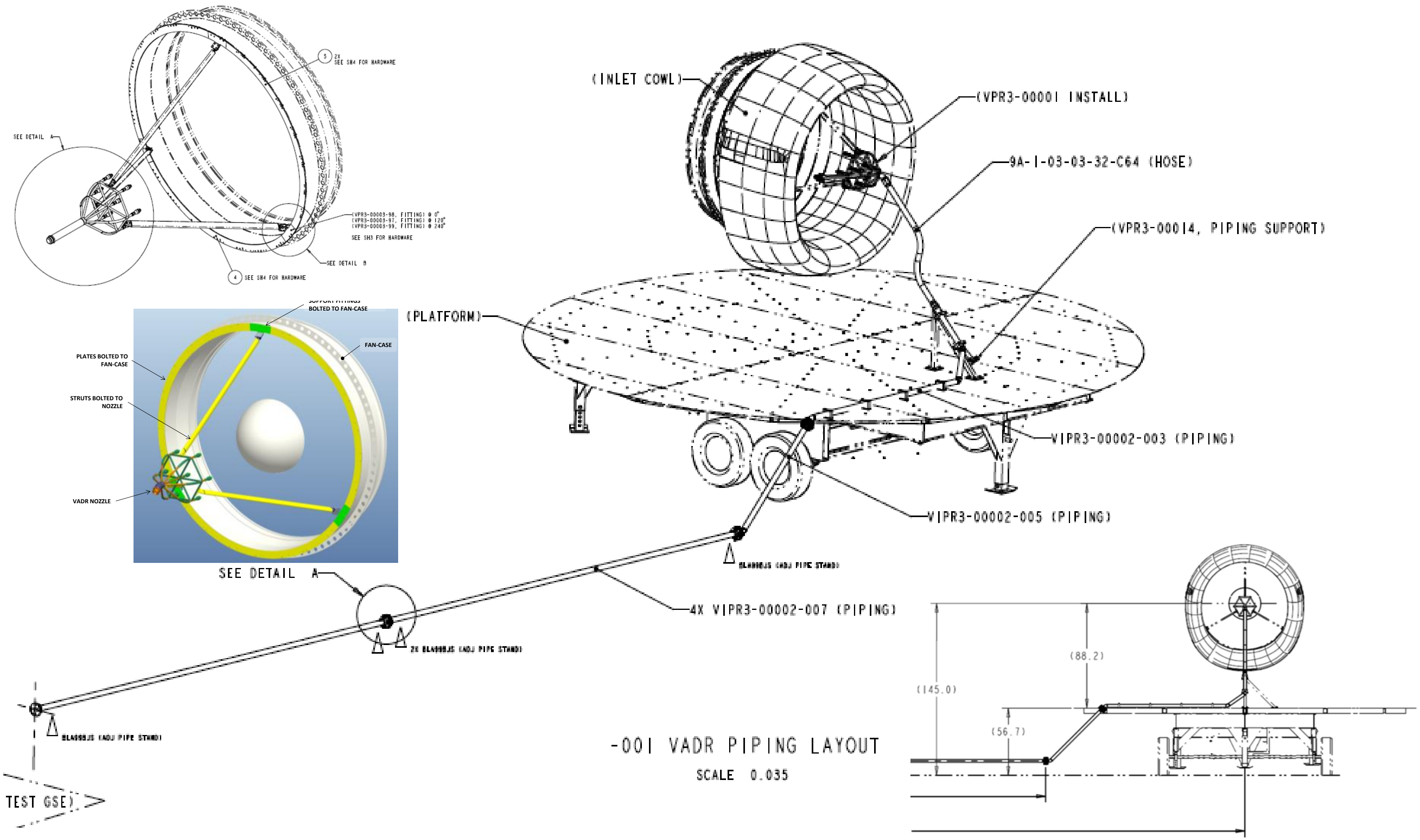


Support Equipment Layout

Test Location

Combined Systems Test Operations

Integration of the VADR and SPIDER to the ground platform V2.0



On Engine Installation & Testing



Volcanic Ash Ingestion Setup

Test Operations

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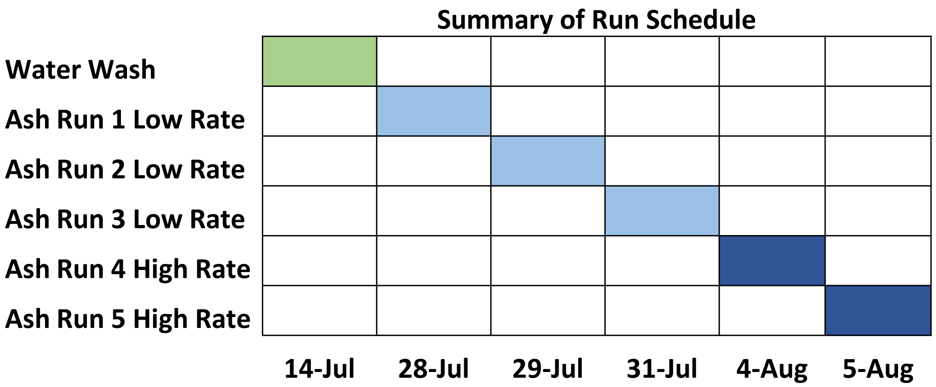
Overview

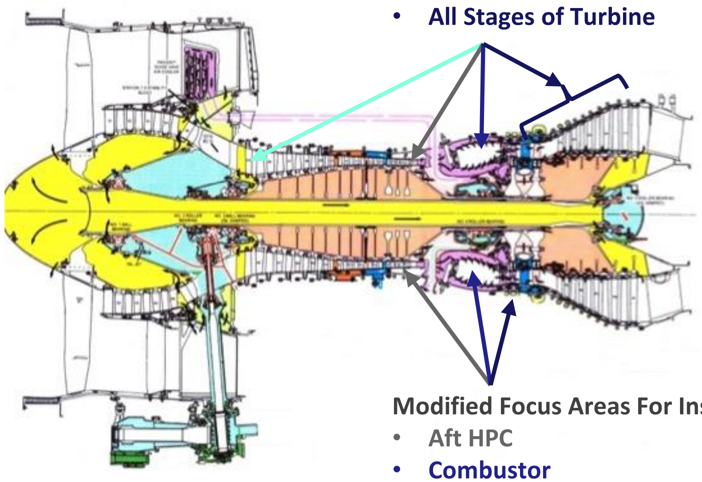


Notes

- Low rate is a target concentration
  - ~1mg/M^3 ≈ .11 gm/sec feed rate
- High rate is a target concentration
  - ~10mg/M3 ≈ 1.1 gm/sec feed rate
- Baseline engine inspection
  - Industry and government evaluations
  - Forward and aft compressor
  - Entire turbine was selected
- Findings
  - Aft compressor, burner section & forward turbine
    - Most critical
  - Control lines (Pb/P4.9)

High Pressure Turbine – HPT
High Pressure Compressor – HPC
Fuel Nozzle – FN
Stage of Compressor – SC
Trailing Edge – TE
Leading Edge – LE
Combustor Liner - CL

Original Focus Areas For Inspection
- Forward Compressor
- Aft Compressor
- Combustor
- All Stages of Turbine



Modified Focus Areas For Inspection
- Aft HPC
- Combustor
- Forward Stage of HPT

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

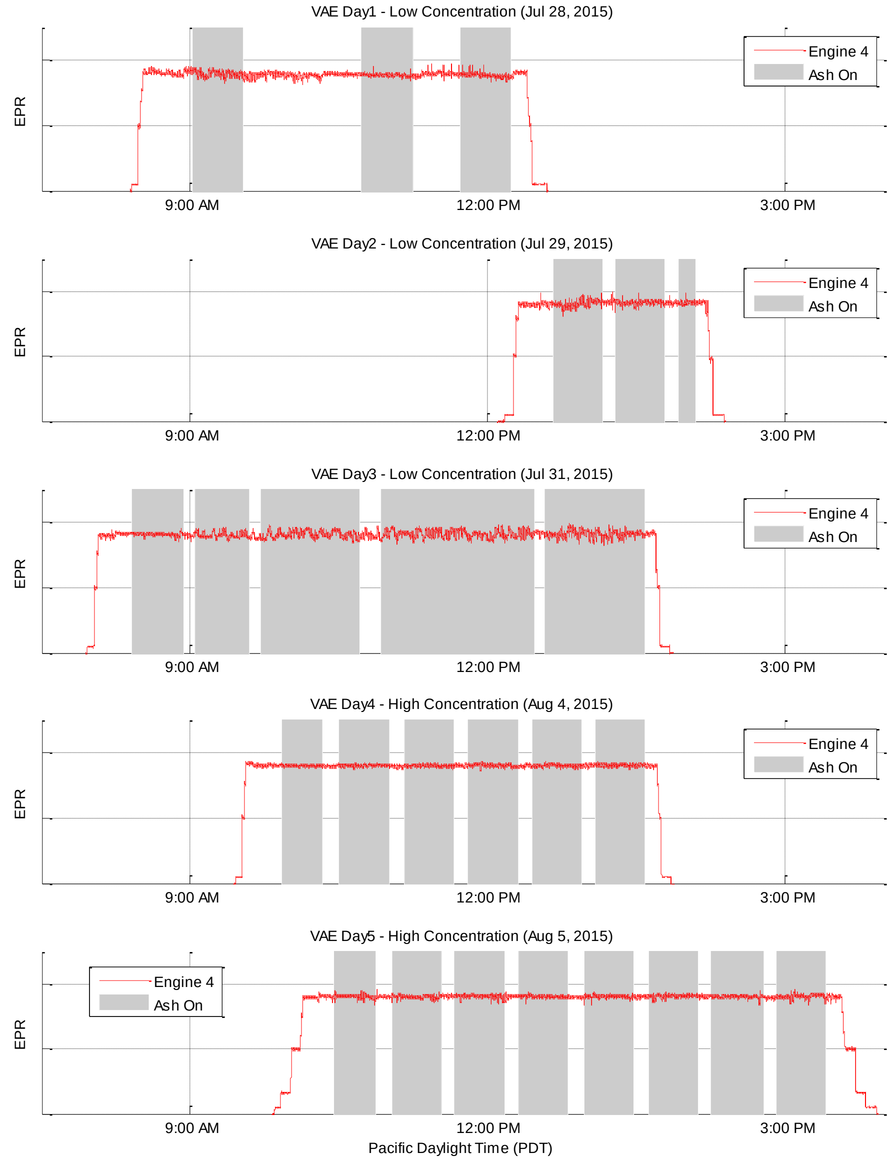
July 22: Calibration run conducted to establish baseline engine performance level

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/m³)	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



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Volcanic Ash Delivery

Date	Target Rate	Ash Flow Duration	Initial Ash Wt	Ash out during auger prime	Ash added during test	Ash augered out post-test	Actual Rate	Total Ash Delivered
	g/sec	minutes	g	g	g	g	g/sec	wt
28-Jul-15	0.1	90	2991	40	0	2221	0.14	730
29-Jul-15	0.1	68	3014	39	0	2426	0.13	549
31-Jul-15	0.1	269	2967	35	1000	1776	0.13	2156
4-Aug-15	1	175	2998	57	8977	901	1.05	11017
5-Aug-15	1	235	3001	64	12449	921	1.03	14465
All Tests Sum:	N/A	837	N/A	N/A	N/A	N/A		28917

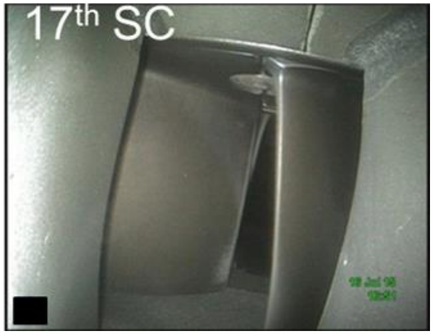
✓ ✓

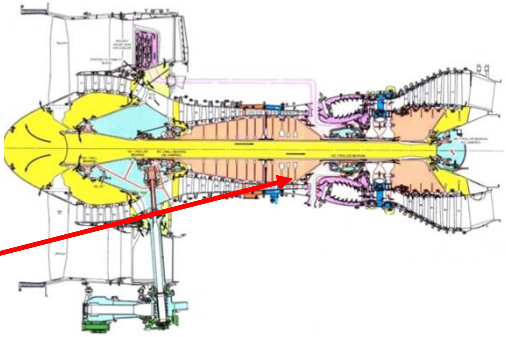
ENGINE ASH INGESTION OBSERVATIONS
5 DAYS OF ENGINE TESTS

Summary – Compressor Degradation

Post Water Wash

Baseline





Compressor

Low Concentration

Run 1

Run 2

Run 3

High Concentration

Run 4

Run 5

Observations – Compressor Degradation

Baseline
- No issues observed with blades or vanes

Run 1 (low concentration)
- HPC very clean, no obvious wear or discoloration
- Mild ash accumulation on 10th stage bleed cap

Run 2 (low concentration)
- No noticeable changes

Run 3 (low concentration)
- No noticeable changes

Run 4 (high concentration)
- No degradation observed

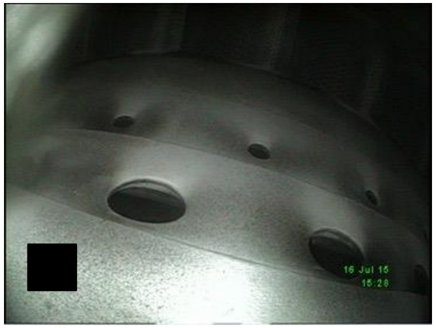
Run 5 (high concentration)
- No degradation observed

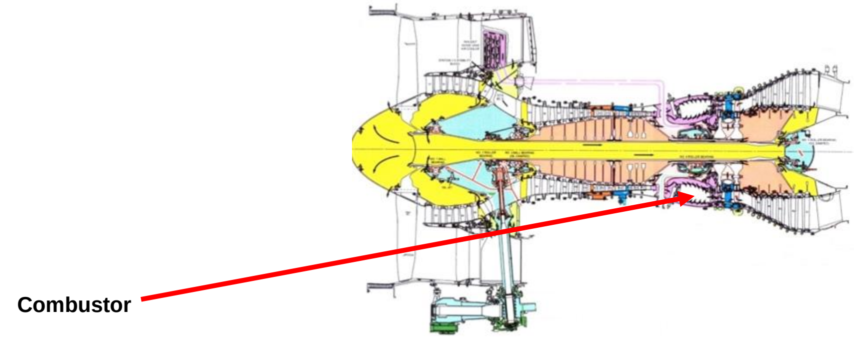
Note: Some degradation later observed in compressor during engine teardown. Will be discussed in next section of presentation.

Summary – Combustor Degradation

Post Water Wash

Baseline

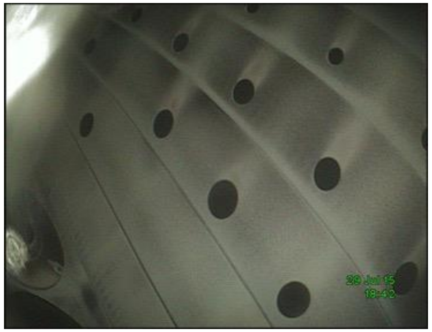




Low Concentration

Run 1

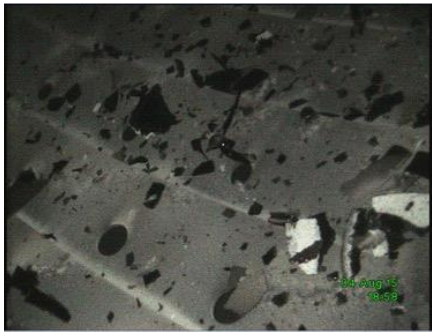
Run 2



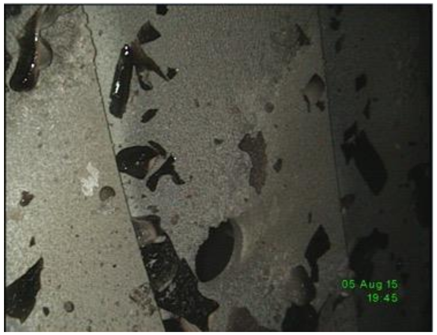
Run 3

High Concentration

Run 4



Run 5



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Observations – Combustor Degradation

Baseline
- Baseline state looks clean

Run 1 (low concentration)
- No major changes from baseline

Run 2 (low concentration)
- No major changes from baseline

Run 3 (low concentration)
- Shedding material starting to show up in combustor area
- Other areas around the fuel nozzle show some very local ash accumulation

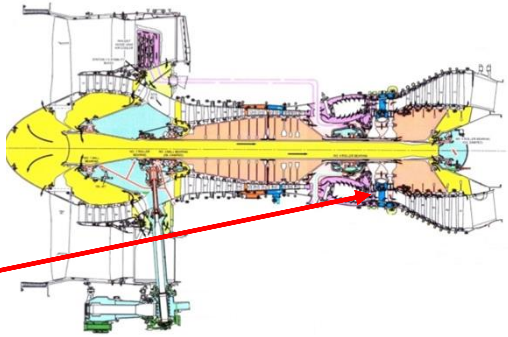
Run 4 (high concentration)
- Showing large thin flakes of ash shedding

Run 5 (high concentration)
- Similar to first high flow run day (Run 4) showing large thin flakes of ash shedding

Summary – First Stage Turbine Vane Degradation

Baseline

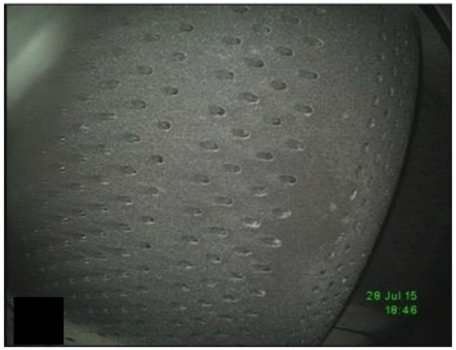
Post Water Wash



First Stage
Turbine Vanes

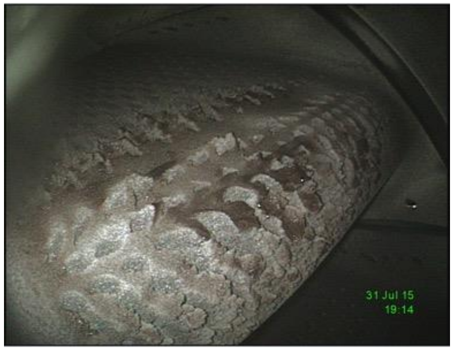
Low Concentration

Run 1



Run 2

Run 3



High Concentration

Run 4

Run 5

Observations – First Stage Turbine Vane Degradation

Baseline
- No issues with vanes, No appearance of coating or alloy burning

Run 1 (low concentration)
- No evidence of ash accumulation on turbine parts
- Slight plugging of cooling holes in first stage turbine vane
- Cooling air still flowing, not a concern to continue running

Run 2 (low concentration)
- Slight ash seen on first vane leading edge
- No ash seen on gauge point area of 1st vane

Run 3 (low concentration)
- More build up
  - 1st vanes leading edge and forward pressure side
- Aft pressure side gauge area (A4)
  - No built up thus not reducing the gauge area

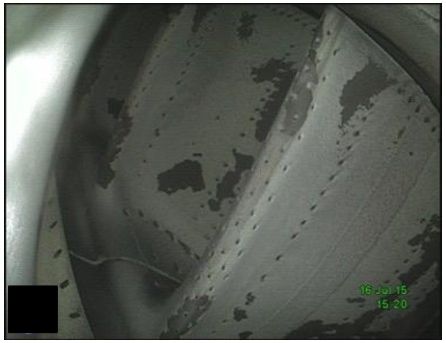
Run 4 (high concentration)
- 1st stage turbine vanes
  - Build up appears to be glassified ash as expected
  - Gauge point region, still not significantly closed down

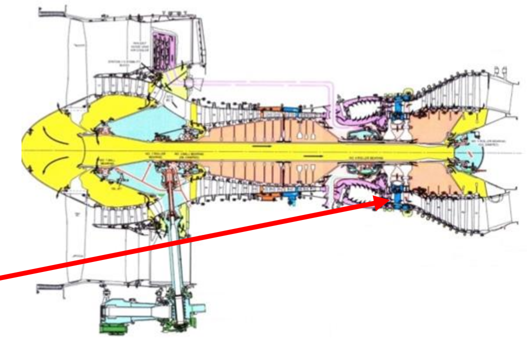
Run 5 (high concentration)
- Build up and shedding looks similar to Run 4
  - Gauge area (A4) still not built up

Summary – 1st Stage Turbine Rotor Degradation

Post Water Wash

Baseline





First Stage
Turbine Rotor

Low Concentration

Run 1

Run 2

Run 3

High Concentration

Run 4

Run 5

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Observations – 1st Stage Turbine Rotor Degradation

Baseline
- TBC intact, no blade distress
- Darker areas on blades potentially soot from shutdown, no appearance of coating or alloy burning

Run 1 (low concentration)
- No major changes from baseline

Run 2 (low concentration)
- No ash seen on first blade
- 1st blade outer edge seal leading edge region
  - May have small ash particles

Run 3 (low concentration)
- 1st stage blades , Still show very little effect of the ash
- Turbine ash accumulation is still very low

Run 4 (high concentration)
- 1st blades still are relatively clean but starting to show some accumulation

Run 5 (high concentration)
- Slight build up on some 1st blade leading edges
- Assume it's ash, but did not look "glassified"

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ENGINE ASH INGESTION OBSERVATIONS
POST TEST – ENGINE TEAR DOWN

Teardown - Observations

- Fan/Fan Case
  - No indication of ash buildup in fan bypass, transitions, joints, or interfaces
  - Fan blade leading edges had slight change in roughness and rounding
- Low Pressure Compressor
  - 1st stage LPC appeared to have surface finish changes between blade platforms, 5th stage LPC contained blades with trailing edge tip distress and polishing
  - Ash accumulation on outer side of flanges
- High Pressure Compressor
  - All blades and stator vane assemblies were "polished" on the outer 1⁄4 - 1⁄3 span
  - 8th stage HPC wear at leading edge tips
  - 11th stage HPC wear at trailing edge tips
  - Variable stator segments (6th- 10th stages) were "stiff", normally smooth when turning by hand
  - Blade Outer Air Seals (BOAS) intact for forward stators (6th – 10th stages)
  - Blue tinting appearing on metal disk stages 10-17, with heaviest notes on 14th and 15th
  - HPC exit stators contain leading edge distress extending radially outwards

Teardown - Observations

- Combustor
  - Inner and outer combustor liner intact with no evidence of distress
    - Ash accumulation on inner and outer liner surfaces with additional build up in the outer cavity between the burner and diffuser case. Inner liner had a light tan ash deposits aft of the cooling holes
  - Green tint on outside wall of outer basket, increasing further aft
  - Combustor was more difficult to remove than typical
  - Glass-like deposits found at 6 o’clock position when engine held horizontal
  - Fuel nozzle air holes had significant ash build up but did not appear to obstruct air flow

Teardown - Observations

- High Pressure Turbine
  - 1st Stage Vane Assemblies
    - Ash deposits of various transformations accumulated on most of the vanes and varied in thickness, reflectivity, color and coverage
    - Shedding appeared to have occurred multiple times at some locations
    - Some deposits were estimated to be 7- 10 mm thick
    - Some of the heavier deposits completely covered leading edge cooling holes, preventing flow
    - Trailing edge surface accumulation was notably different in texture and color compared to leading edge buildup
    - Cooling circuit inner flow path appeared to be clear of ash

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Teardown - Observations

- High Pressure Turbine (continued)
  - 1st Stage Blades
    - Majority of leading edge of blades had sporadic blockage of cooling holes
    - Leading edges of blades exhibit mechanical impact erosion and some appear to have divots
    - The pressure side of the blades a matte tan color was evident
    - Various levels TBC spallation and removal observed throughout blades
    - Ash accumulation found in cooling passage at root but did not show plugging
    - Platform cooling holes were not plugged
    - Typical wear on outer edge BOAS

Teardown - Observations

- High Pressure Turbine Continued
  - 2nd Stage Vane Assemblies
    - No visual evidence of cooling flow blockage on vane and inner cooling flow path circuit is clean
    - Few vanes had TBC missing
  - 2nd Stage Blades
    - Blades were normal, unremarkable
    - Loose ash found on blades and blade roots
    - Heavy ash content found below the platform
    - Coating material on BOAS missing in blade path

ENGINE PERFORMANCE DATA – VOLCANIC ASH INGESTION

&

RESULTS – SELECT INDIVIDUAL SENSOR TECHNOLOGIES

Gas Path Diagnostics

Background:
- Analysis of gas path parameter measurements for performance monitoring, diagnostics, and prognostics

Benefits:
- Safety: Reduce propulsion system malfunction plus inappropriate crew response accidents
- Affordability: Reduce life cycle cost

Advances to state-of-the-art:
- Gas Path Diagnostics (GPD): Model-based approach for analysis of continuous full-flight data, improved diagnostic accuracy and reduced diagnostic latency.
- Prognostics and Decision Making (PDM): Accurate estimation and forecasting of remaining useful life.
- Information Fusion: Systematic approach for combining disparate information sources to produce a unified assessment of engine health

Aircraft engine performance deterioration mechanisms and gas path fault types

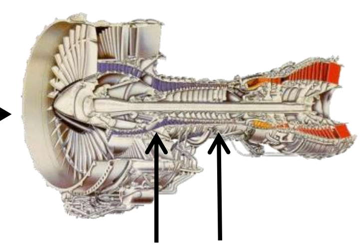
Turbomachinery Deterioration
- Fouling
- Corrosion
- Erosion

Turbomachinery Faults
- Foreign object damage
- Blade/Vane failure

Controls & Accessories Faults
- Sensor faults
- Actuator faults

VIPR 3 gas path faults and deterioration

Volcanic Ash Ingestion Induced Deterioration



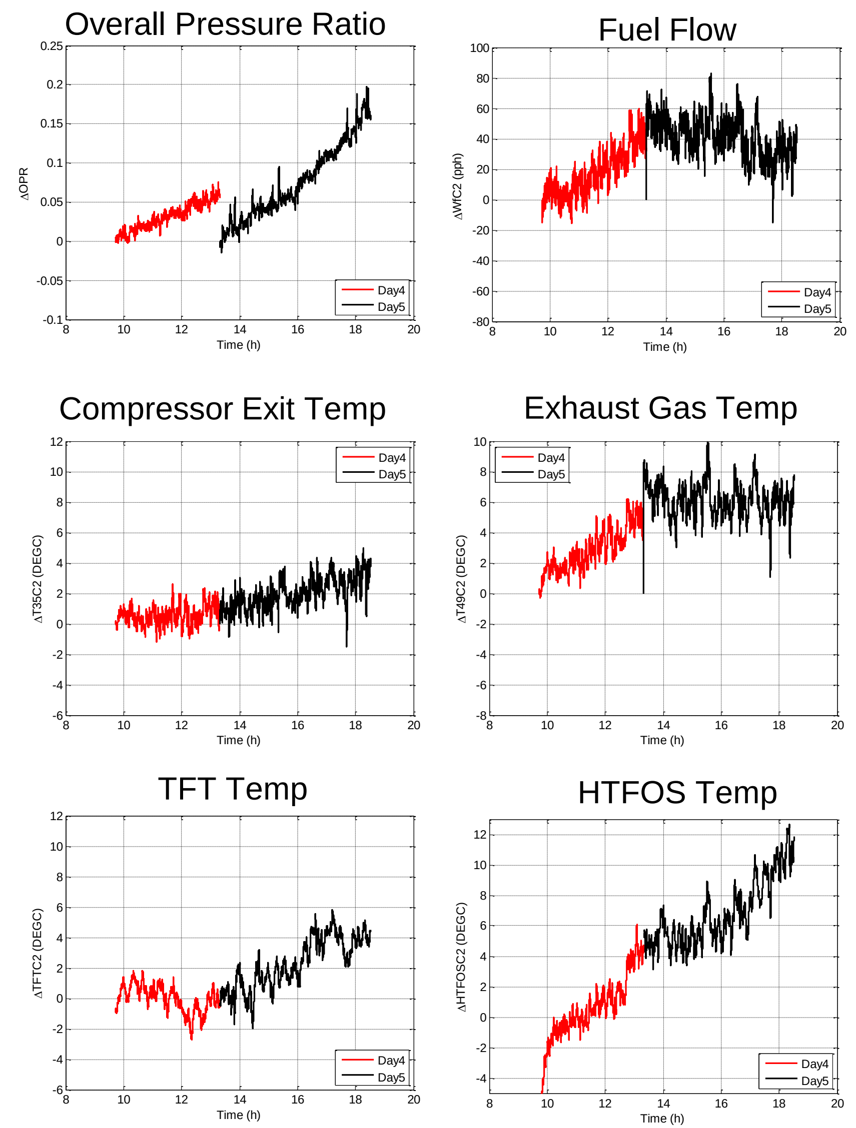
Station 2.5 Bleed Fault

14th Stage Bleed Fault

Gas Path Measurement Data – Volcanic Ash Test Runs

RESULTS AND SIGNIFICANCE (Preliminary)

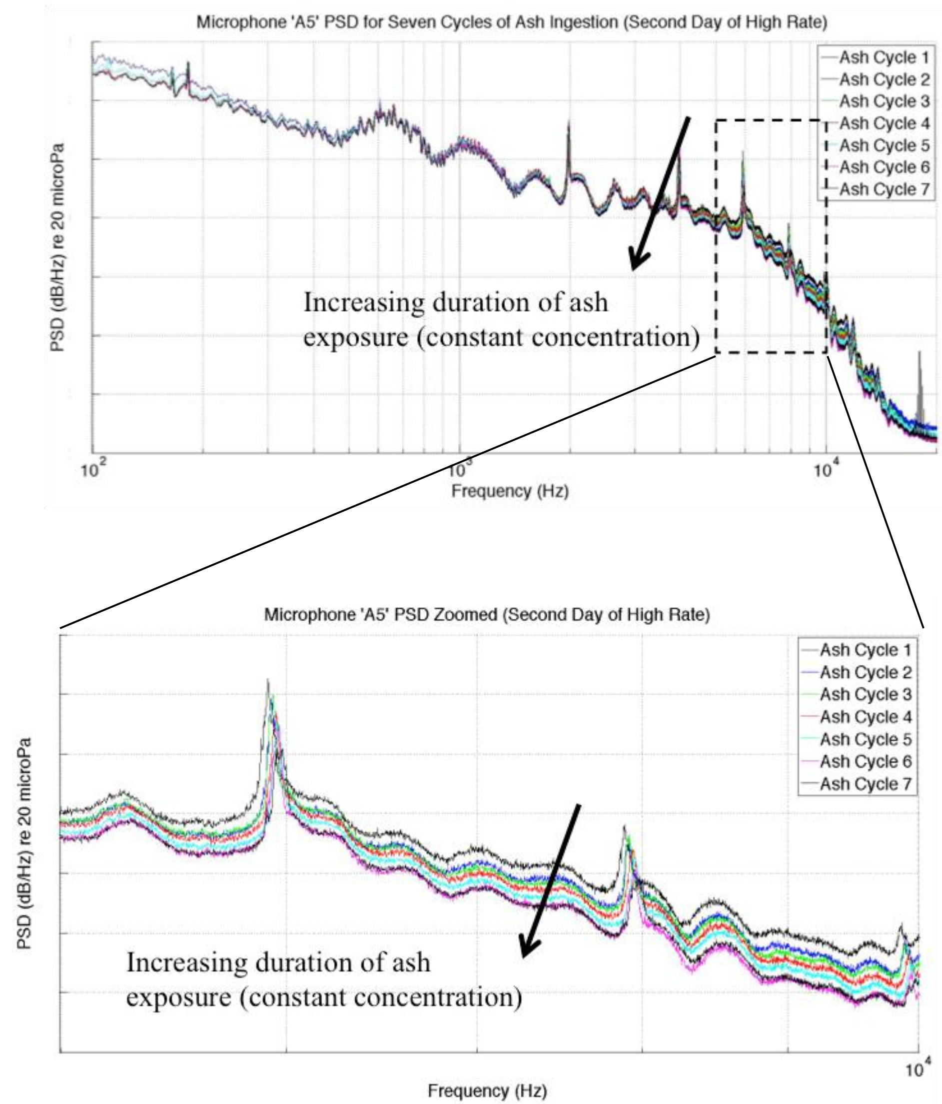
- Five (5) days of volcanic ash ingestion testing
  - – Days 1, 2, and 3 ran low concentration ash ingestion
  - – Days 4 and 5 ran higher concentration ash ingestion
- No significant engine performance variations were observed during low concentration ash runs
- On high ash concentration run days, discernable 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
  - – Thin Film Thermocouple (TFT) trends with compressor exit temperature
  - – High Temperature Fiber Optic Sensor (HTFOS) trends with exhaust gas temperature



VAE Performance Trend Shifts – Day 4 & 5

Acoustic Detection of Faults Experienced by a High-Bypass Turbofan Engine

- **Cumulative exposure to volcanic ash caused detectable changes in engine acoustics**
- Spectral noise discontinuities evident during engine degradation as an apparent function of cumulative ash ingested by the engine
- Qualitatively demonstrated the feasibility of detecting certain faults
- Fault detection successful in the presence of numerous contaminating noise sources
- Could lead to a diagnostic tool capable of fault identification or engine health evaluation



Emissions Sensor Suite
Volcanic Ash Testing

OBJECTIVE

- Demonstrate the ability to diagnose engine faults and performance loss effects using a multiparameter emission sensor array

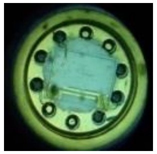
APPROACH

- Engine Emission Monitoring System developed using selective microsensors and smart electronics
- Includes the capability to measure CO, CO2, O2, hydrocarbons, and NOx.
- Sensor suite mounted at engine exhaust and exposed to both nominal conditions and simulated faults, as well as volcanic ash

RESULTS AND SIGNIFICANCE (Preliminary/Volcanic Ash)

- Emissions Sensor Array Monitored Engine Emissions during Days 1-3, 5 of Ash runs
- Days 1-3: Candidate "Steady-State" Emissions Parameter Identified
- Day 5 Deviation in "Steady State" Emissions Profile Suggestive of Change in Engine State During Heavy Volcanic Ash Deposition
    - Not Presently Explainable By Reference to Other Engine Parameters

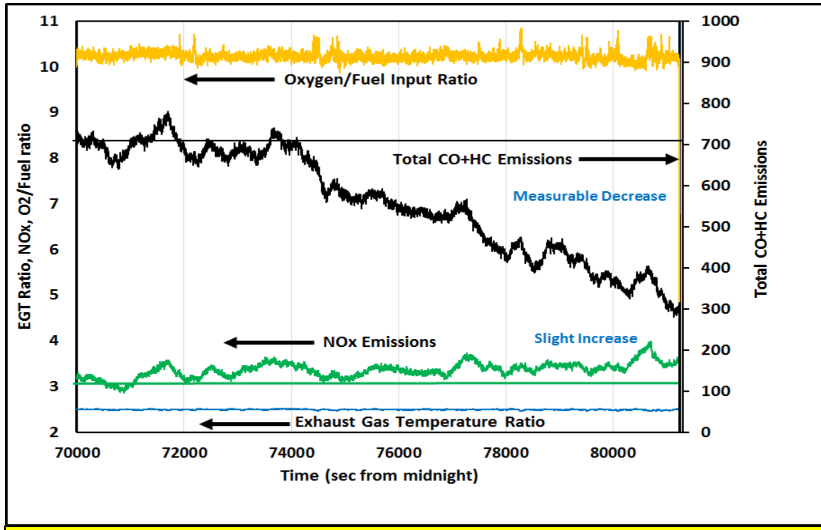
Multiparameter Engine Exhaust Measurements Track Major Species



CO sensor

Sensor probe

Sensor probes in emissions testing rig manifold



Preliminary Emissions Data –
- **Pattern Established Over Several Runs**
- **Deviations from Baseline Observed Suggesting Possible Volcanic Ash Effects**

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Performance of High Temperature Fiber Optic Sensor

OBJECTIVE

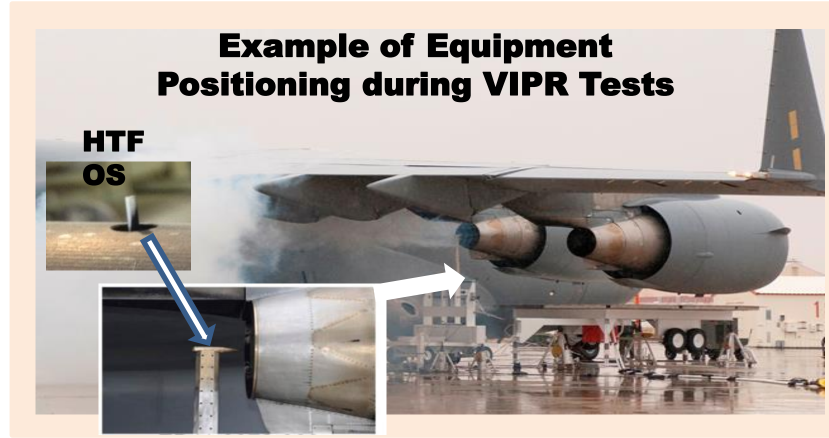
- Evaluate performance of a high temperature fiber optic sensor (HTFOS) and it responses to various engine operation conditions and the ash ingestion

APPROACH

- Develop silica-based HTFOS suitable for operation at engine exhaust temperatures
- Install the sensor in the exhaust plume behind the jet engine
- Evaluate the sensor performance in the engine exhaust plume under various engine operating and ash ingestion conditions. Compare results with the EGT sensor data.

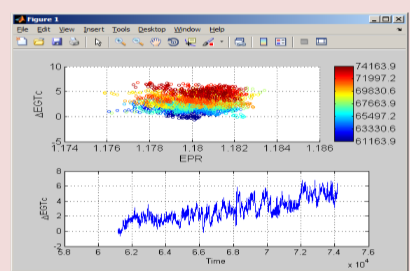
RESULTS AND SIGNIFICANCE

- NASA GRC developed a HTFOS capable to withstand thermal and vibrational environments of the jet engine exhaust plume.
- NASA completed a series of tests of the HTFOS in the NASA AFRC facility in July 2015.   The tests demonstrated operability of the sensor in the above mentioned environments.
- The results were close to those from the EGT sensors and clearly showed a path for incorporation the HTFOS into EGT ports inside the jet engine exhaust nozzle structure.

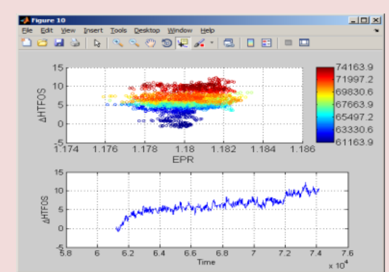


ESS with HTFOS installed behind the engine exhaust

Preliminary Data Comparison



EGT Sensor



HTFOS

Suggested Next Steps – Volcanic Ash Research

- Volcanic ash ingestion testing was successful
  - Engine did not degrade as much as originally expected
  - Good first step, but recognize more data is needed to provide better understanding of impact
- Volcanic ash questions still open
  - Determine the effect of volcanic ash cloud chemistry
  - Determine the effect of different ash compositions
  - Build model that predict VA buildup in different engines
    - Modeling of glass build-up & degradation – like what has been done for icing
  - Understand the effect of VA on new N+3 materials and higher operating temperatures
    - Will ceramic parts shed ash similarly to metal parts?
    - Will ash build up in more sections of the engine due to higher temperature?
  - What is the effect of ash concentration?
    - Testing with different concentration levels, populate the database
  - Enhanced engine control and/or procedures on ash detection & recovery
- Fuel Efficiency
  - Leverage VIPR technologies to improve fuel efficiency
  - Can be leveraged into further Volcanic Ash and other Environmental Particulate FOD Research

VIPR 1, 2 and 3 Summary
Testing complete: highly successful

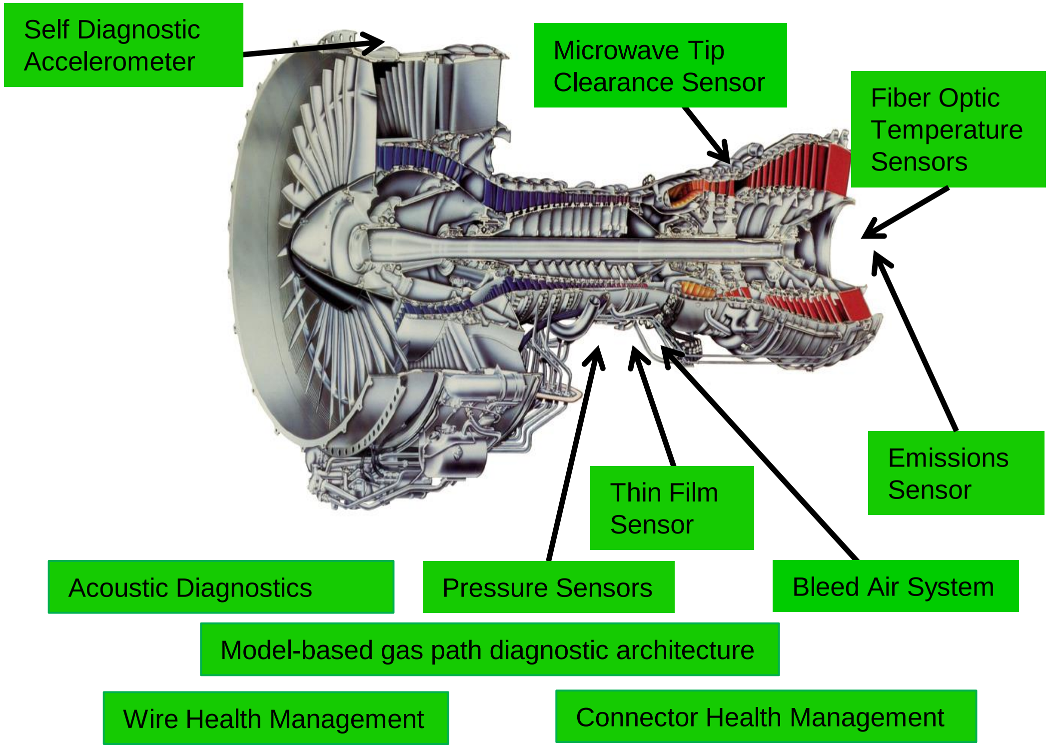
Test Objectives:

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

Overall Summary

- **Overall Impact of VIPR Technologies**
  - **Efficiency Trends**
    - **Higher Thermal Efficiency and Overall Pressure Ratios implies potential need for:**
      - Compressor and Turbine clearance control
      - Dynamic monitoring of gas path parameters
      - Active combustion control
      - Distributed engine control
      - Sensor packaging
    - **Propulsive Efficiency**
      - Larger Structures may require more extensive structural monitoring
    - **Active tuning can compensate for degradation and maintain efficiency**
  - **Reliability and Safety impacts**
    - **New materials may require new monitoring technologies**
    - **Smart Sensor Systems**
    - **Active tuning can compensate for degradation and mitigate acceleration**
  - **Operations impacts**
    - **Slowing degradation acceleration has the potential to keep engines on wing longer**
    - **Volcanic ash engine degradation testing with IVHM augmented engine**
      - Tests capability to detect volcanic ash affects in flight
      - Exercises the capability of IVHM systems for monitoring engine state
      - Adds to the knowledge base for operators to make better decisions in airspace with volcanic ash

Overall Summary (continued)

- **Paper titled "Volcanic Ash Ingestion Test of an Aircraft Turbofan Engine" to be released later this year.**

- **Questions?**

Backup Slides

Gas Path Diagnostics

Gas Path Diagnostics (GPD) Tests: Engine will be operated nominally (fault-free) and with bleed valve faults (station 2.5 and 14th stage bleed valves) under the following test scenarios

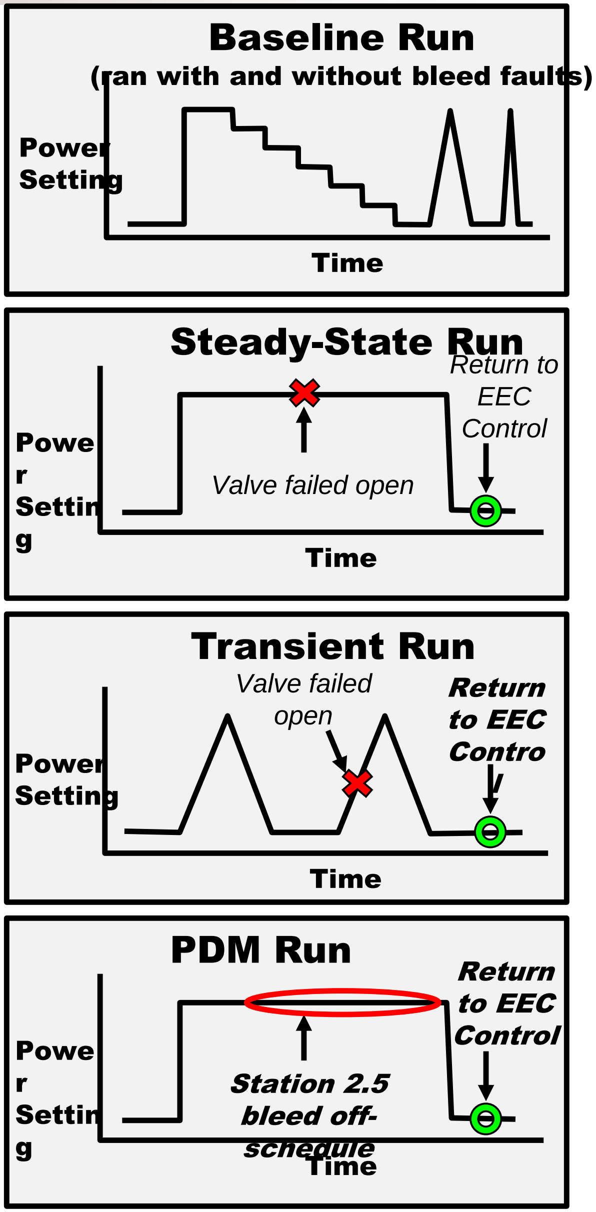
- Baseline runs
- Steady-state runs
- Transient runs

Prognostics and Decision Making (PDM) Tests:

- Incrementally bias station 2.5 bleed valve off-schedule (towards failsafe OPEN position)

Data Acquisition and Analysis:

- Specified bill-of-material (BOM) and 2.5 probe measurements will be acquired and archived
- Limited on-board data analysis to compare fault-induced engine performance shifts against model predictions (Microsoft Excel spreadsheet)
- Post-test down-load and analysis of VIPR3 test data archived on Omega Data Environment (ODE) server
- ***Model-based diagnostic technique successfully detected and classified engine bleed faults introduced during test***

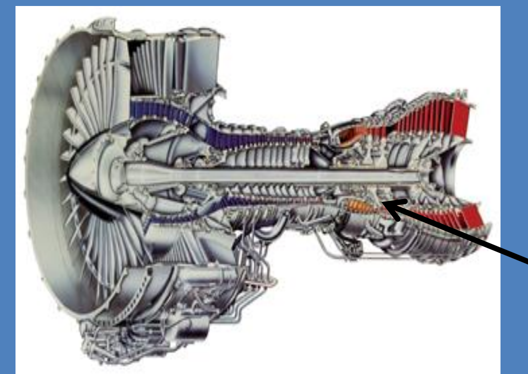


Microwave Blade Tip Clearance Sensors

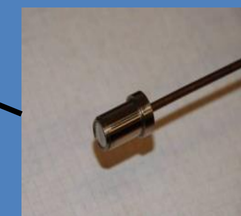
OBJECTIVE
Evaluate response to various engine operation conditions and ash ingestion

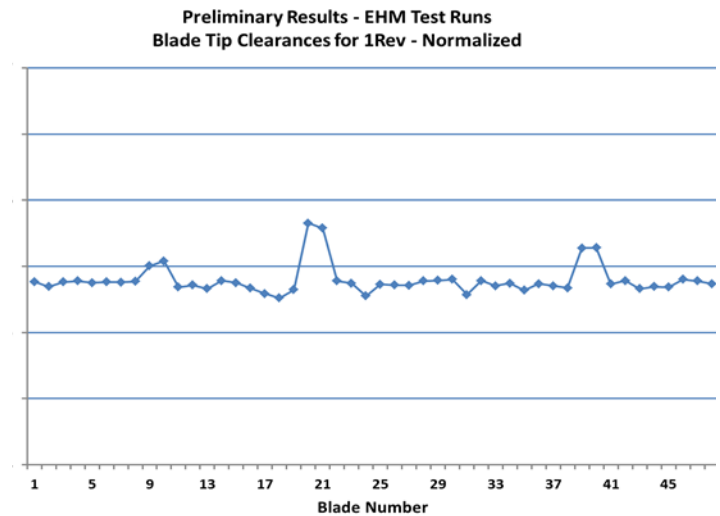
APPROACH
- Installed two sensors in the high pressure turbine
- Compare results with initial clearances measured at the build-up of the engine and analyze changes as ash ingestion progressed

RESULTS AND SIGNIFICANCE
- Preliminary results
    - individual blade-to-blade tip clearances were discernable
    - six (6) “marker” blades with known different lengths were detected



Microwave Blade Tip Clearance Sensor





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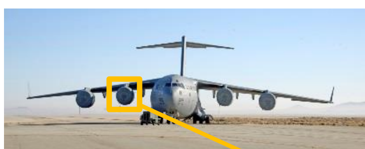
Self Diagnostic Accelerometer

Self Diagnostic Accelerometer System successfully provided

- vibration data
- health of the sensor
- sensor attachment condition

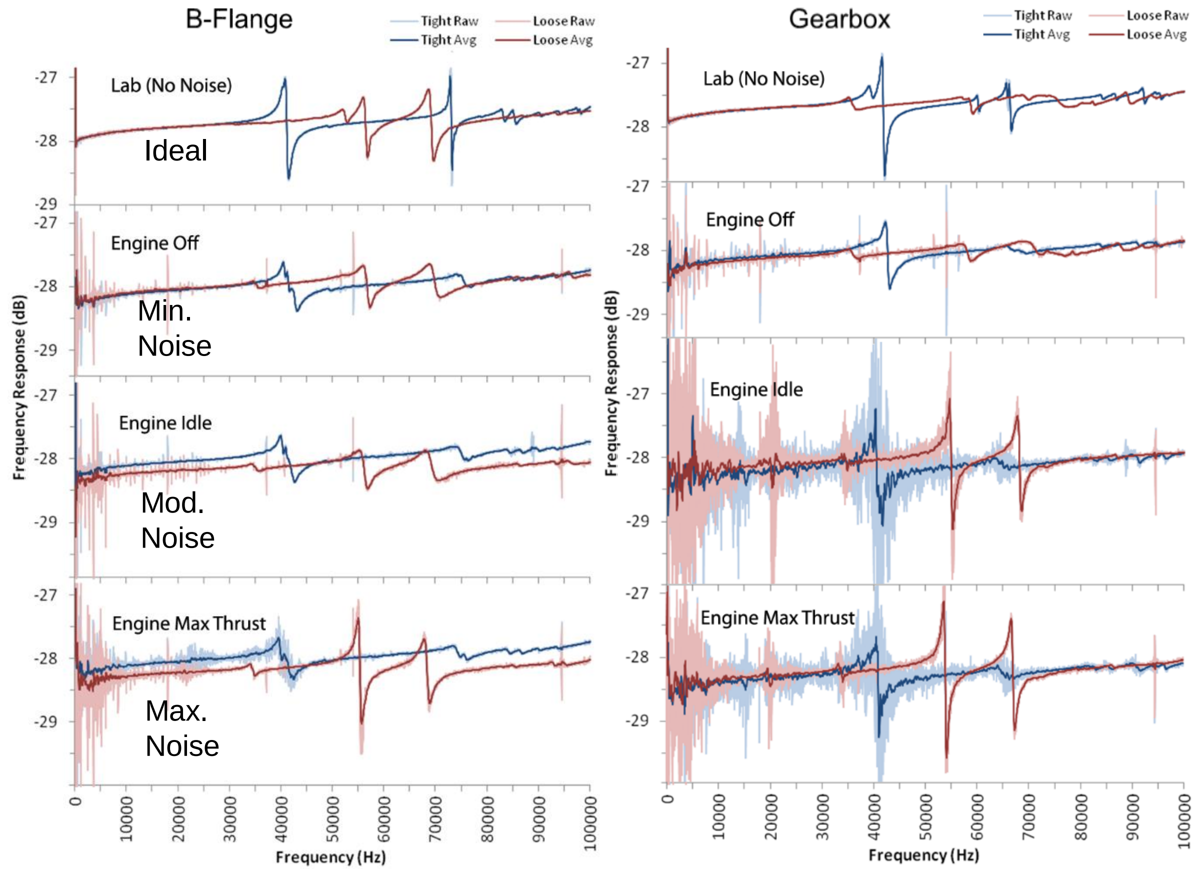
Test Locations



Accelerometer mount

Results

- Pattern recognition software successfully discriminated **all** tight and loose conditions



Thin Film Thermocouple

OBJECTIVE

- Enable improved dynamic temperature measurements at higher temperatures using thin film sensor technology

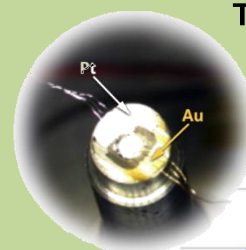
APPROACH

- Thin film sensors have negligible mass, are minimally intrusive, and can be applied to a variety of materials including ceramics
- Two high temperature prototype thermocouple probe designs fabricated and demonstrated
- Each sensor probe design demonstrated different thin film thermocouple types and packaging approaches

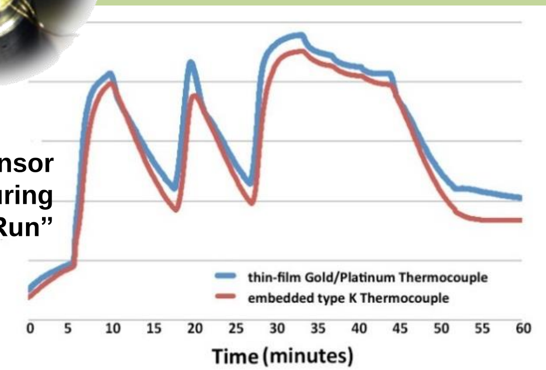
SIGNIFICANCE

- Operation of thin film thermocouple sensor prototypes validated as installed in bleed-air borescope ports
- Sensors tracked dynamic engine temperature changes through multiple power cycles with faster response than embedded thermocouples
- Data included monitoring VAE performance trends
- Tracked performance changes were observed elsewhere in engine
- Application not limited to bleed-air borescope ports
- Part of information fusion to better understand the overall health state of the engine

VIPR 2 Design: Metal Probe / Au-Pt Thermocouple



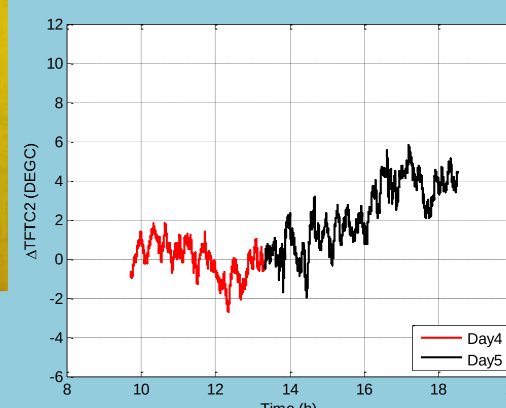
Sensor tip with 0.003" wires attached to deposited thin films



Thin Film Sensor Operation During "Green Run"

VIPR 3 Design: Spark Plug / Pt-Pd Thermocouple

Thin film deposition processing on "Spark Plug" sensor tip



Thin Film Sensor Data: Volcanic Ash Runs Day 4-5

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Pressure Sensor with Electronics

OBJECTIVE

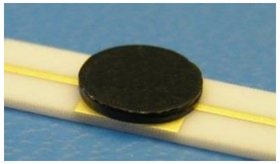
- Demonstrate the ability to measure engine conditions with a higher temperature pressure sensor integrated with electronics

APPROACH

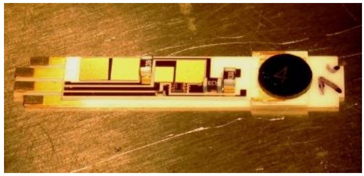
- High temperature sensor coupled with: first generation high temperature smart sensor
- Integrate multiple components into a single package to provide a
  - Capacitive pressure sensor composed of silicon carbon nitride (SiCN)
  - Silicon carbide electronics and passive devices for sensor signal processing
  - Packaged system for insertion in borescope port

RESULTS AND SIGNIFICANCE

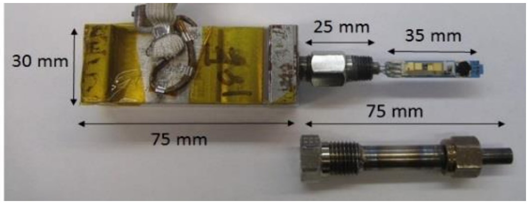
- Pressure sensor/electronics demonstrated in engine environment
- Data shows clear tracking of changes in engine operating conditions
- Provided communication of conditioned data (across a wire) using high temperature electronics.
- *First step towards smarter high temperature sensor systems*



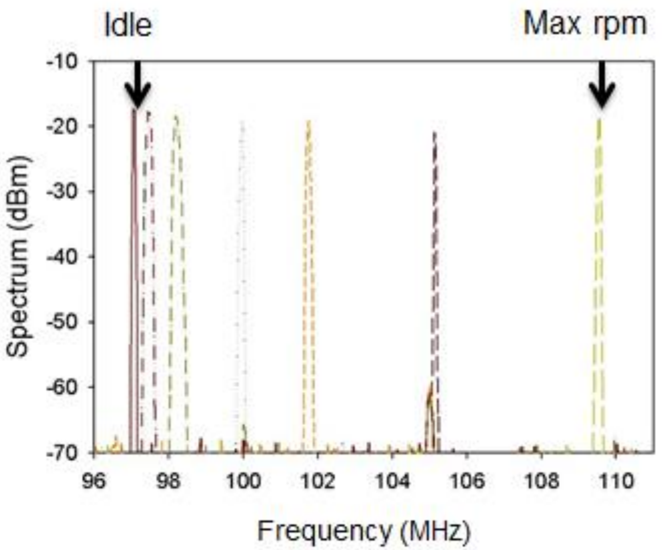
Capacitive pressure sensor



High Temperature Electronics Circuit



Sensor probe with electronics



Pressure Sensor Operation in Engine Conditions

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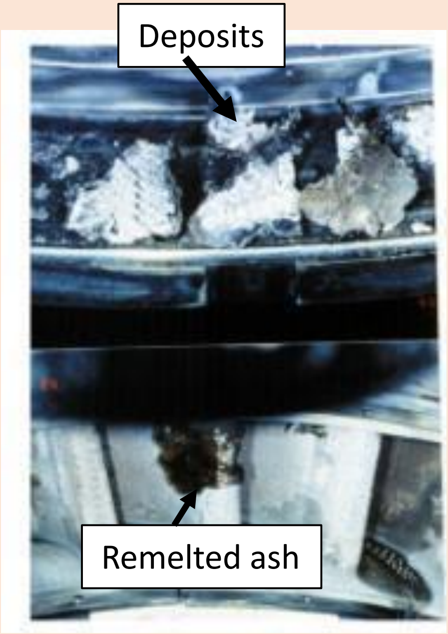
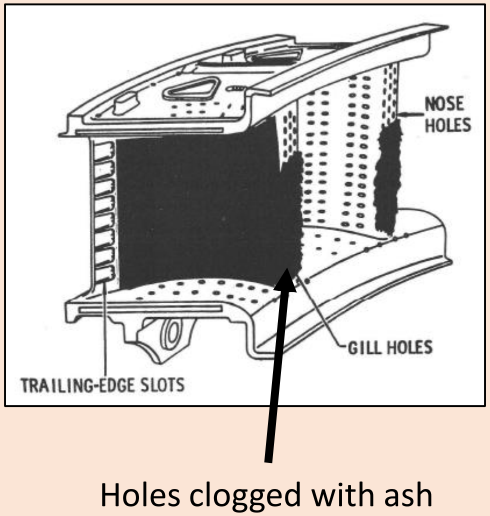
How does ash damage engines?

- Much of our knowledge has come from descriptions of damage to the KLM Redoubt engines, published by Przedpelski and Casadevall (1994).
- In that study, they
  - Observed melted deposits coating the Stage I HPT and nozzle guide veins, as shown to the right.
  - They concluded that *"The primary cause of engine thrust loss . . . was the accumulation of melted and resolidified ash on the stage-1-turbine nozzle guide vanes."[1]*
- From this work, it is generally assumed that:
  - Ash softens, sticks to moving parts, and stops them from operating; and that
  - Softened ash clogs nozzle guide vane holes, causing heat damage



Stage I HPT
Nozzle guide vanes



KLM 747 engines following 1989 Redoubt encounter
(figures from Przedpelski & Casadevall, 1994)

[1]Przedpelski, Z. J., and T. J. Casadevall (1994), *U.S. Geological Survey Bulletin 2047, edited by T. J. Casadevall, pp. 129-135.*

USGS
science for a changing world

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

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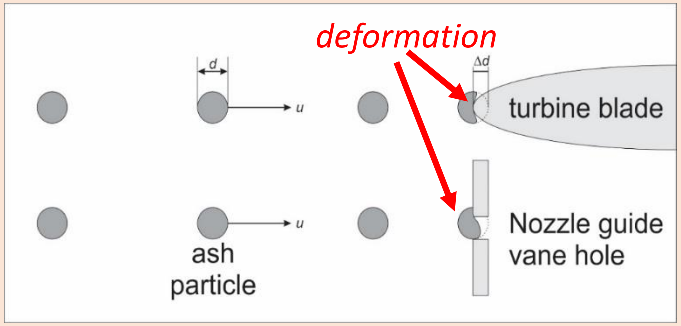
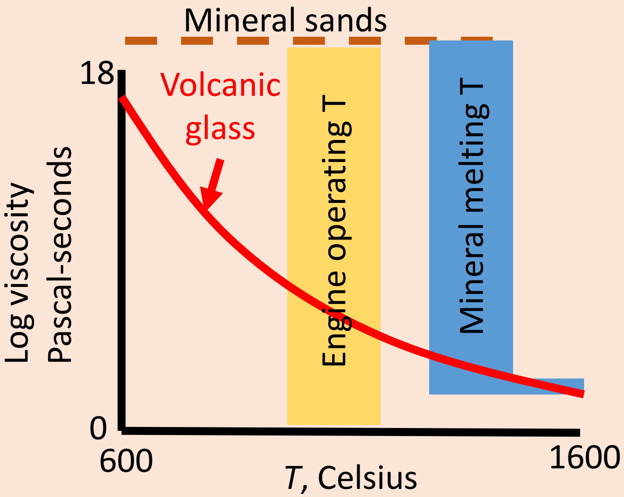
Ash properties differ from mineral dust and sand

- Ash is a mixture of *mineral crystals* and glass
  - Mineral crystals are solid at the operating temperature of most jet engines.
- Glass is *not a solid*. It is a liquid, with a very high viscosity.
  - With increasing temperature, its viscosity decreases as illustrated in the figure to the right
- We define a "critical viscosity" as one below which glass particles are soft enough to deform and coat engine parts, as illustrated below. Some studies[1] suggest this occurs at a viscosity near 10^8 Pascal seconds





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[1]Kueppers, U., et al., (2014), *Journal of Applied Volcanology, 3(1), 4.*

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

The deposit

Pyroclastic-flow deposit

Tephra fall deposit

- The pumice was collected from a commercial quarry[1] that produces mostly agricultural products
- Deposits were laid down during
  - Pyroclastic flows, or avalanches of debris like this one at Mount St. Helens, and
  - Tephra falling from ash clouds, like the one shown in 1980 in central Washington
- There was no significant difference in pumice properties from these two deposits.
- Most ash collected was from the lower fall deposit.

[1]South Chemult Pumice®

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

Pumice collection

- The pumice was collected from piles sieved by the quarry operator into pieces ½” to ¾” in diameter
- We collected 12 barrels, each weighing about 300 pounds
- The weight included about 40% water

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