National Aeronautics and Space Administration

Experiment to Test Low Concentration Volcanic-Ash Ingestion by a Jet Engine

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VIPR Partnership

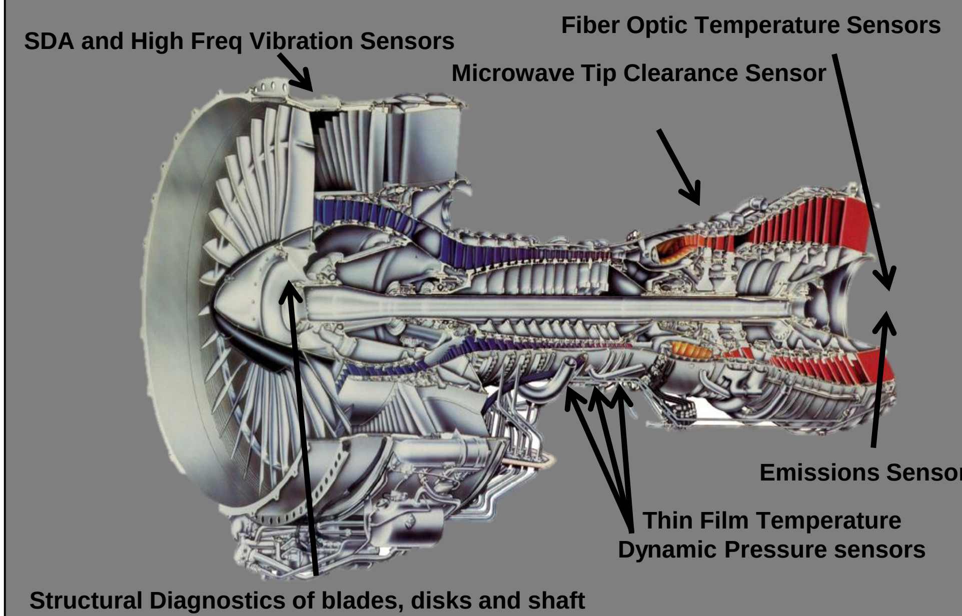
PARTNERSHIPS MAKE IT POSSIBLE

VIPR Stakeholders Contribution

- Direct: funds, equipment, material
- In-kind: resources for project success

Installed Engine Ground Tests

- Large bypass transport engine
- Baseline as-is engine operations
- Induced mechanical faults
- Induced gas path faults
- Simulate ash-air laden exposure
- Characterize degradation



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

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Engine Health Management

Existing Aircraft

- 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

Propulsion System Malfunction combined with Inappropriate Crew Response Accidents

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Engine Health Management
Potential Technology Benefits

- Safety
  - Improved engine life prediction
  - Improved real-time failure diagnosis
- Performance and Reliability
  - Improved engine performance
  - Reduced maintenance costs
  - Increased asset availability
  - Improved fuel efficiency
  - Increased range

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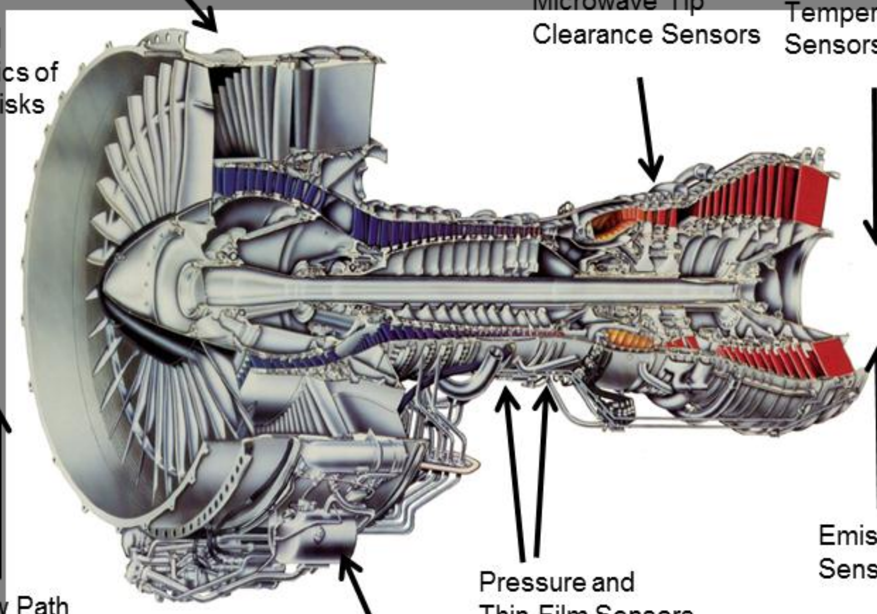
VIPR 3

Goal: Determine capability of advanced detection, diagnostic and prognostic systems to characterize engine performance, and identify fault modalities, during rapid engine degradation caused by the ingestion of volcanic ash.



Model-based gas path diagnostic architecture

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

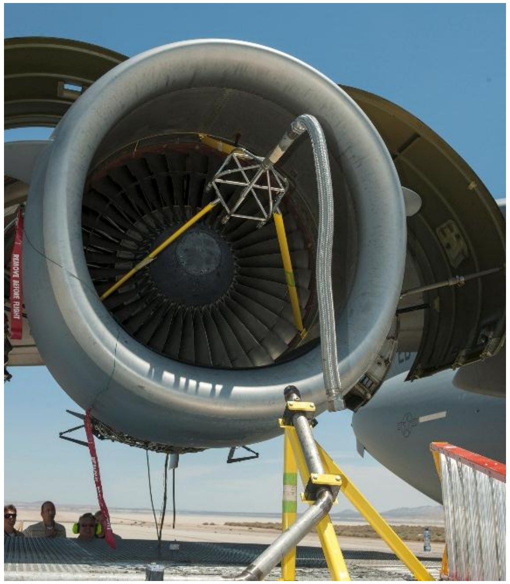
- Successfully integrated experimental technologies
  - Microwave Blade Tip Clearance Sensor
  - Thin Film Pressure Sensors
- Detected & characterized induced fault impacts

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

Test Completion

- **Advanced Instrumentation installed on engine and initial testing and check out occurred during hanger integration test February 2015**
- **Engine: Commercial variant that was significantly modified to demonstrate the VIPR technology and additional sensor suite installed on wing of an aircraft May 2015**
- **Testing**
  - Test Start Date: June 16, 2015
    - Combined Systems Test (CST)
    - Bleed Air Extraction & Sampling System (BAESS)
    - Engine Health Management (EHM)
    - Volcanic Ash Environment (VAE)*
  - Test Completion: August 5, 2015
- **5 Volcanic Ash Ingestion Tests completed**



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

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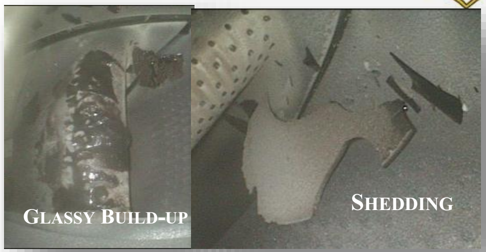
Overview
Vehicle Integrated Propulsion Research (VIPR) III
GREAT NEWS!

E15 Volcanic ash cloud in Iceland
April 2010



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

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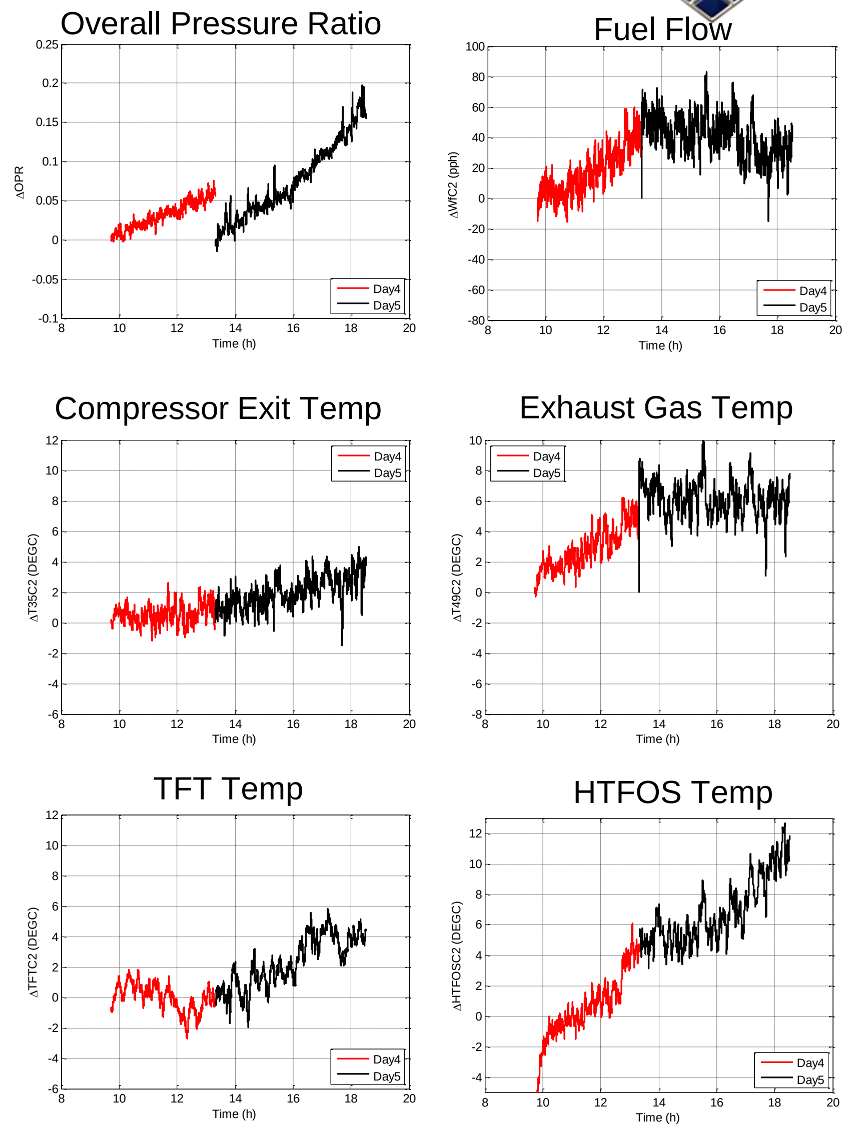
Gas Path Measurement Data

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

High Temperature Fiber Optic Sensor

OBJECTIVE
- Develop and evaluate silica-based fiber optic sensor suitable for operation at the engine exhaust temperatures

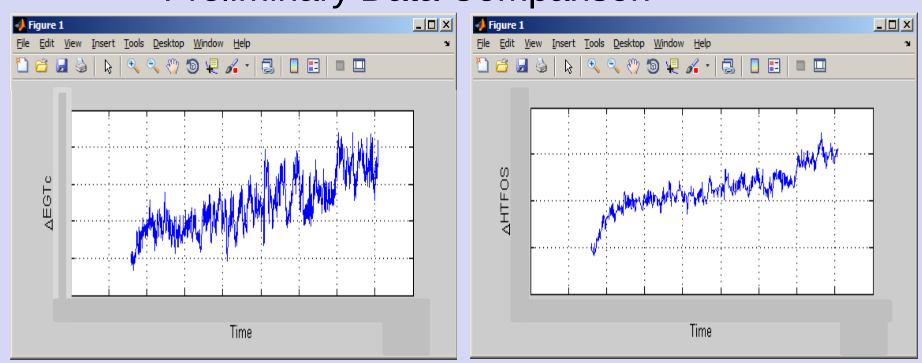
APPROACH
- Evaluate the sensor performance in the engine exhaust plume under various engine operating and ash ingestion conditions.
- Compare results with the EGT sensor data

RESULTS AND SIGNIFICANCE
- Shown capable of withstanding thermal and vibrational environments of the jet engine exhaust
- Significance of the sensor is immune to EMI and EMP, has high resistance to chemicals, low noise, signal fidelity, low maintenance
- Preliminary results show lower noise than existing EGT sensors

Configuration for VIPR Tests

Sensor installed behind the engine exhaust

Preliminary Data Comparison



EGT Sensor HTFOS

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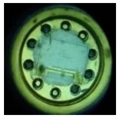
Emissions Sensor Suite
Volcanic Ash



CO sensor

Sensor probe

Sensor probes in emissions testing rig manifold

OBJECTIVE

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

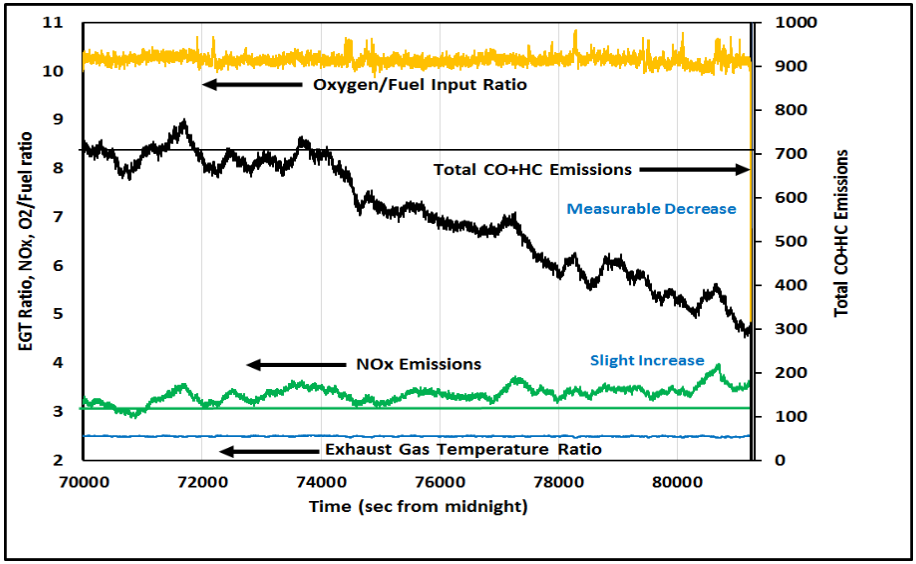
APPROACH

- Install sensor suite in engine exhaust

RESULTS AND SIGNIFICANCE (Preliminary)

- 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

Preliminary Emissions Data – Patterns Established/ Deviations Observed Suggesting Possible Volcanic Ash Effects



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Test Results

	Information targeted for release
Hardware degradation Specifications	% of hardware deemed repairable and unserviceable via borescope inspections as a function of time and locations. Description of failure mode.
Measured parameters **(Absolute and percent change)**	EGTcorr Corrected exhaust gas temperature EPR Engine pressure ratio N1C2 Corrected low rotor speed N2C2 Corrected high rotor speed WFcorr Corrected fuel flow PBcorr Corrected burner pressure Time history of engine data.
Derived Parameters **(percent change from baseline)**	W2corr Corrected station 2 core flow (estimated) OPR Overall pressure ratio Op. Lines LPC and HPC operating lines (estimated) Surge Line HPC low power surge line (estimated)
Other Engine Data	Ambient conditions during test. Oil analysis test results.
Ash Analysis	Composition going in, % deposited in different locations (if obtained), composition of what is deposited (if obtained)
Air circuit information	% of airflow circuit

Note all information must be reviewed to confirm there are no data release restrictions

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Report Plan

Goal is to have a report released next summer

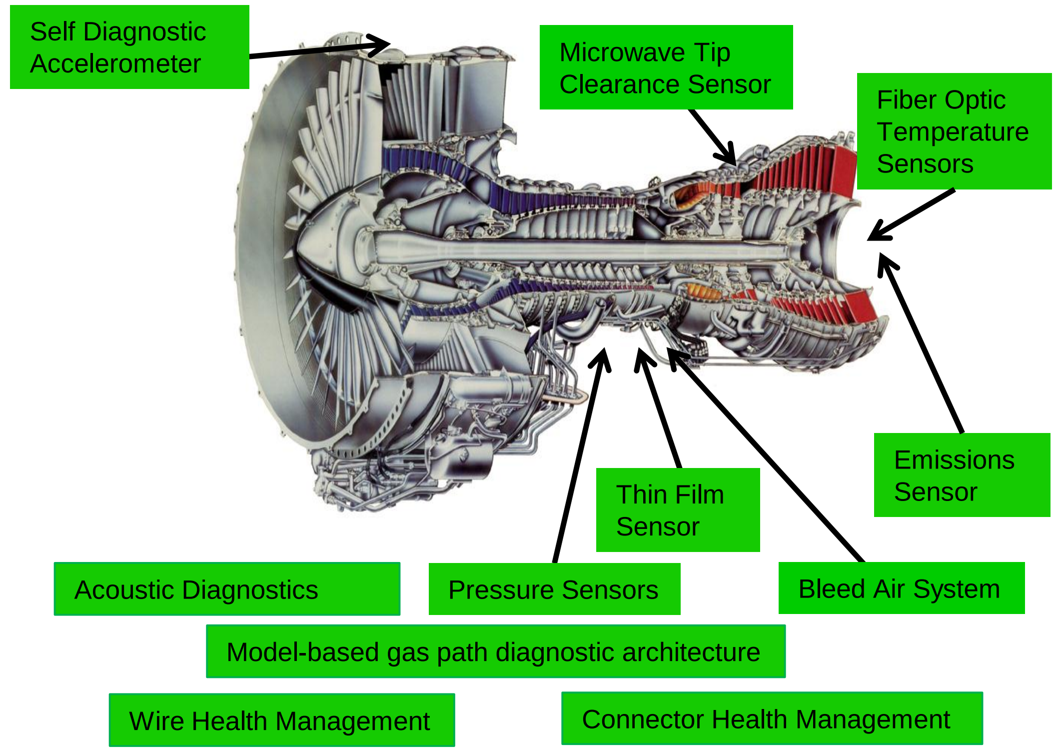
1) Executive Summary
2) Background/Motivation
3) VIPR3 VAE Test Plans and Test Configuration
4) Description of VIPR3 VAE Test Execution
5) VIPR3 VAE Test results
   a) Performance results
   b) Shedding Results
   c) Observations of engine degradation
6) Summary / Conclusions / Recommendations / Caveats

13

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