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

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October 22, 2015
Anchorage, Alaska
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

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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

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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
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.
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

- Induced volcanic ash ingestion - rapid engine degradation
- Determined capability of advanced detection
- Characterized engine performance \([\text{diagnostic} & \text{prognostic}]\)
- Identified fault modalities

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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

<table>
<thead>
<tr>
<th>Date</th>
<th>Target Concentration (mg/m³)</th>
<th>Daily Run Time (min)</th>
<th>Daily Ash Ingested (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28-Jul-15</td>
<td>1</td>
<td>90</td>
<td>0.730</td>
</tr>
<tr>
<td>29-Jul-15</td>
<td>1</td>
<td>68</td>
<td>0.549</td>
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<tr>
<td>31-Jul-15</td>
<td>1</td>
<td>269</td>
<td>2.156</td>
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<tr>
<td>04-Aug-15</td>
<td>10</td>
<td>175</td>
<td>11.017</td>
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<tr>
<td>05-Aug-15</td>
<td>10</td>
<td>235</td>
<td>14.465</td>
</tr>
</tbody>
</table>

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

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**  
☑ **Ash Shedding**
☑ **14HR Cumulative Test NO Red-line Breach**  
☑ **Turbine Molten Ash Glassy Build-Up**
☑ **Engine Performance Degradation @10HR**

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**
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

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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
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
# Test Results

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

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

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