https://ntrs.nasa.gov/search.jsp?R=20170004122 2020-05-09T09:46:55+00:00Z

Packaged Capacitive Pressure Sensor System for Aircraft Engine Health Monitoring

Dr. Maximilian C. Scardelletti – NASA Glenn Research Center

Dr. Christian A. Zorman – Case Western Reserve University

Distribution A - Approved for Public Release (88ABW-2016)

Introduction

- *Sensing systems for harsh environments:*

High temperature electronics and sensors

Three Major Industries

- Downhole Oil and Gas
  - Drilling operations were limited 150 to 175°C for reserves in easily accessible wells
  - Declining reserves force deeper wells, which increase drilling temperatures to 300°C
- Automobile
  - Cylinder pressures temperature: 300°C
  - Exhaust sensing temperature: 850°C
- Aerospace
  - Monitoring the health of aircraft engines at temperatures above 300°C (emissions, temperature, blade tip clearance and pressure)
  - Atmospheric and surface conditions of Venus (480°C)

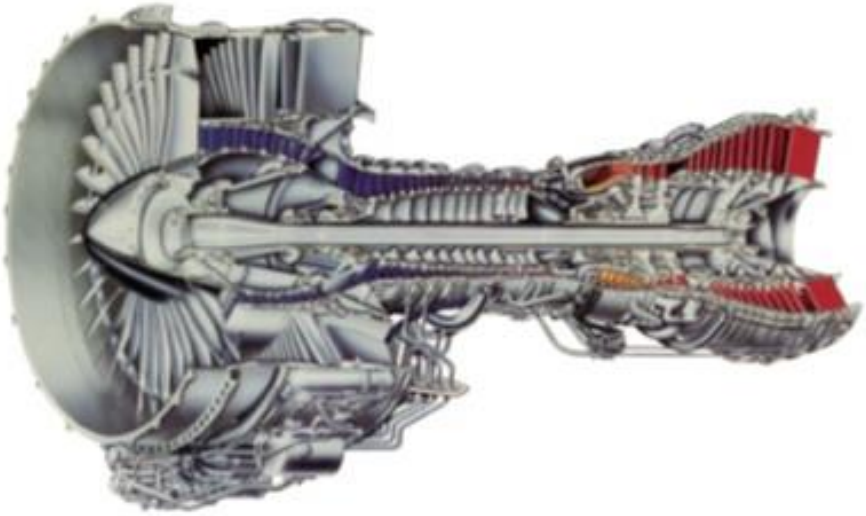
Distribution A - Approved for Public Release (88ABW-2016)

Introduction

Develop a SiC-based MEMs capacitive pressure sensor system that can be used to monitor the pressure of a conventional gas turbofan engine.

Operating Conditions:

Temperature: 25 to 500°C
Pressure: 0 to 300 psi
Vibration: up to 5.3 G_{rms}



Distribution A - Approved for Public Release (88ABW-2016)

System Design

The system is realized by integrating the following components on a common, high temperature substrate

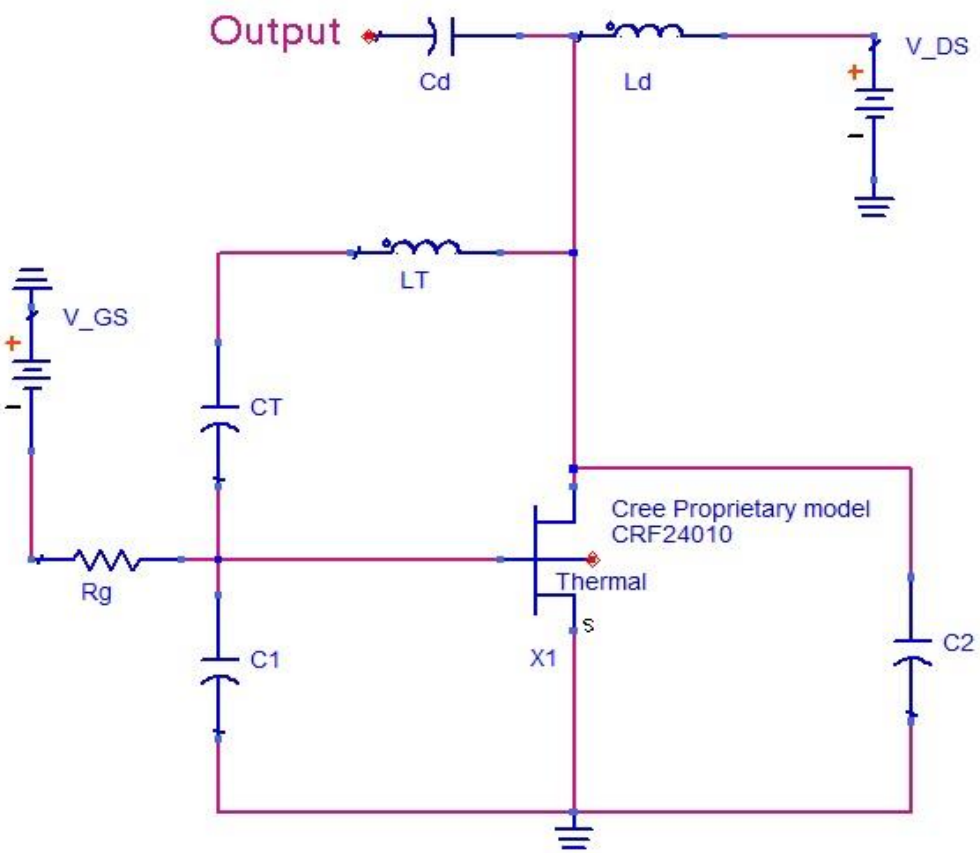
1. A novel SiCN MEMS capacitive pressure sensor
2. 6H-SiC MESFET as active device
3. MIM capacitors, wirewound inductors, thick film resistors
4. Low form factor packaging
5. Borescope plug adaptor

Distribution A - Approved for Public Release (88ABW-2016)

Electronics Design

The proposed system uses a Clapp-Type Oscillator Design

- The integrated system uses a Clapp-type oscillator with capacitive pressure sensor located in LC tank circuit
- As pressure increases, pressure sensor capacitance decreases, which causes the operational frequency to increase
- Cree SiC MESFET used for driving circuit into oscillation



Electronics Design

Clapp-Type Oscillator vs Colpitts Oscillator

- The proposed Clapp oscillator requires one inductor, three capacitors and one MESFET. Requires fewer components vs. Colpitts oscillator design
  - Increases system efficiency
  - Increases system reliability under harsh environment conditions
- L_T and C_{SENSE} are in series and C_{SENSE} is used to set the operational frequency
- C_1 and C_2 are used to control the gain conditions
- This arrangement increases frequency stability, making it more frequency stable than the Colpitts design.

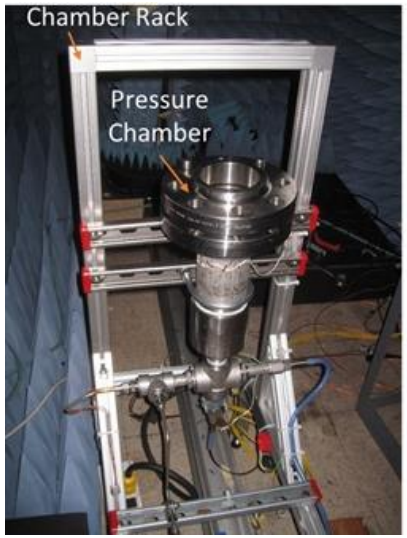
Distribution A - Approved for Public Release (88ABW-2016)

Pressure Sensor Testing

High Temperature and Pressure Chamber

System Key Features

- Pressure range: 0 to 100 psi
- Temperature range: 25 to 500°C
- LabVIEW control program
- Power source
- Multiple thermocouple
- Multiple feedthroughs
- Sight glass for signal transmission

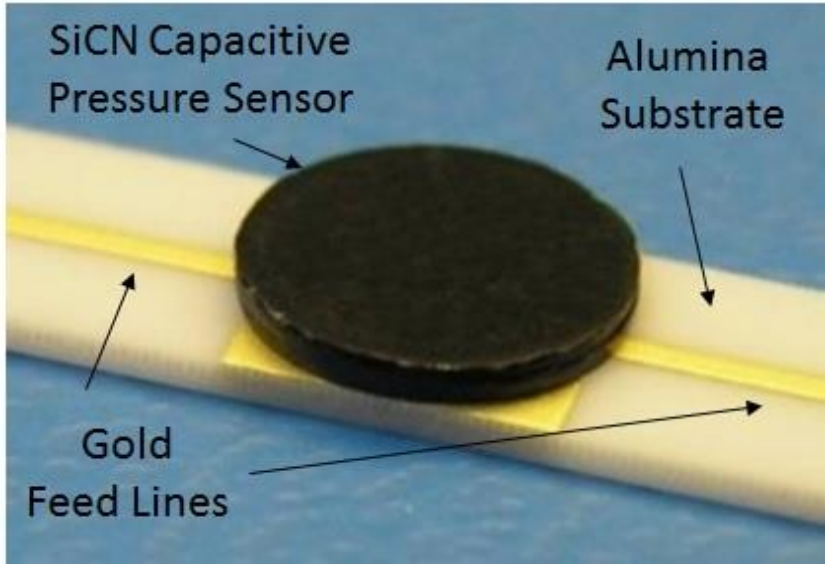


Pressure Sensor

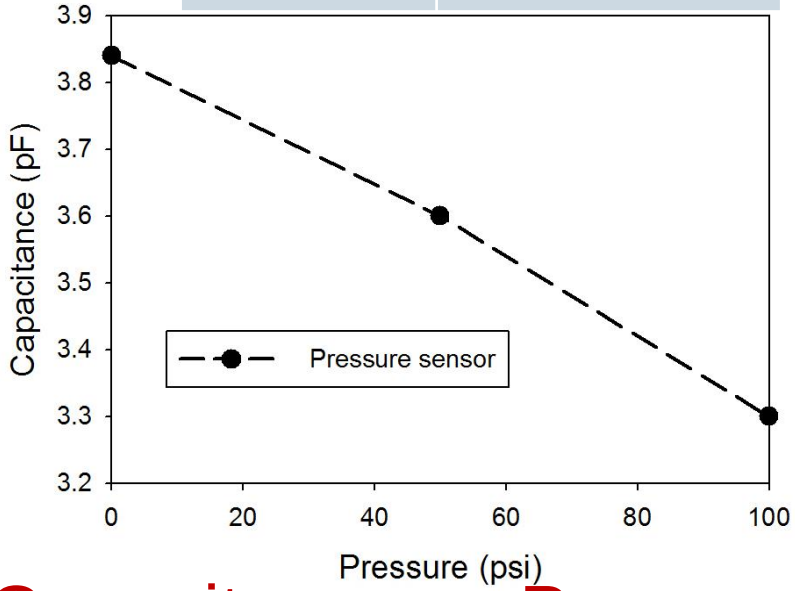
Sporian SiCN Capacitive Pressure Sensor

- Parallel plate capacitor model
- SiCN membrane
- Temperature range: up to 1000°C
- Pressure range: 0 to 400 psi

Pressure (psi)	Capacitance (pF)
0	3.84
50	3.6
100	3.3



SiCN pressure sensor



Capacitance vs Pressure

Distribution A - Approved for Public Release (88ABW-2016)

Oscillator Design

Circuit Simulations

Keysight's Advanced Design System (ADS) Software suite

CT =3.84 pF
LT = 780 nH
C1 = 14 pF
C2 = 41 pF
RG = 10KΩ
LD = 390 nH
CD = 188 pF

Cree SiC MESFET model

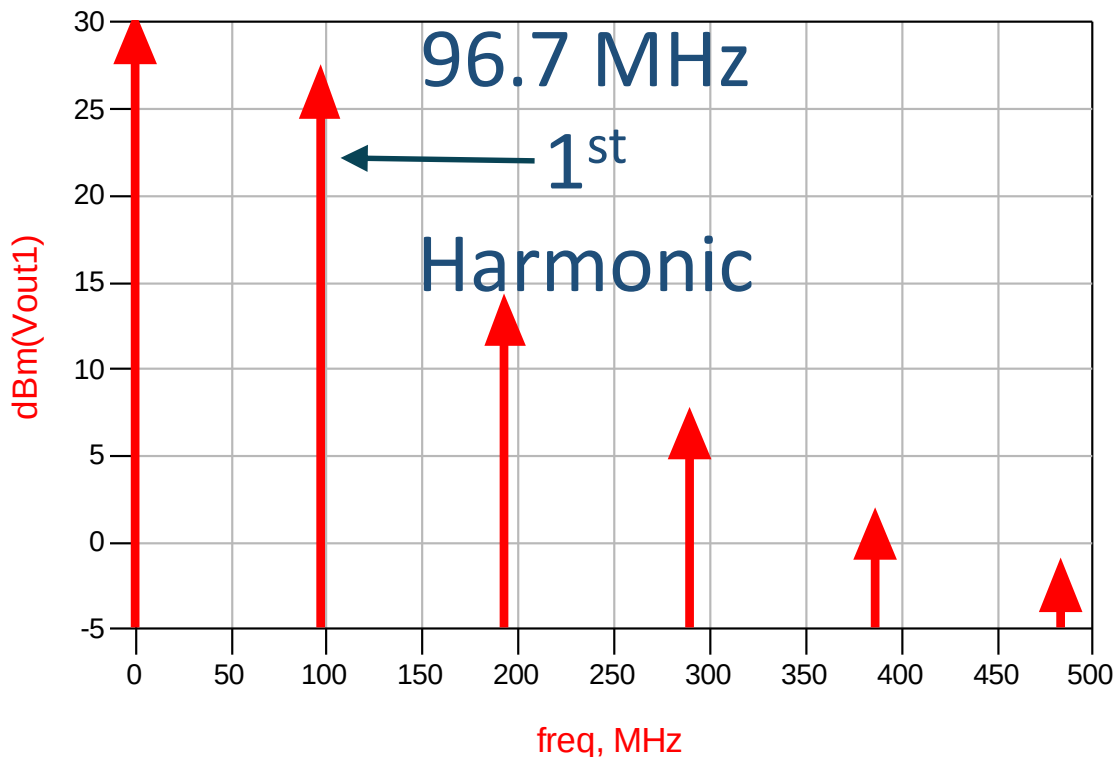
Oscillation Frequency 96.7 MHz

Distribution A - Approved for Public Release (88ABW-2016)

Oscillator Design

Circuit Simulations

Harmonic Balance Simulation



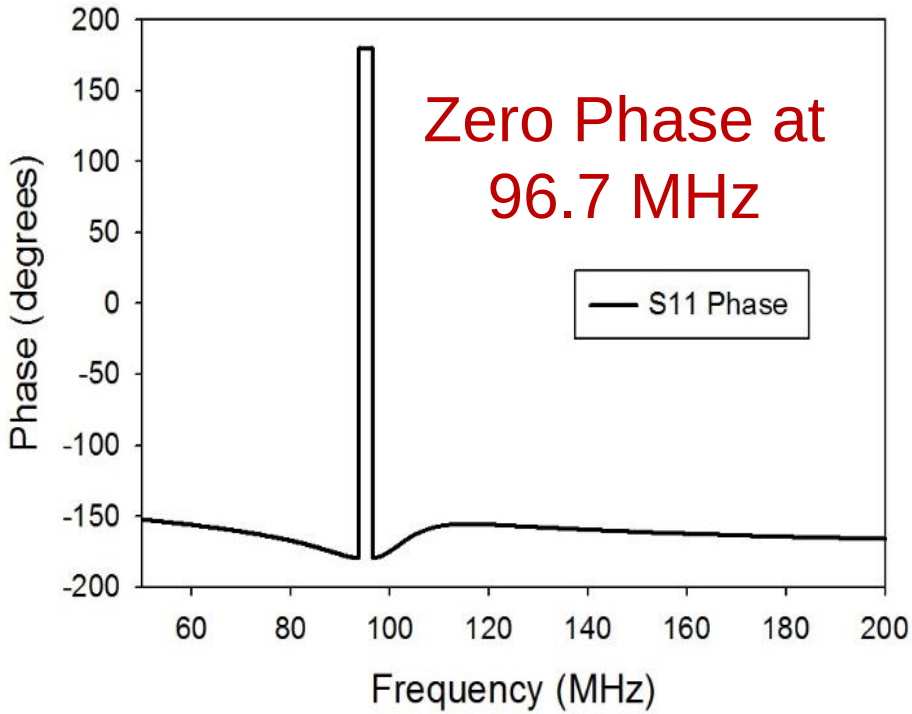
Oscillator Design

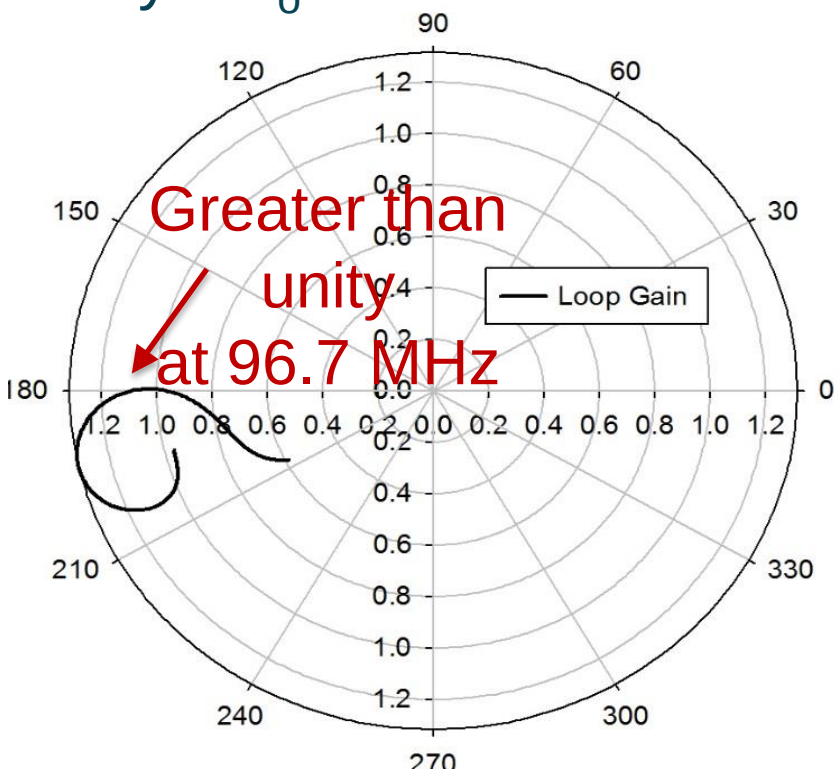
Circuit Simulations

To achieve oscillation stability

1) Phase must be zero at f_o

2) Loop gain must be greater than unity at f_o



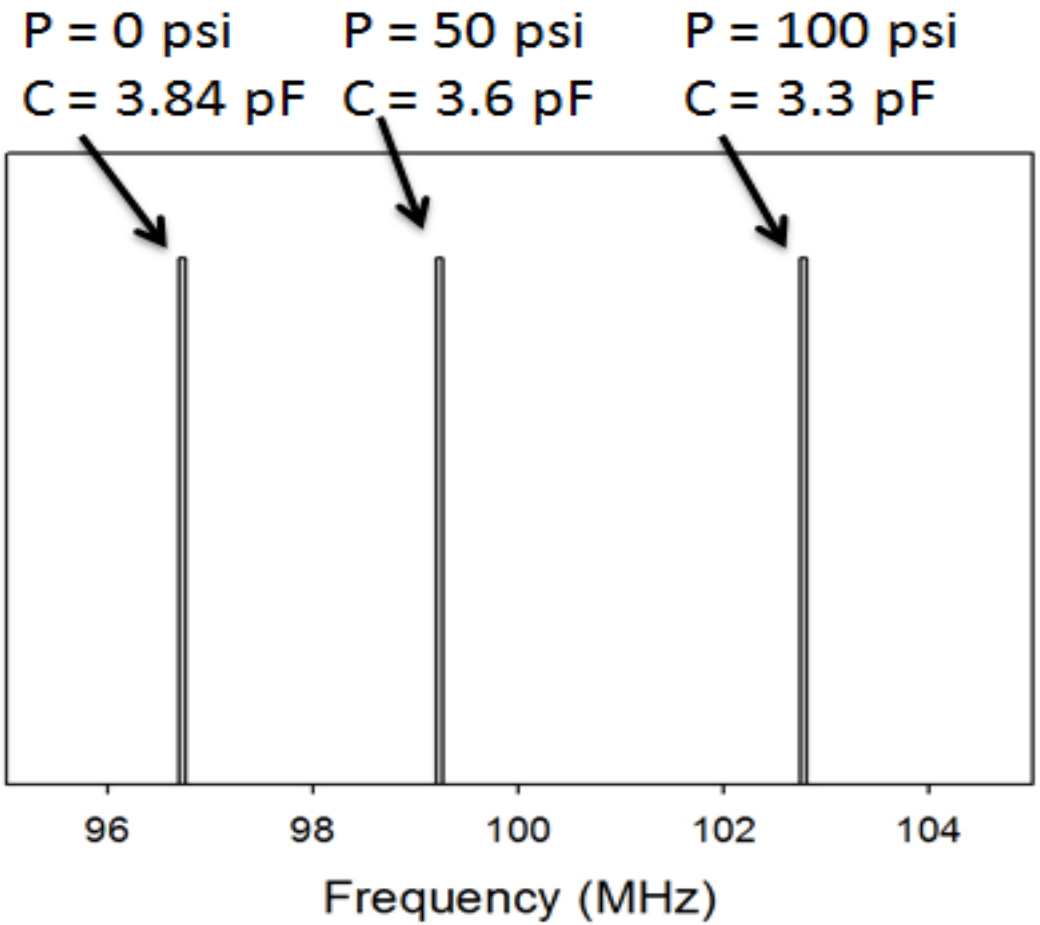


Oscillator Design

Circuit Simulations

Harmonic Balance Simulation

P = 0 psi f = 96.7 MHz
P = 50 psi f = 99.2 MHz
P =100 psi f = 102.8 MHz



Engine Testing

Packaged wired prototype has the following characteristics

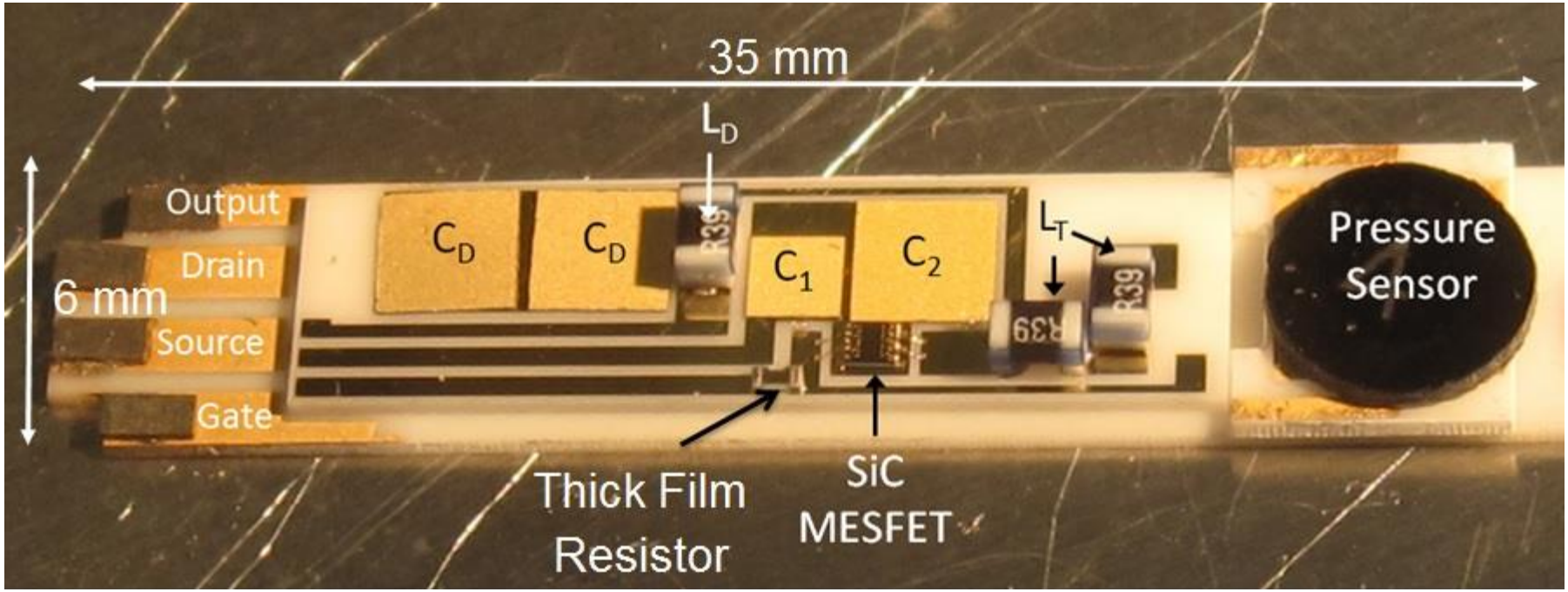
- *Unpackaged Sensor System Size: 8 x 40 x 4 mm^3 (including on-board DC bias circuits)*
- *Form Factor: Packaged sensor equipped with borescope adaptor for a borescope plug on engine*
- *Maximum Operational Temperature: 500°C for 1 hour at tip of borescope adaptor*
- *Maximum Vibration: 5.3 G_{rms} along X-, Y- and Z-axis for 20 min*

Distribution A - Approved for Public Release (88ABW-2016)

Pressure Sensor System

Entire circuit assembled on a single alumina substrate

(6 x 35 x 2 mm^3)



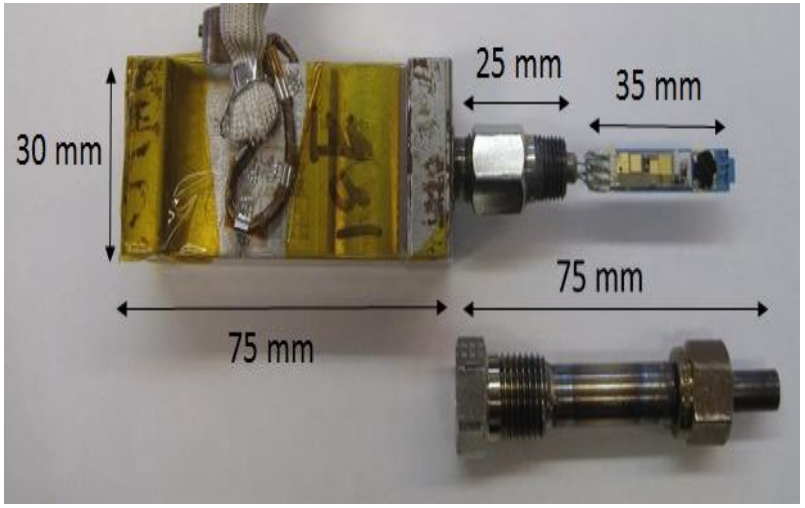
Distribution A - Approved for Public Release (88ABW-2016)

Pressure Sensor System

Packaged Sensor System Assembly

Key Features

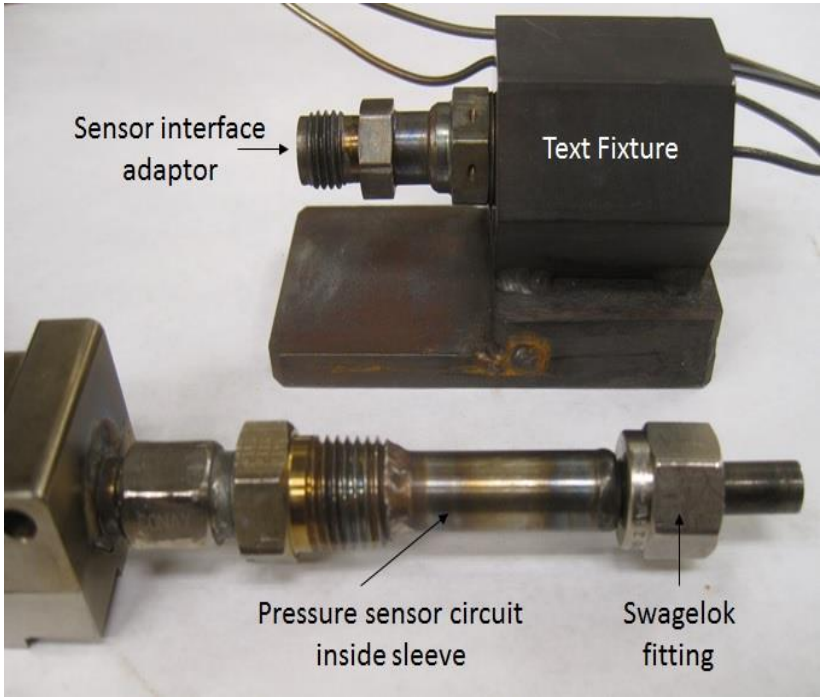
- Stainless steal packaging
- Thermo couples
- Custom connector/cable from package to facilitate input power and output signal
- Borescope plug adaptor
- Size: 30 x 150 mm



Pressure Sensor System

Bench-Top Acceptance Testing

- Custom-in-house pressurized fixture
- Packaged sensor is attached to quasi-borescope adaptor
- Thermocouple inside fixture to emulate inner engine temperature

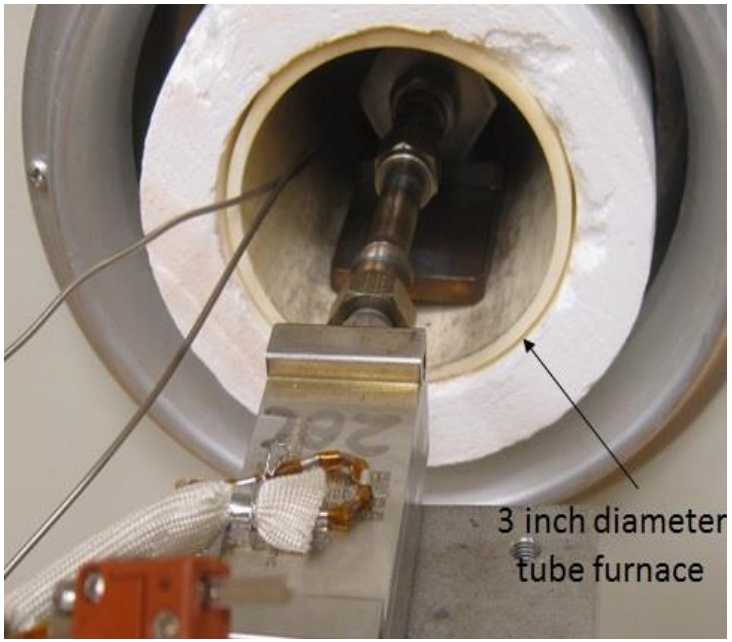


Pressure Sensor System

Bench-Top Packaged System Characterization

To emulate actual jet turbofan engine conditions the packaged sensor was heated to over 500°C and the pressure was increased from 0 to 300 psi.

Note: The temperature recorded on the metal sleeve was ≈ 400°C, which is assumed to be the steady-state temperature of the system

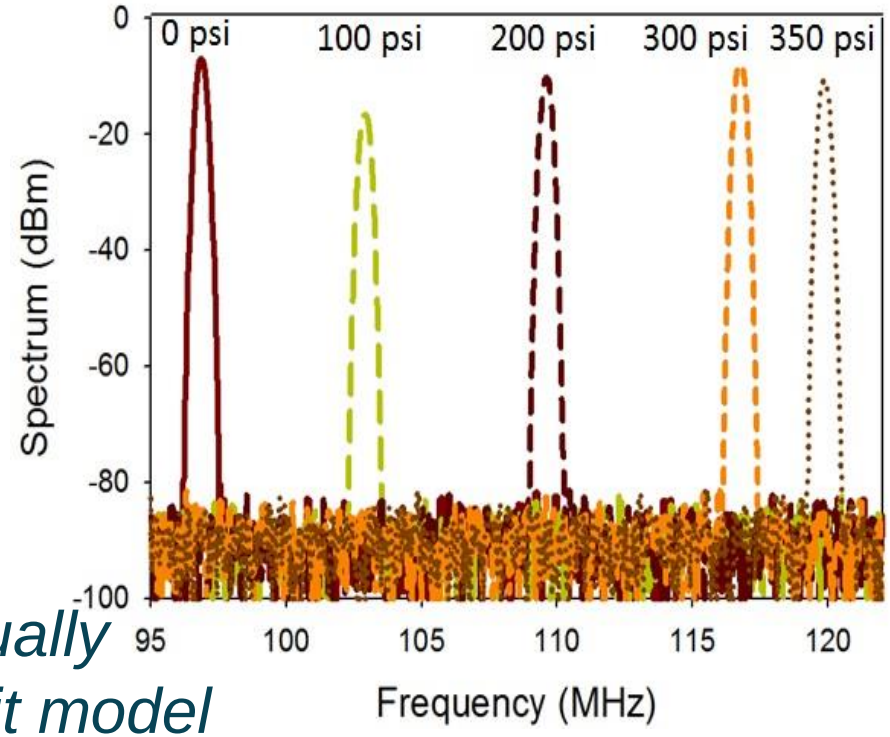


Distribution A - Approved for Public Release (88ABW-2016)

Pressure Sensor System

Bench-Top Packaged System Characterization

0 psi	→ 96.88 MHz
100 psi	→ 102.79 MHz
200 psi	→ 109.54 MHz
300 psi	→ 116.77 MHz
350 psi	→ 119.86 MHz



Note: Simulated and measured response at 0 and 100 psi are virtually identical: Incredibly accurate circuit model

6.57×10^{-2} $\Delta f/\Delta P$ MHz/psi
Percent difference = 21.2%

Spectrum response of packaged pressure sensor from 0 to 350 psi at 25°C

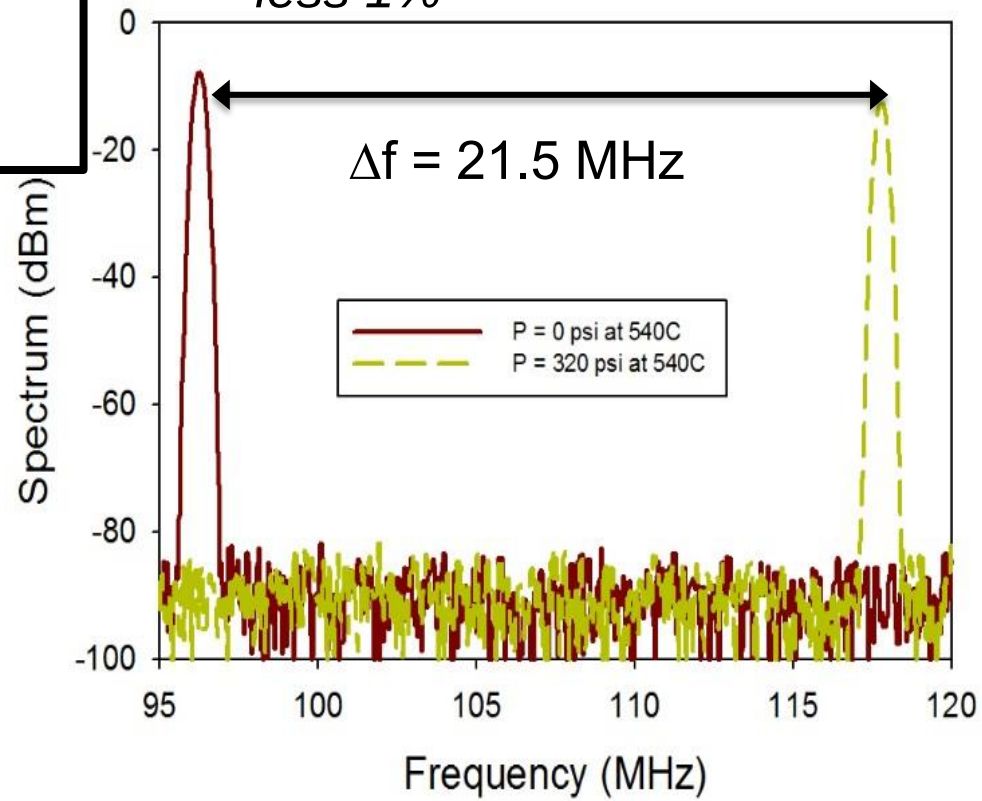
Distribution A - Approved for Public Release (88ABW-2016)

Pressure Sensor System

Bench-Top System Characterization

The temperature at the tip of the sensor inside the pressurized is fixture is 540°C
(≈ 400°C at the sleeve)

The change in frequency at 25 and 540°C at 0 psi is less 1%



0 psi → 96.3 MHz
320 psi → 117.8 MHz

6.8×10^{-2} $\Delta f/\Delta P$ MHz/psi
Percent difference = 20 %

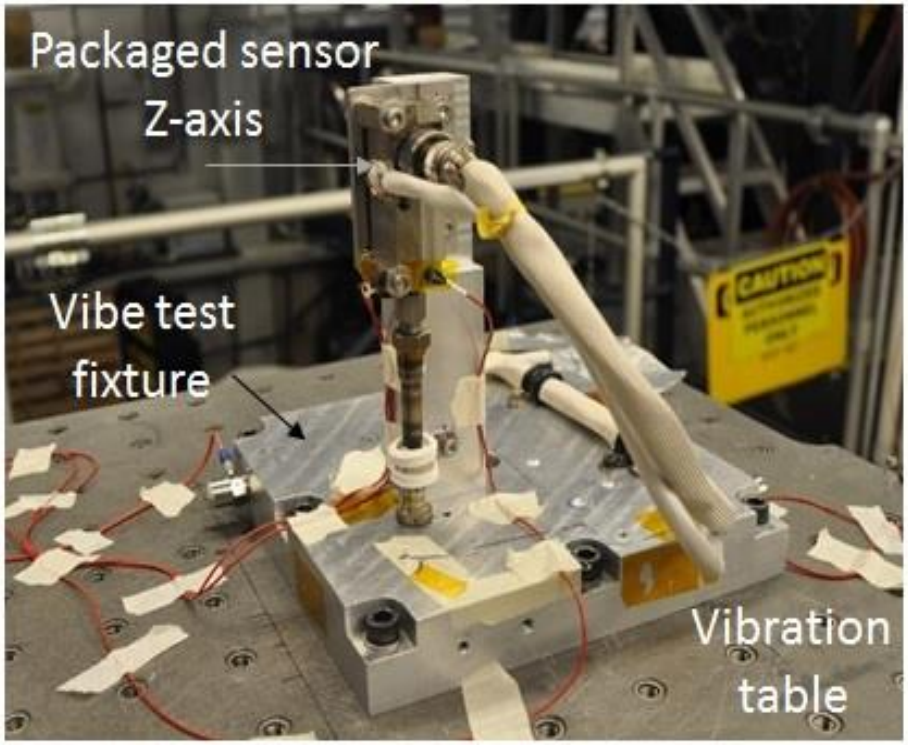
Distribution A - Approved for Public Release (88ABW-2016)

Pressure Sensor System

Bench-Top Packaged System Characterization

Structural Dynamic Testing

- Emulate on engine testing
- Sine wave sweeps
- Random vibration
- Maximum vibration 5.3 G_{rms}
- X-, Y- and Z-axis testing
- Resonate frequency recorded at the beginning and end of each axis test. NO change!!

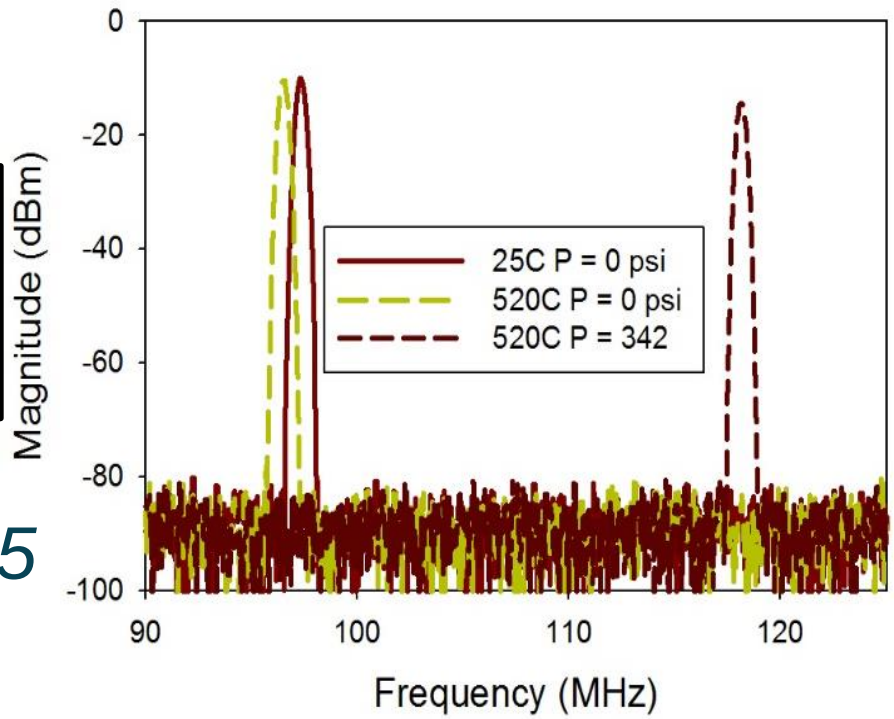


Pressure Sensor System

Bench-Top Packaged System Characterization

The packaged sensor system was again measured after structural dynamic testing.

0 psi	→ 25°C	→ 97.3 MHz
0 psi	→ 520°C	→ 96.5 MHz
342 psi	→ 520°C	→ 118.1 MHz



The change in frequency at 25 and 540°C at 0 psi is less 1%

Distribution A - Approved for Public Release (88ABW-2016)

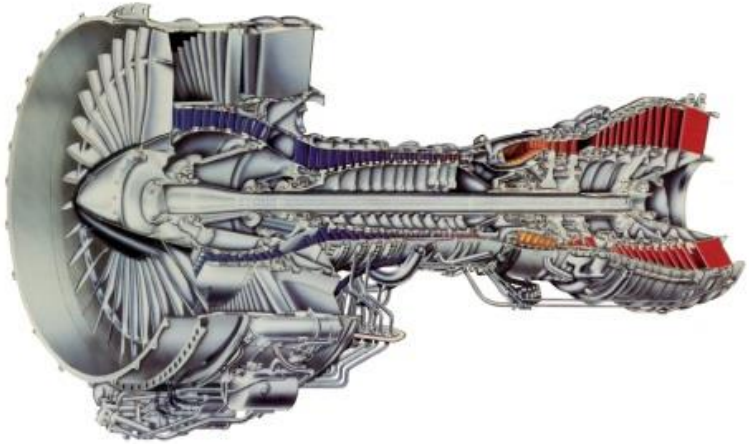
Vehicle Integrated Propulsion (VIPR)

VIPR was a series of ground-based on-wing engine demonstrations to mature aircraft engine health management technologies

Test vehicle was a U.S. Air Force C-17 aircraft equipped with Pratt & Whitney F117 engines

VIPR partners include NASA, U.S. Air Force, Pratt & Whitney, GE, Rolls Royce, Boeing, FAA, USGS, and other external organizations

Boeing C-17 Globemaster III



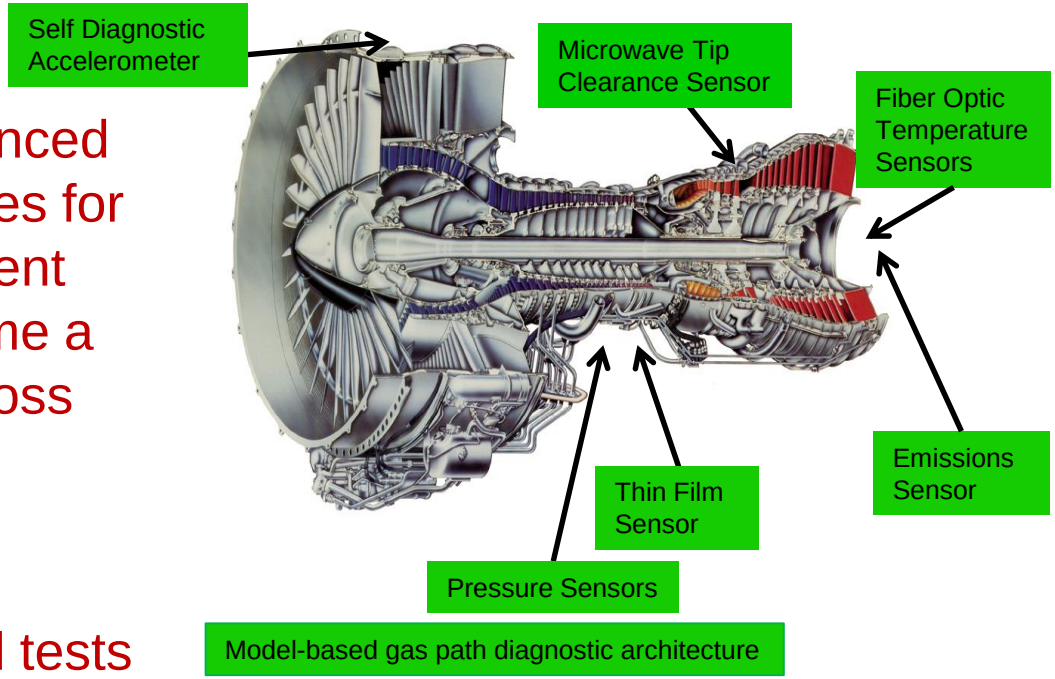
Pratt & Whitney F117 Turbofan Engine

Distribution A - Approved for Public Release (88ABW-2016)

VIPR3

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:

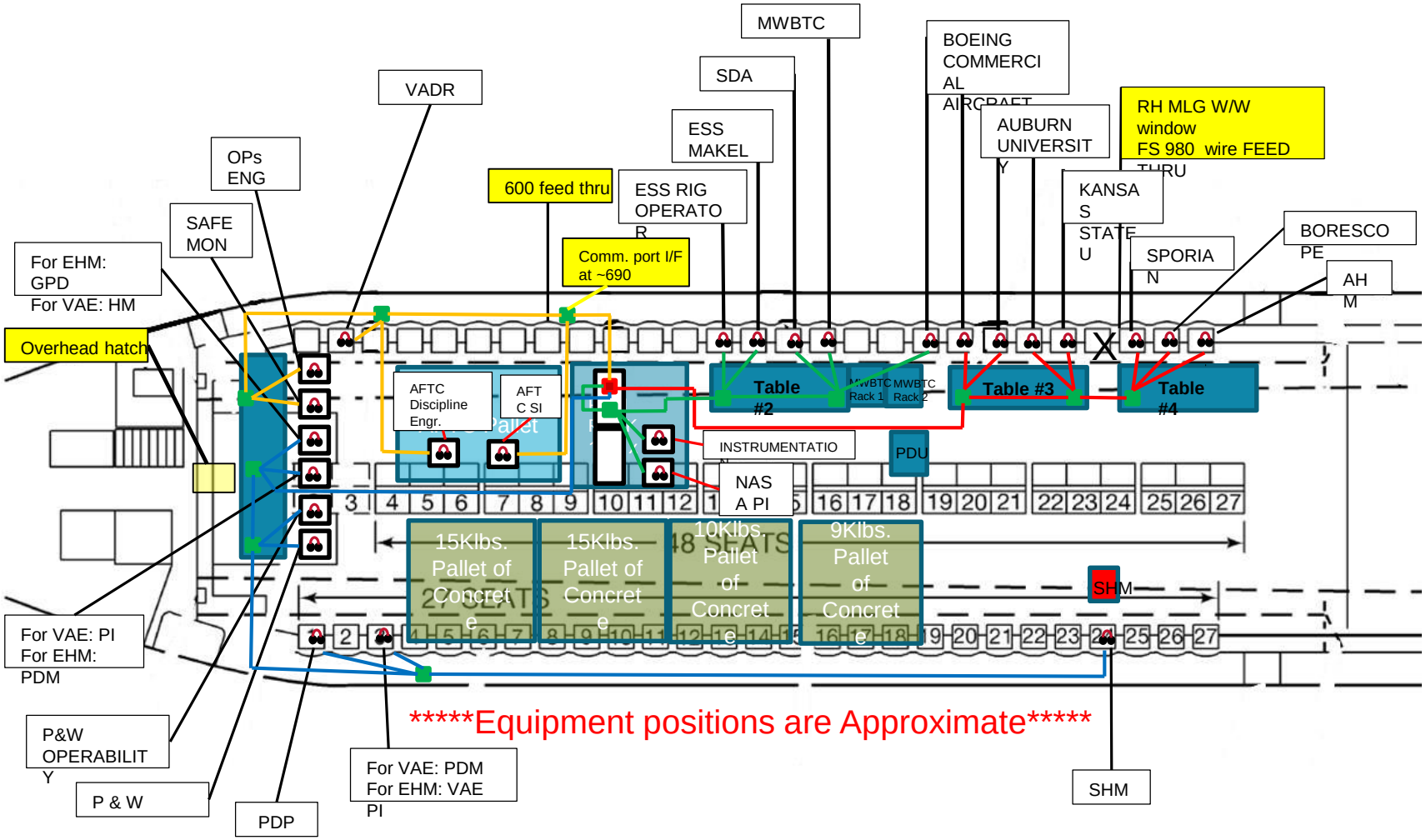
Perform on wing engine ground tests

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

Distribution A - Approved for Public Release (88ABW-2016)

VIPR3

CST Aircraft / Communication Layout



Aircraft Research Station Layout

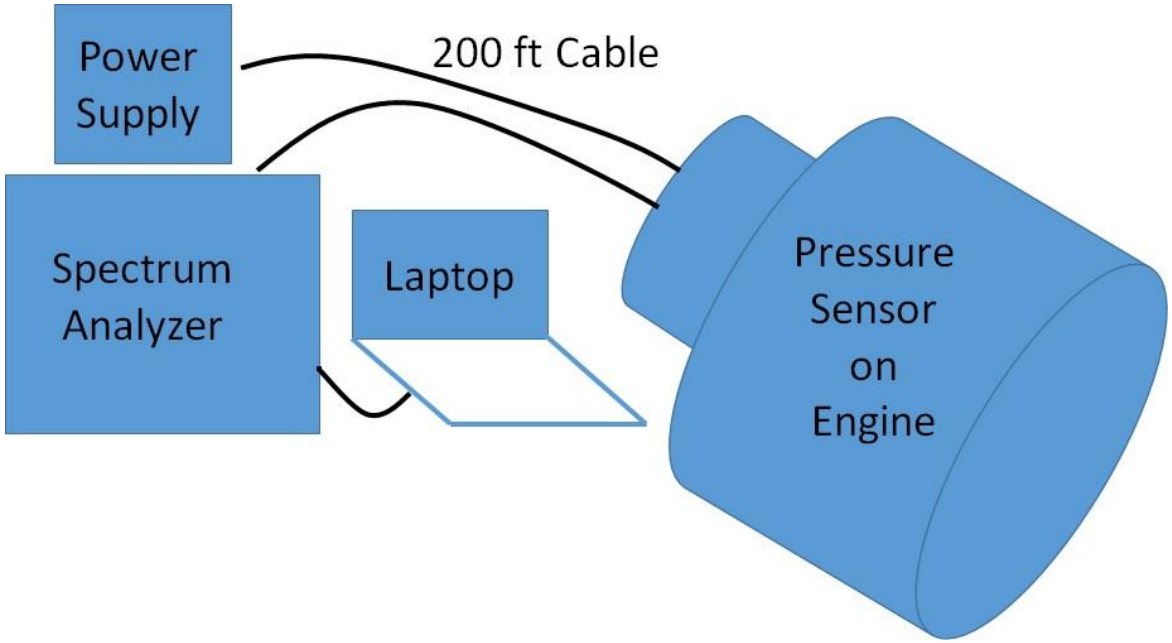
VIPR3

Aircraft Research Station Layout

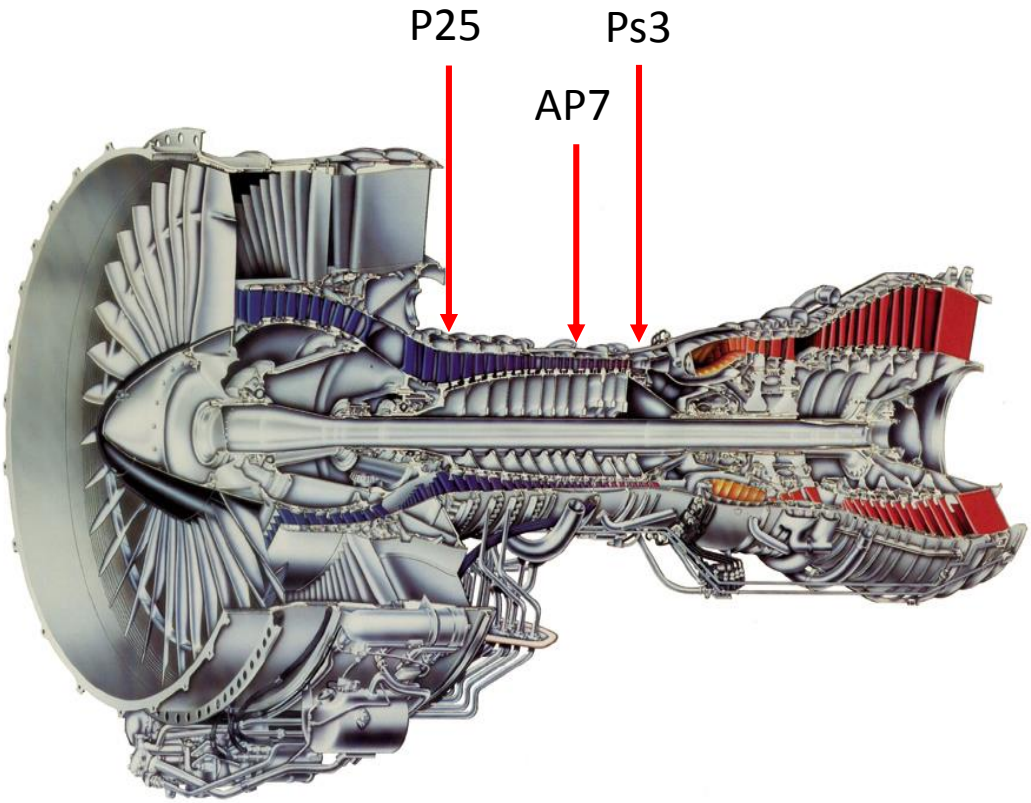
VIPR3

Measurement setup in fuselage to sensor on the engine attached to the wing

- Spectrum analyzer
- Power supply
- Laptop
- Labview program to record measurements
- 200 ft cable going from equipment to sensor on engine



Sensed Pressure Locations



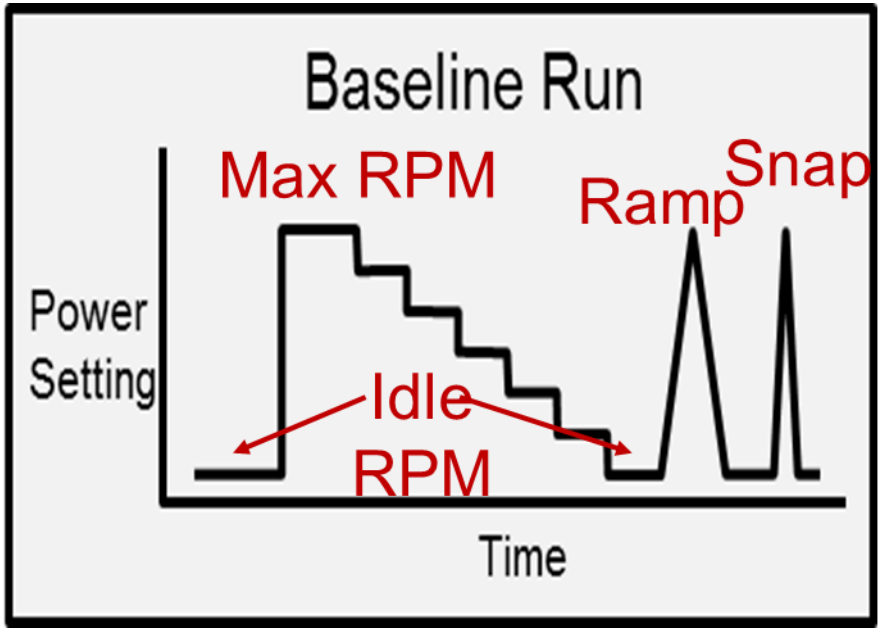
AP7:

High temp capacitive pressure sensor system

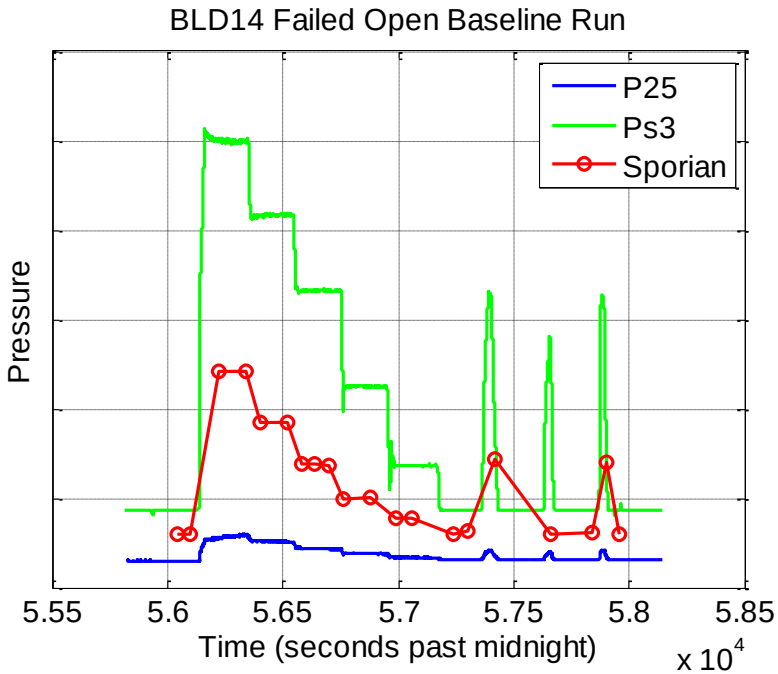
Packaged Sensor On-Engine

Environmental Health Monitoring Test

Baseline Engine Test Profile



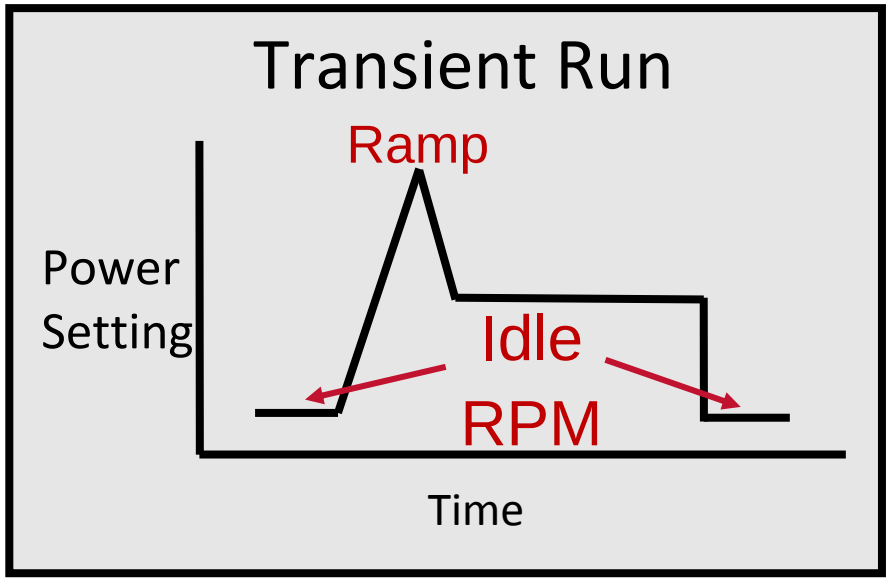
Sensor Output Data



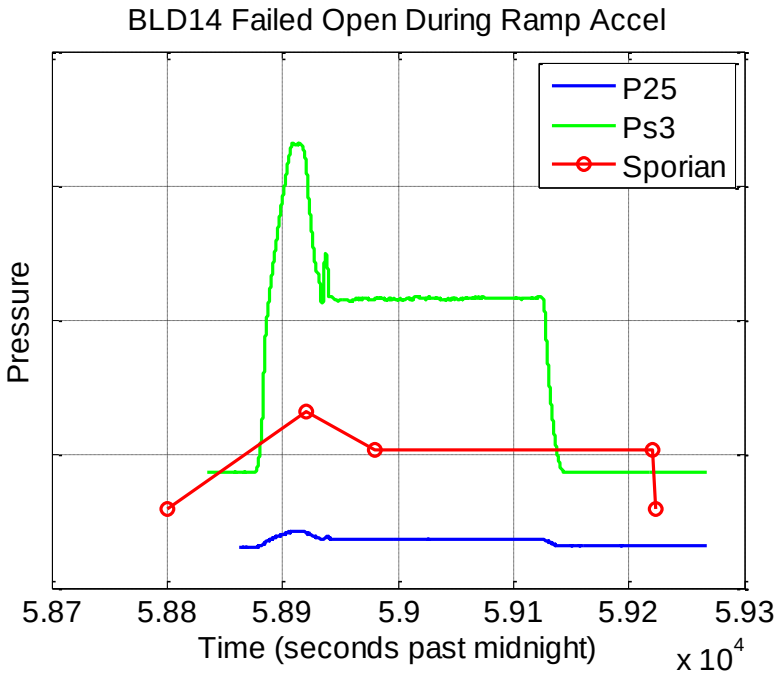
Packaged Sensor On-Engine

Environmental Health Monitoring Test

Transient Engine Test Profile



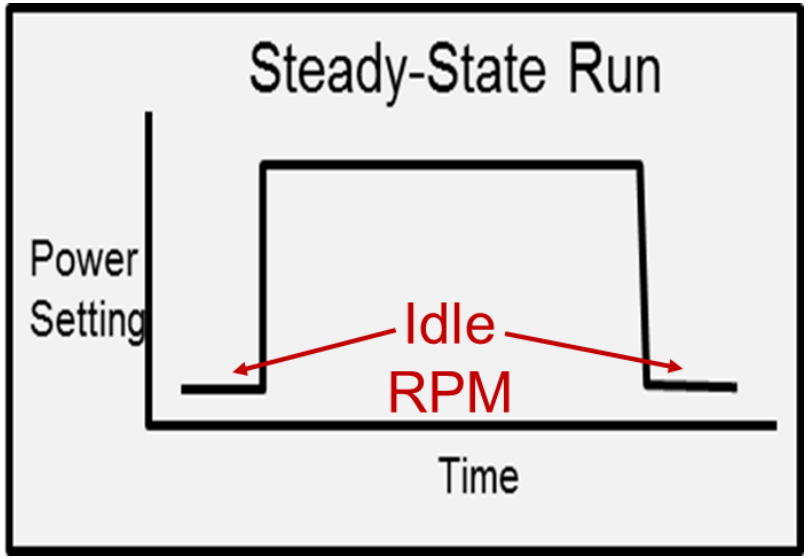
Sensor Output Data



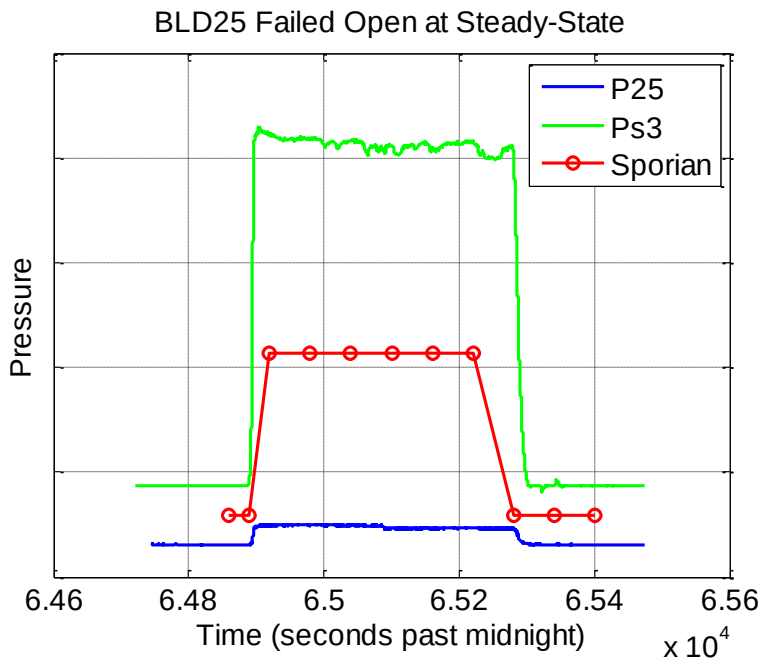
Packaged Sensor On-Engine

Environmental Health Monitoring Test

Steady-State Engine Test Profile



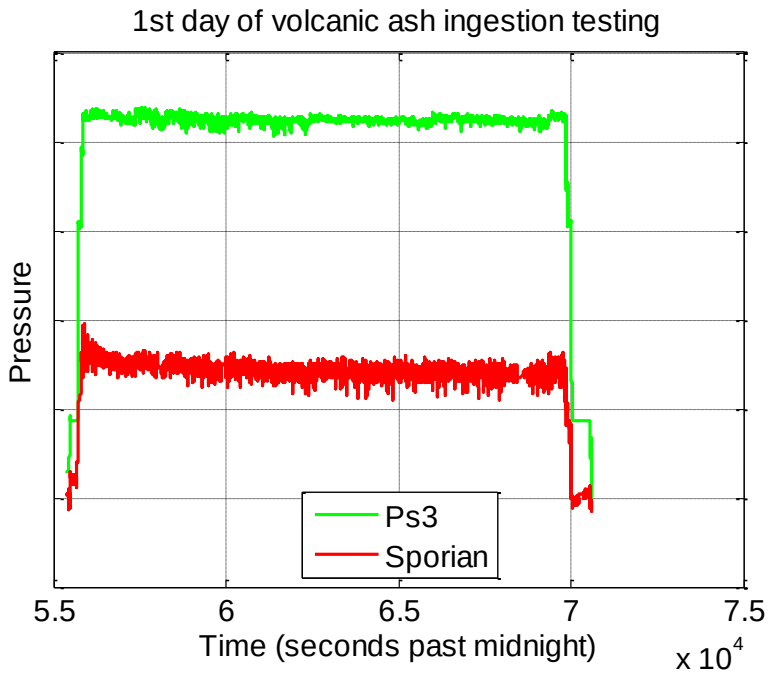
Sensor output data



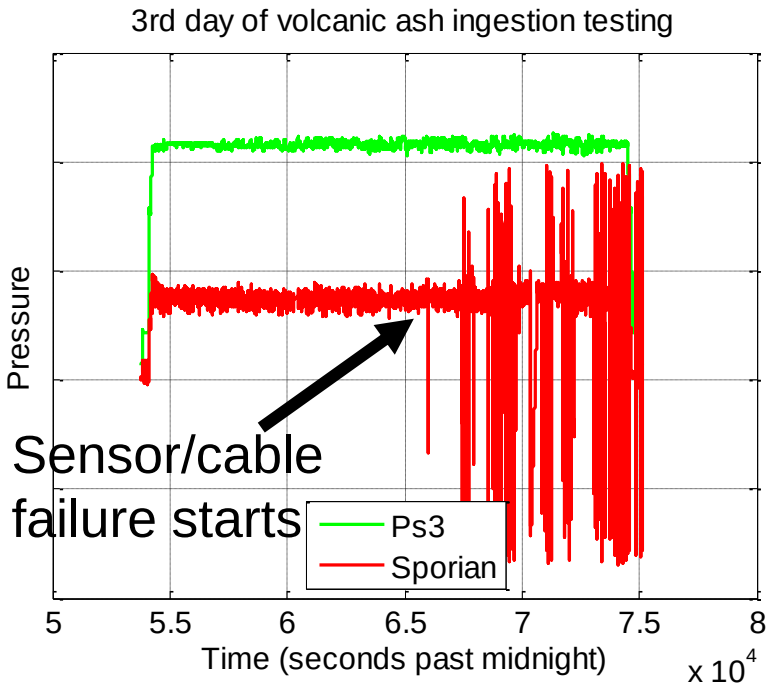
Packaged Sensor On-Engine

Volcanic Ash Testing

1st day of low flow volcanic ash ingestion testing



3rd day of low flow volcanic ash ingestion testing



14 hours low rate ash testing 1 mg/cu meter

Distribution A - Approved for Public Release (88ABW-2016)

Summary

- Simulated Clapp-type oscillator to prove concept
- Developed a packaged pressure sensor system
- Demonstrated accuracy of simulations vs. measured
- Performed pressure, temperature and vibration acceptance testing
- Successfully demonstrated sensor system tracking engine performance

Distribution A - Approved for Public Release (88ABW-2016)

Acknowledgements

NASA Glenn Research Center

Roger Meredith, Elizabeth Mcquaid Jennifer Jordan, Nick Varaljay, Robert Butler, Glenn Beheim and Gary Hunter

Sporian Microsystems

Keven Harsh, Evan Pilant and Mike Usrey

Distribution A - Approved for Public Release (88ABW-2016)

Thank you

Distribution A - Approved for Public Release (88ABW-2016)

Appendix Slides

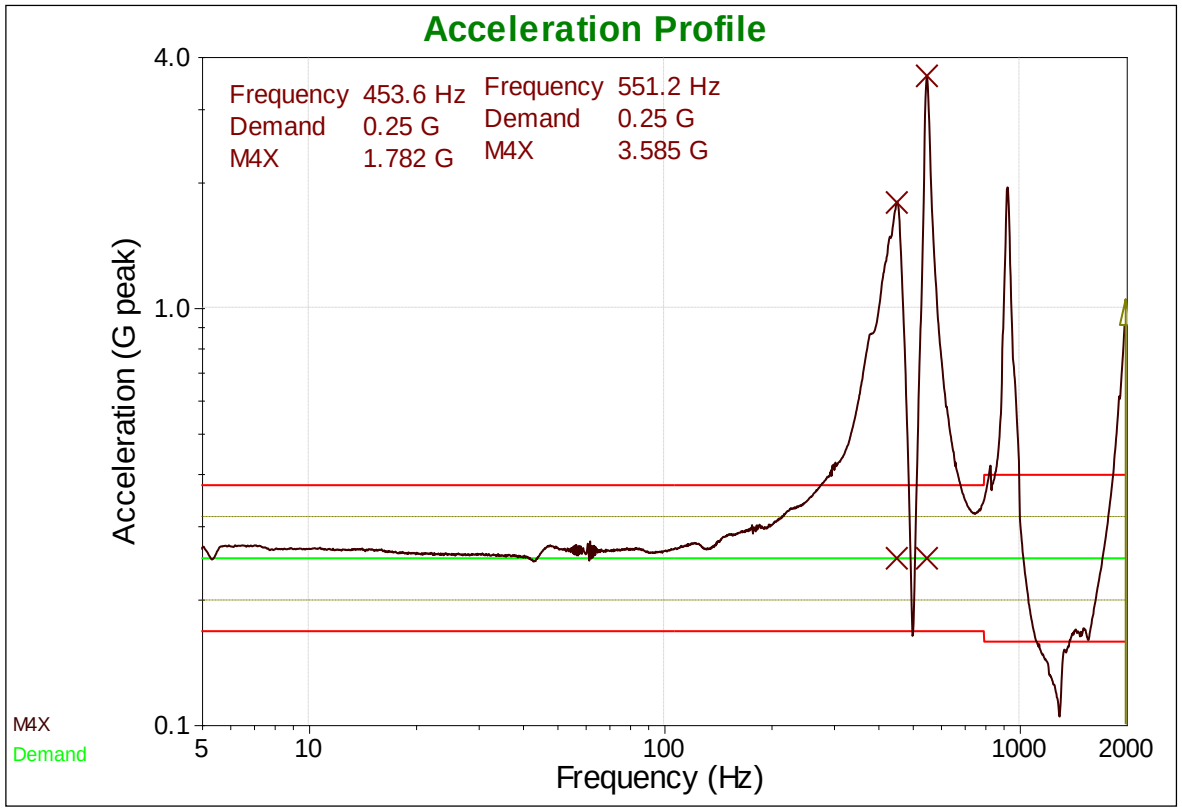
Distribution A - Approved for Public Release (88ABW-2016)

Pressure Sensor System

Bench-Top Packaged System Characterization

Structural Dynamic Testing

1.4 g sinusoidal sweep profile



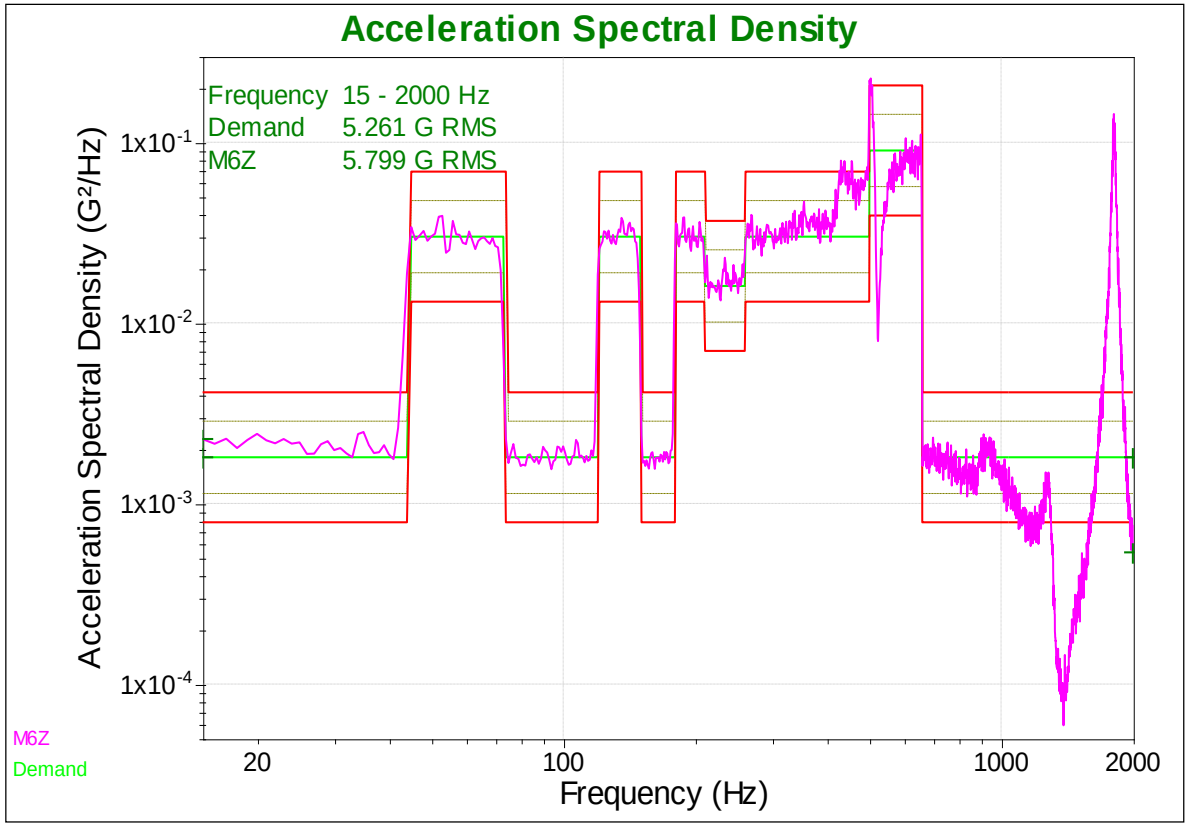
Distribution A - Approved for Public Release (88ABW-2016)

Pressure Sensor System

Bench-Top Packaged System Characterization

Structural Dynamic Testing

5.3 Grms random vibration profile



Distribution A - Approved for Public Release (88ABW-2016)