Design and operation of a fast, thin-film thermocouple probe on a turbine engine

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Outline

- Introduction
- Thermocouple Probe Design and Fabrication
- Data Acquisition Unit
- Qualification, Verification and Operational Test
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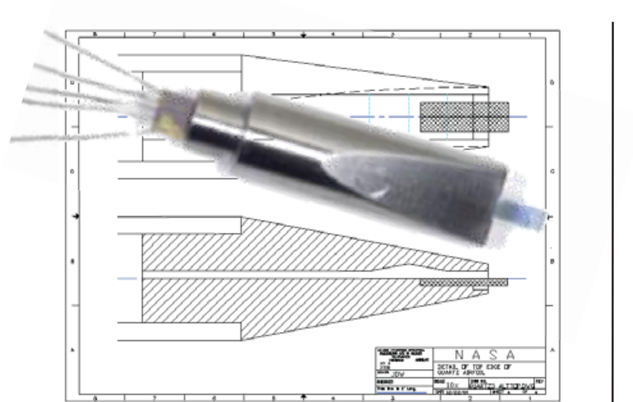
- Conclusions
- Acknowledgements

Thin Film Thermocouple Probe on a Turbojet Engine

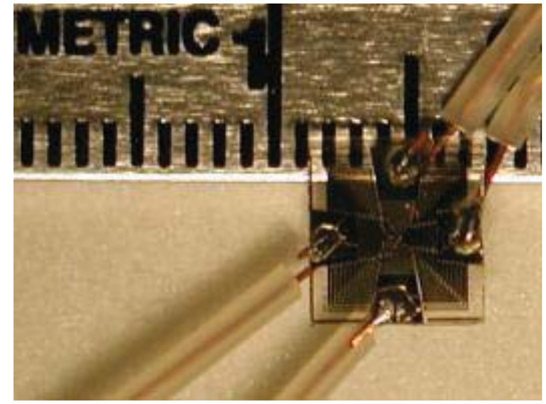
Trade names that appear in this work are provided for information only and their use does not constitute an official endorsement, either expressed or implied, by NASA.

GRC Physical Sensor Instrumentation Research Progress

- R&D 100 Awards in 1991, 1995, and 1998
- NASA Group Achievement Award 2003
- NASA Tech Briefs *Create the Future Design Contest* Award 2008
- 2013 Sensors Expo Applications Award
- Partnerships in Sensor Development:



2003 NASA Group Achievement Award
SiC High Temperature Drag Force Transducer as part of the Integrated Instrumentation & Testing Systems project



2008 NASA Tech Briefs Create the Future Design Contest - Machinery & Equipment
Flexible Small Area Heat Flux Sensor developed for Goodyear Tire & Rubber Co.

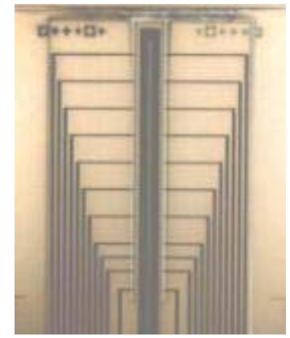
1991 R&D 100 Award
PdCr wire strain gauge applied on Ford Motor Co. exhaust manifold

1998 R&D 100 Award
Long-lived Convoluted Thermocouples For Ceramic Temperature Measurements

Thin Film Physical Sensors for High Temperature Applications

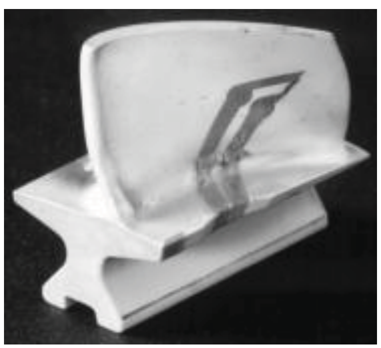
Advantages for temperature, strain, heat flux, flow & pressure measurement:

- Negligible mass & minimally intrusive (microns thick)
- Applicable to a variety of materials including ceramics
- Minimal structural disturbance (minimal machining)
- Intimate sensor to substrate contact & accurate placement
- High durability compared to exposed wire sensors
- Capable for operation to very high temperatures (>1000°C)

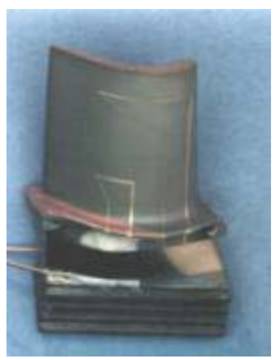


Flow sensor made of high temperature materials

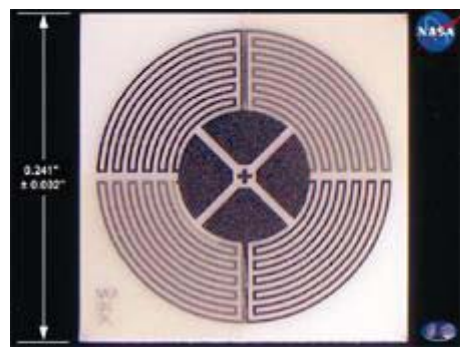
Multifunctional smart sensors being developed



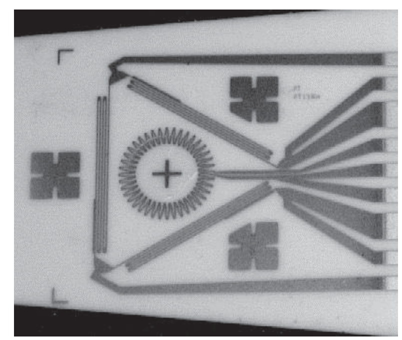
PdCr strain sensor to T=1000°C



Pt- Pt/Rh temperature sensor to T=1200°C



Heat Flux Sensor Array to T=1000°C



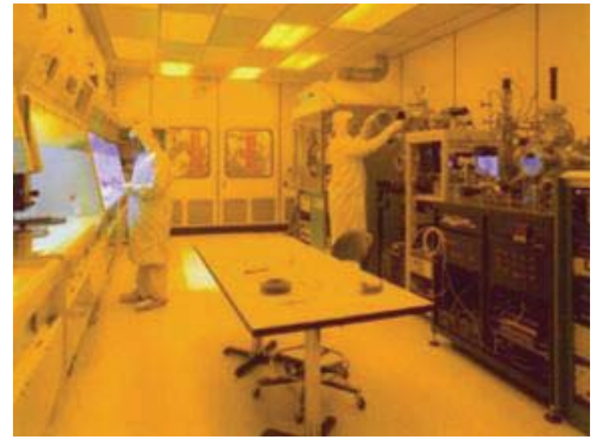
Multifunctional Sensor Array

Physical Sensors Facilities

Sputtering PVD Systems

Sensing Film layers are fabricated with physical vapor deposition methods (sputter deposition, e-beam vapor deposition)

Sensors are patterned by photolithography methods and/or stenciled masks



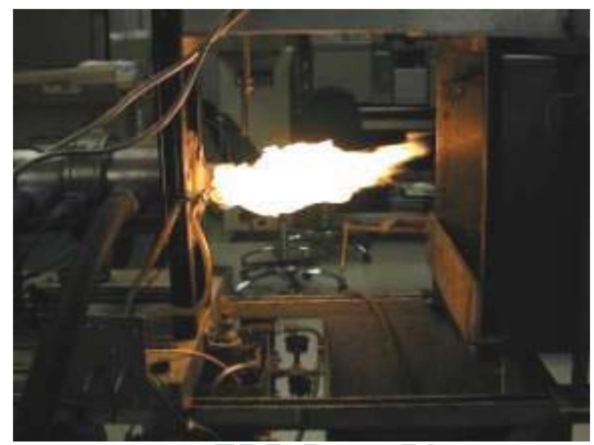
Microfabrication Clean Room

Evaluation of thin films with in-house Materials Characterization Facilities

Testing of films with in-house high-temperature furnaces & burn rigs

SEM/EDAX

Thin Film Characterization Lab



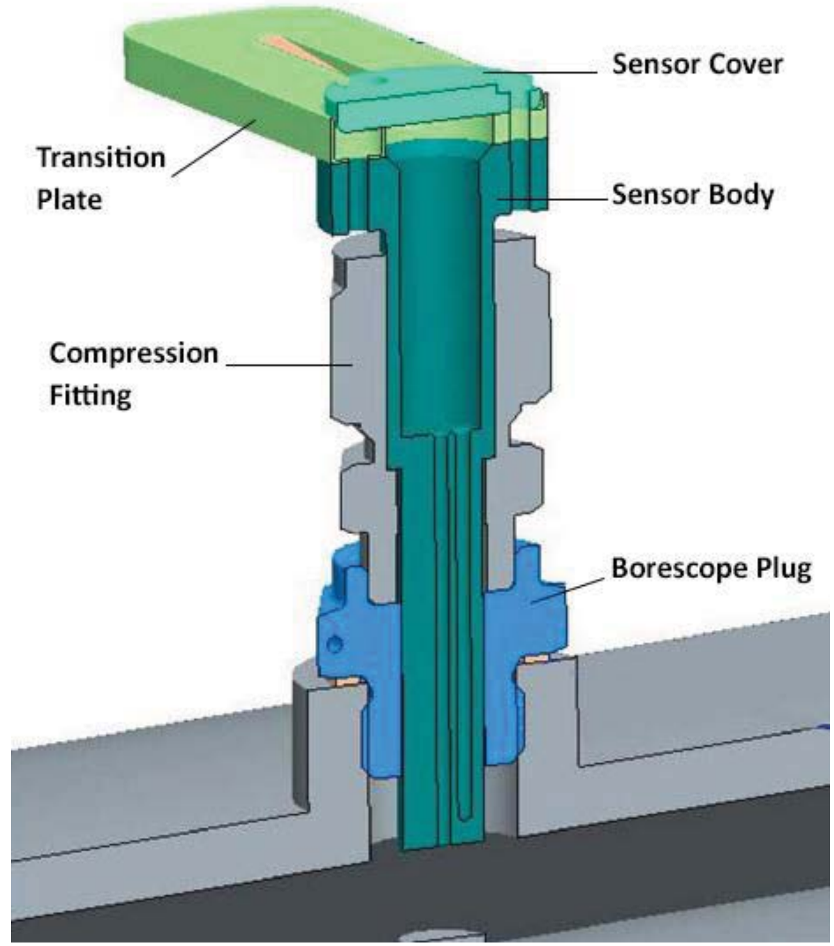
ERB Burn Rig

Thermocouple Probe

- VIPR (Vehicle Integrated Propulsion Research)
  - On-going ground-based engine test venture (since 2011)
  - Utilizes a Pratt & Whitney F117 turbofan engine
  - Maturing Engine Health Management (EHM) technologies
- VIPR2 (2013) Objective O13.0 — acquire data from a thin-film thermocouple probe installed in the engine
  - Establish a core capability for implementing thin-film sensor probes in harsh environments.
  - Allows new information for gas-path models
  - Demonstrate the viability of thin-film sensor probes in an engine environment
- A sensor probe was designed for installation in a borescope port in the high-pressure compressor section of the test engine.
  - Easy implementation
  - Gold versus platinum (Au-Pt) thermocouple selected based on material stability and GRC experience in Stirling convertors to 960°C

Thermocouple Probe Design

- Compression Fitting welded to a Borescope Plug
  - Sensor probe tip flush with internal wall of the bleed air passage
- Sensor Body Stainless Steel 316 bored out for thermocouple lead wires
  - Lead wires 0.076 mm dia. of Au, Pt in alumina tubes cemented in place
  - Embedded Type K thermocouple
  - Thin films of Au and Pt deposited on sensor body tip, lead wires bonded to films
  - Protective crown on tip to prevent cement from dislodging into engine
- Transition Plate held in place with a Sensor Cover held the connectors for the lead wires



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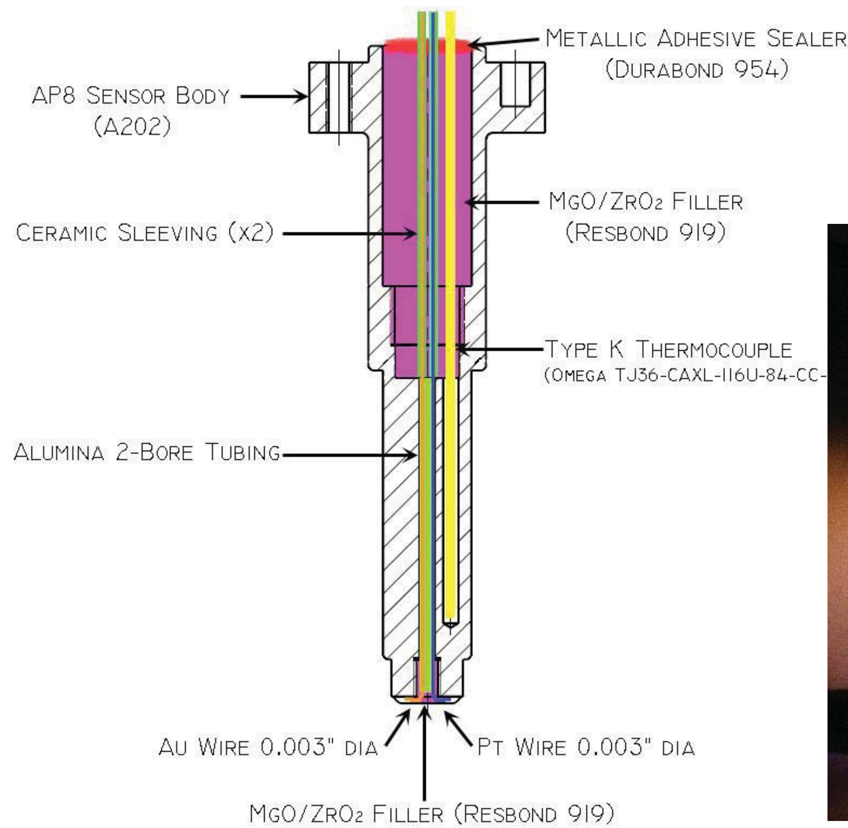
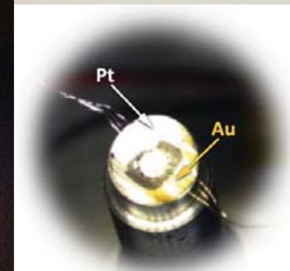
Thermocouple Probe Fabrication



Fabrication Diagram showing wires and potting cement



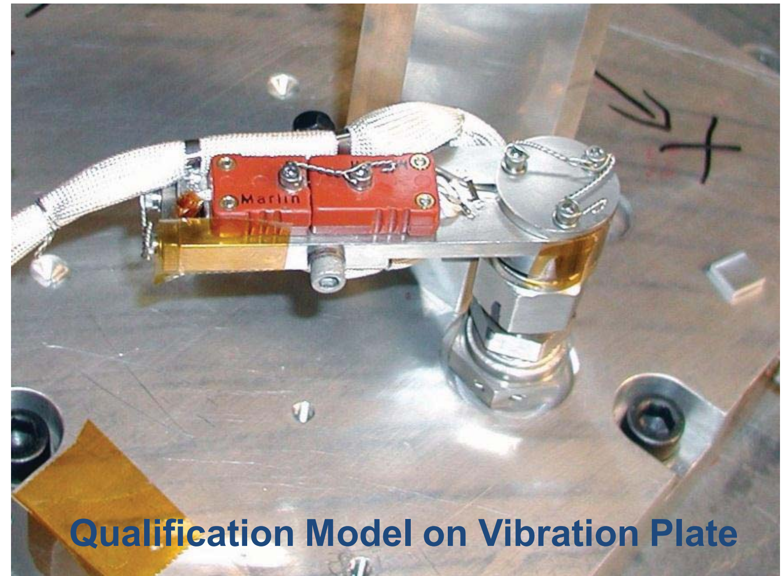
- Sensor probe components designed, fabricated and assembled at NASA GRC

Thermocouple Data Acquisition Unit

- Data Acquisition unit designed to operate with extended temperature range of –40°C to +125°C due to proximity of the jet engine
  - Digitizes the sensor data as close to the sensor as possible and send data packets to a separate receiver unit over a RS-485 bus,
- Digitizer built around automotive-grade thermocouple to digital conversion chips
  - 48 MHz clock, 14-bit conversion of temperature readings
  - Temperature calculated using NIST polynomials for Type K, Au-Pt thermocouples
  - Includes cold-junction compensation
- Receiver unit placed in a cooler area by the PC recording the data via RS-232 so uses standard commercial temperature parts

Verification Tests

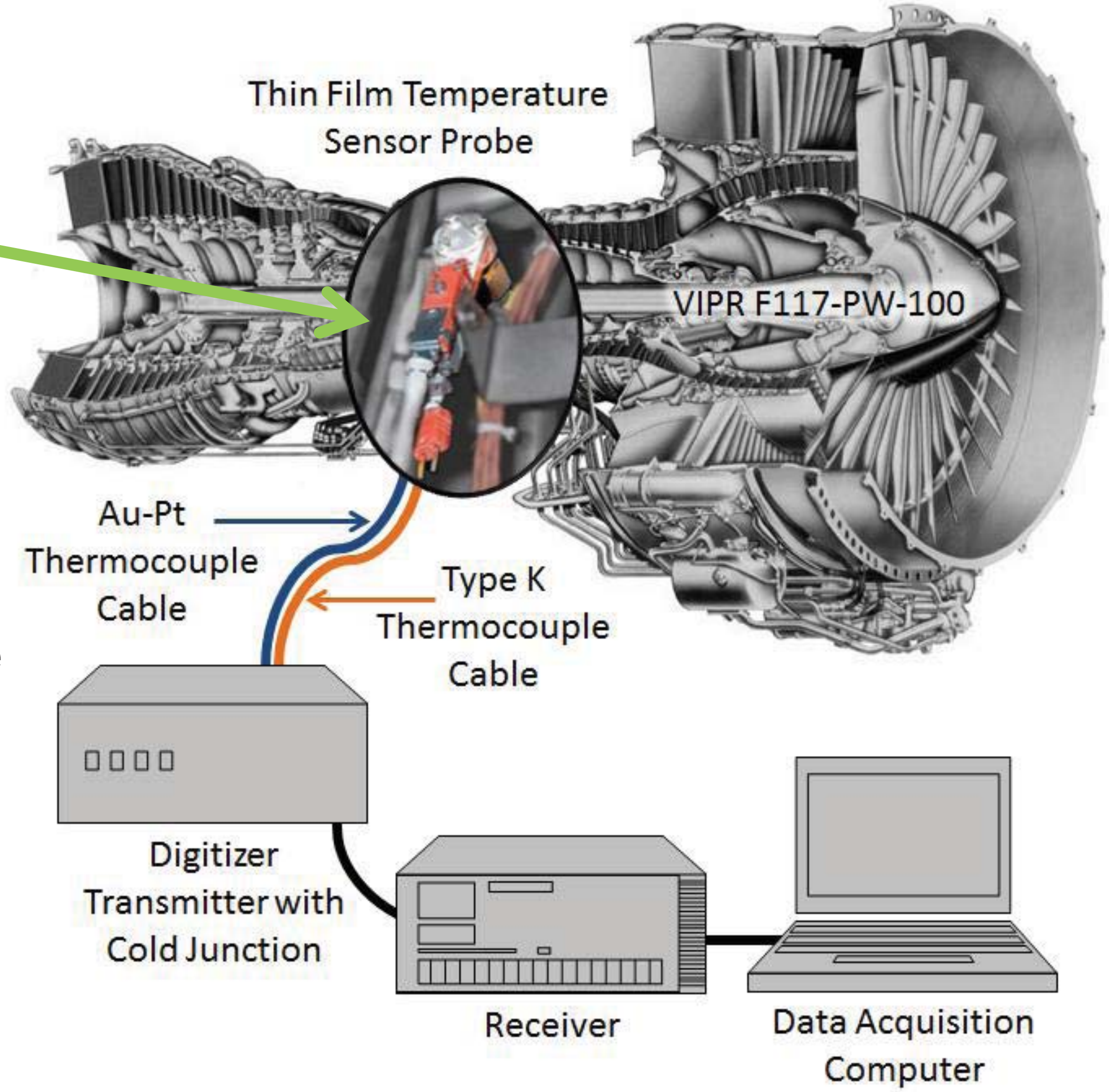
- Sensor Probe underwent a Qualifying Test Protocol as prescribed by VIPR requirements
- Qualifying Conditions:
  - Survivability after 20g shock
  - Operation at 5357 kPa (777 Psia)
  - Operation at 633°C
- Bench test operational unit in 150°C Box Furnace
  - Verified operation
  - Thin Film Au-Pt thermocouple indicated a faster response than embedded Type K probe



Qualification Model on Vibration Plate

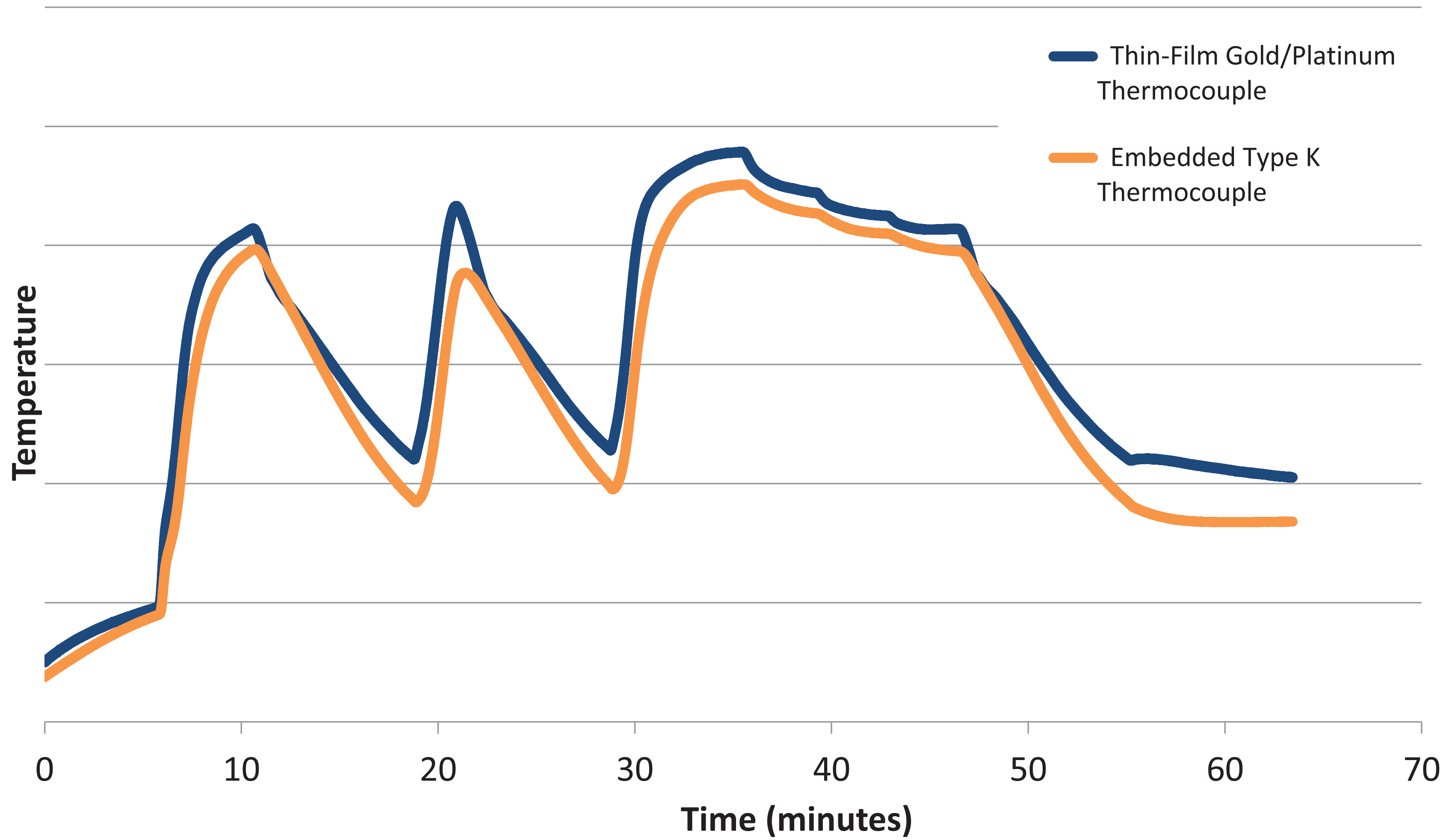
Qualification Model after Qualifying Tests

VIPR2+ Green Run Validation



- Operational unit installed in F117 compressor borescope port for engine validation test
- Grounding issues with sensor during VIPR2 run at NASA AFRC moved test to the VIPR2+ *Green Run* at P&W test cell

VIPR2+ Green Run Data



- Data logging on PC, 8 samples per second (no smoothing)
- Recorded two Probe TC as well as their cold junction temperatures

Multiwire Analysis

- Time constant (τ) convenient to describe reaction of thermocouple temperature change (dT/dt or $\dot{T}$) to change in temperature of the gas/fluid environment (T_g):

$$dT/dt = (1/\tau)\cdot\{T_g(t) - T(t)\}$$

  - "Time constant" dependent on heat transfer to gas and thermal properties of thermocouple
- Gas Temperature can be calculated by temperature (T), time derivative ($\dot{T}$) and time constants (τ) for multiple thermocouples at same location:

$$T_g(t) = T_1(t) + \tau_1\cdot\dot{T}_1$$

$$T_g(t) = T_2(t) + \tau_2\cdot\dot{T}_2$$

$$T_1(t) - T_2(t) + \tau_1\cdot\dot{T}_1 - \tau_2\cdot\dot{T}_2 = 0$$

- Minimize $\mathrm{RMS}(\Delta T_g(t))$ for fitting τ_1, τ_2
- Results:
  - Embedded Type K Thermocouple (τ_1) = 26.2 s
  - Au-Pt Thin Film Thermocouple (τ_2) = 2.40 s

Numerical Analysis

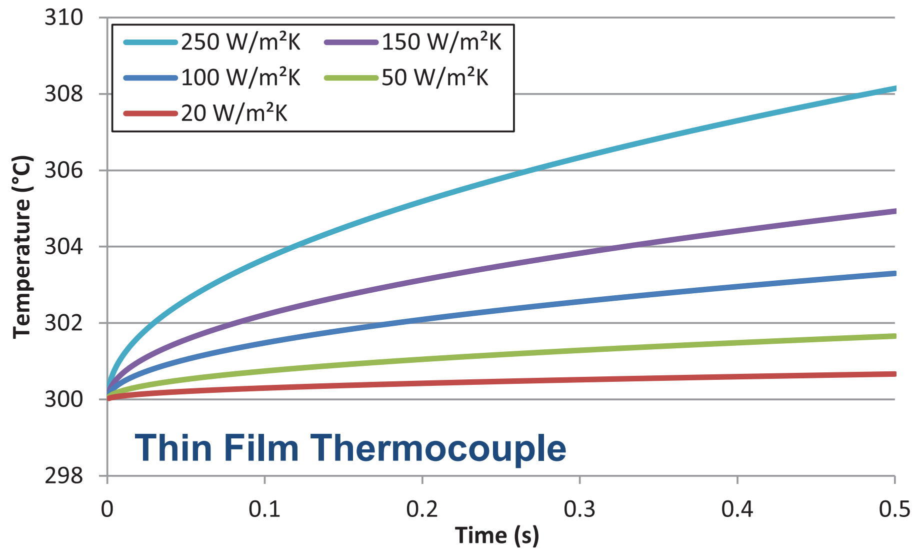
- Determine temperature with time based on the rate of heating :

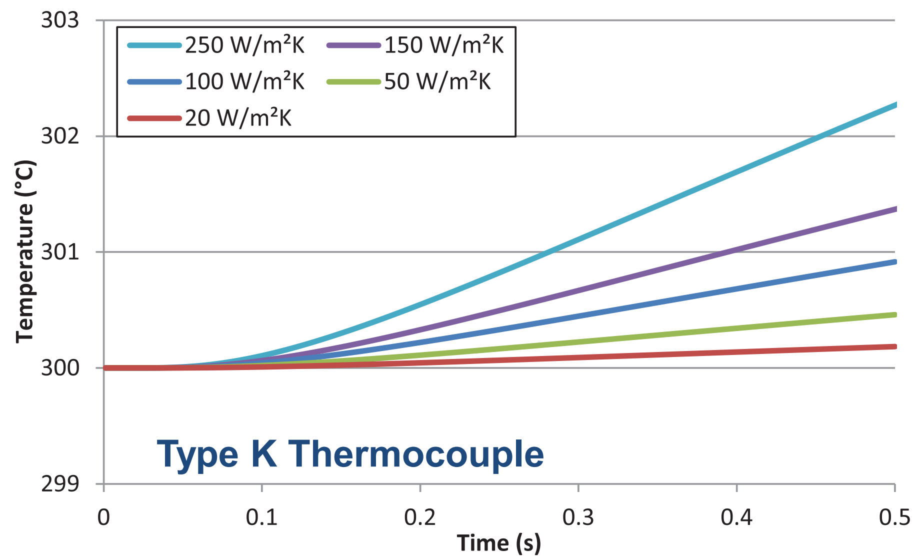
$$\partial T/\partial t = \alpha \cdot \partial^2 T/\partial x^2$$

- At each *node* (j) of a modeled layer, calculate T at each time step (n):

$$T_{j,n} = (-\alpha_M \Delta t/\Delta x_2)\, T_{j-1,n+1} + (1+2\cdot\alpha_M \Delta t/\Delta x_2)\, T_{j,n+1} - (\alpha_M \Delta t/\Delta x_2)\, T_{j+1,n+1}$$

- Model ran for different heat transfer coefficients
  - Thin Film Thermocouple at 1µm
  - Type K thermocouple at 8.76 mm
  - Total 76 mm of Stainless Steel
- Reaction plotted for a 300°C step increase on the tip of the probe at 300°C
  - Two very different curves!





Comparison of Time Constants

- Compare numerical analysis cases using:

$\tau = (\mathrm{d}T/\mathrm{d}t)^{-1} \cdot \{T_g(t) - T(t)\}$

  - $t = 0.25$ s
  - $dt = 0.5$s
  - $T_g = 600°C$
- Very different results compared to data fit

Heat Transfer Coefficient (W/m²K)	τ_1 (s)	τ_2 (s)	τ_2/τ_1
20	225.	815	0.277
50	90.2	326	0.276
100	45.1	164	0.276
150	30.0	109	0.275
250	18.1	66.0	0.274
Green Run Data Fit	*2.40*	*26.2*	*0.0916*

- Complications?
  - Sensor probe tip geometry?
  - Turbulent flow of the bleed air?
  - "Time constant" requires more terms to fully characterize the response?

Comparison to Derived Temperature

- The Thin Film Thermocouple was seen to have a response time up to an order of magnitude faster than the embedded Type K thermocouple
  - A truer indicator of real gas temperature
  - How much better?

$$T_g(t) = \frac{T_2\left(\frac{\dot{T}_1}{\dot{T}_2}\right) - T_1\left(\frac{\tau_2}{\tau_1}\right)}{\left(\frac{\dot{T}_1}{\dot{T}_2}\right) - \left(\frac{\tau_2}{\tau_1}\right)}$$

- FFT to calculate the gas temperature in the frequency domain then convert back to time domain
  - Filter out >2.238 kHz
  - Assumes “time constant” relation is accurate

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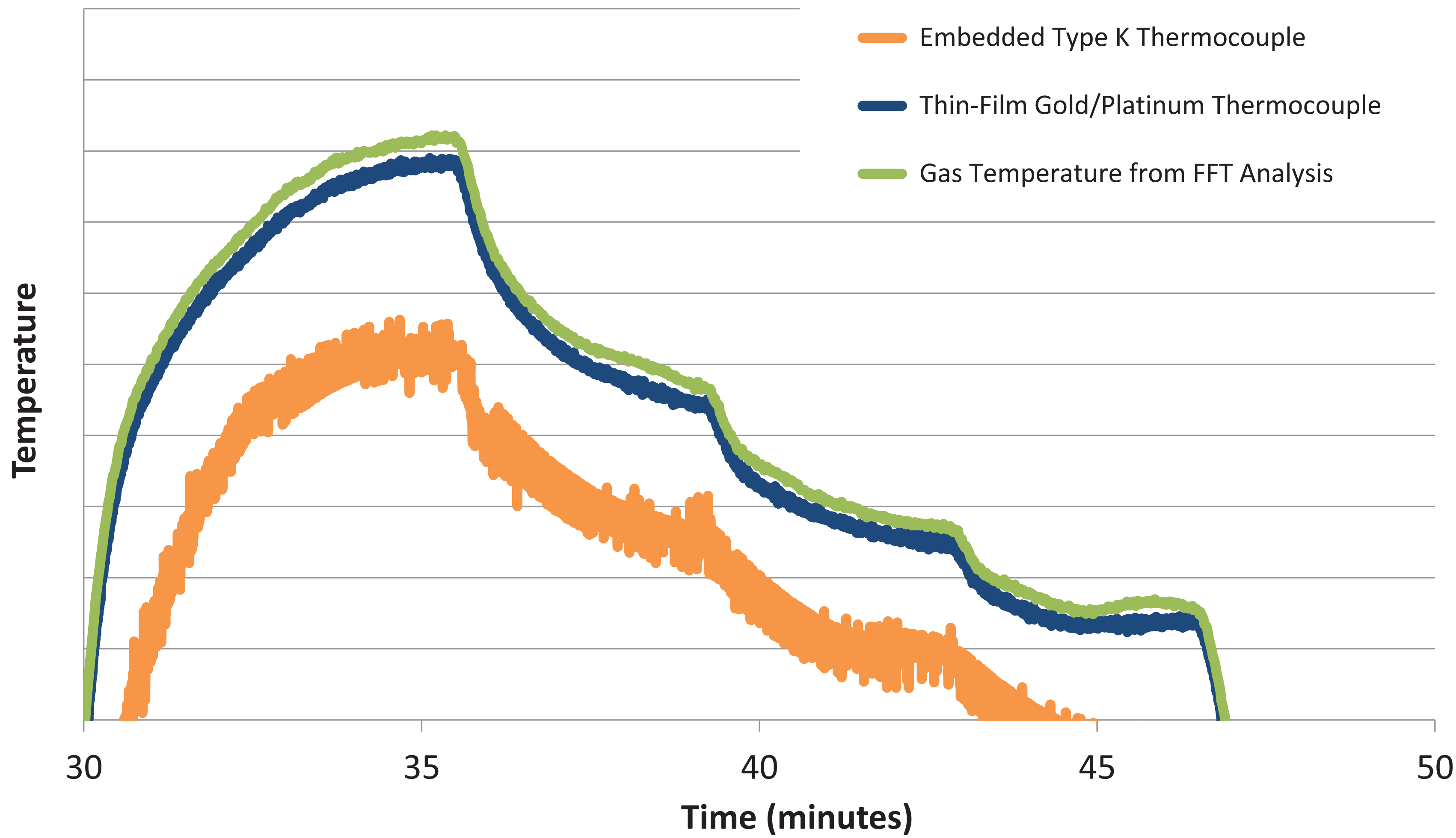
Comparison of Temperatures



- Thin film thermocouple reading within 3.2°C of the gas temperature
  - Total uncertainty of the thin film thermocouple thus ±3.4°C

Conclusions

- Experimental thin-film Au-Pt thermocouple sensor probe was designed, fabricated at GRC, and operated in a borescope port in the bleed air passage of a F117 turbofan engine
  - VIPR Objective
  - Embedded standard Type K thermocouple
  - Sensor probe was fabricated from high temperature materials
- Sensor Probe and assembly subjected to strict qualification testing
  - Multi-axis vibrational testing
  - Elevated temperature pressure testing
- Custom data acquisition unit to digitize the signals from the sensor probe for high accuracy and low noise measurements was designed and built at GRC.
- Measured thin film thermocouple temperature estimated within 3.4°C of gas temperature
  - Acquired data faster than expected from numerical models

Acknowledgments

- **Chuck Blaha** of Jacobs Technology for the thin film depositions and wire bonding
- **Paul Solano** of the GRC Mechanical & Rotating Systems Branch and **Lawrence Kren** of Vantage Partners for mechanical drawing support
- **Daniel Graf, Tracy Cantly, Greg Blank** and the team at the **GRC Fabrication Shop** for machining the sensor body and parts
- **Christopher Hampton** of Sierra Lobo, Inc. for material testing
- **Richard Hanzel** of Honeywell Technology Solutions, Inc. for assistance in pressure qualification tests
- **GRC Structural Dynamics Laboratory** for vibration qualification tests
- **NASA GRC Test Facilities Operations, Maintenance, and Engineering (TFOME)** organization in maintaining the fabrication and test equipment capabilities of the **NASA GRC Microsystems Fabrication Lab**
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