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

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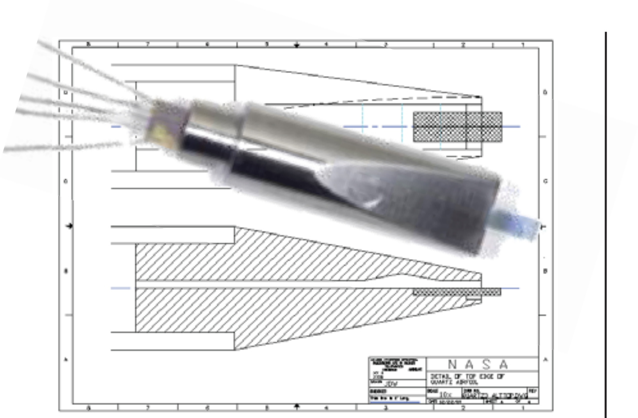
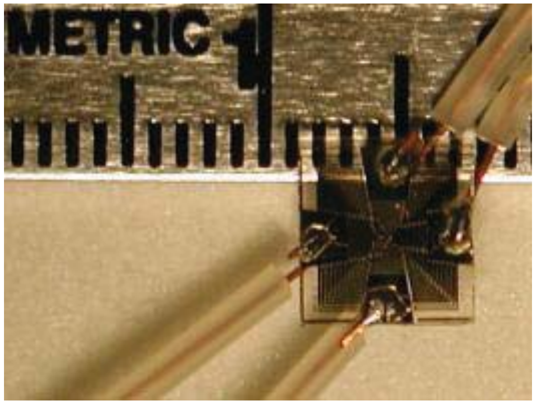
GRC Physical Sensor Instrumentation Research Progress

- 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.

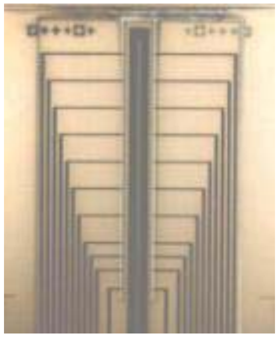
1991 R&D 100 Award
PdCr wire strain gauge applied on Ford Motor Co. exhaust manifold

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

Thin Film Physical Sensors for High Temperature Applications

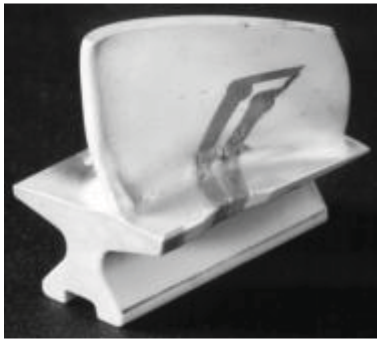
Advantages for temperature, strain, heat flux, flow & pressure measurement:

- 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)



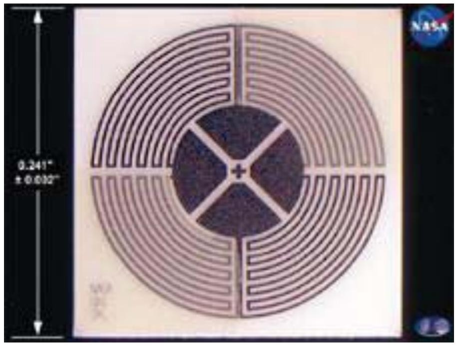
Flow sensor made of high temperature materials

Multifunctional smart sensors being developed

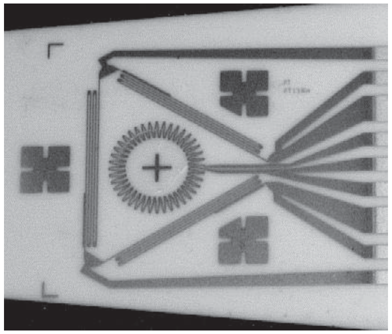


PdCr strain sensor to T=1000°C

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



Heat Flux Sensor Array to T=1000°C



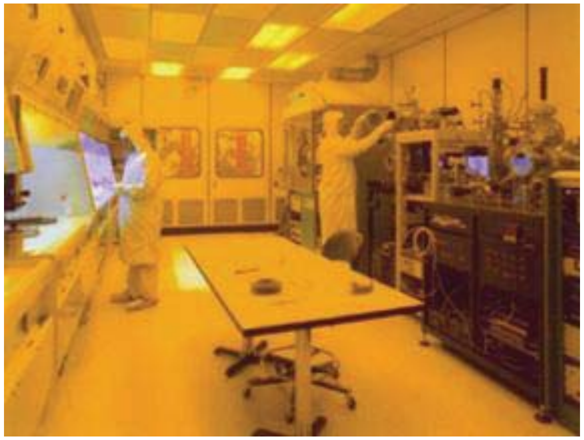
Multifunctional Sensor Array

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

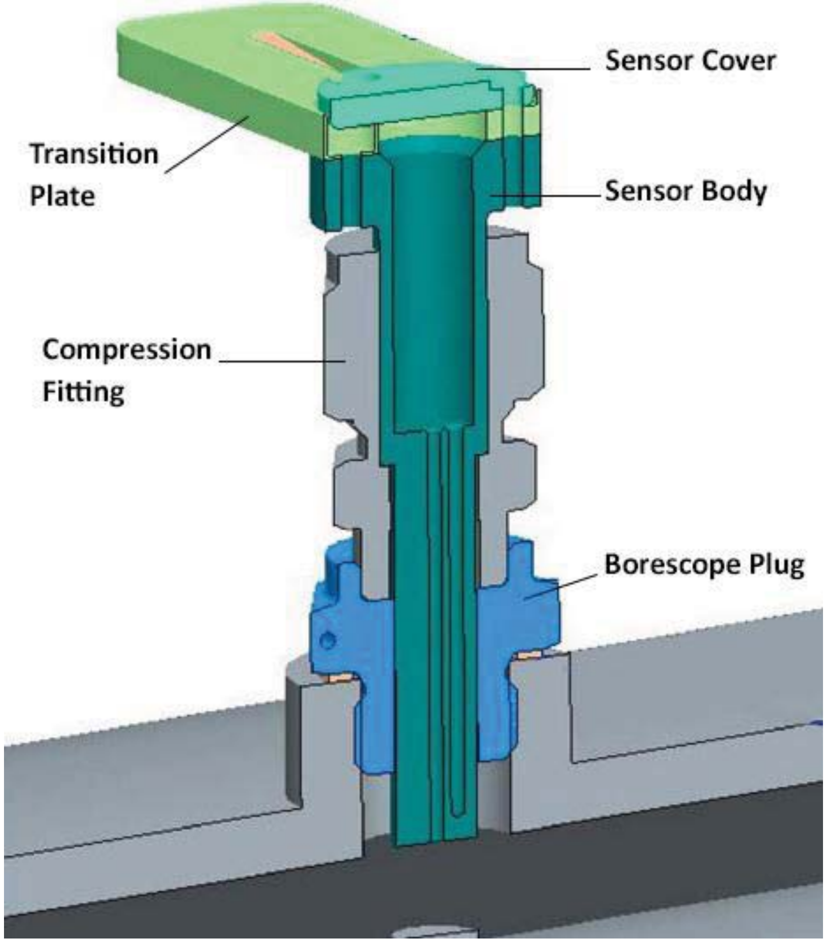
ERB Burn Rig

Thermocouple Probe

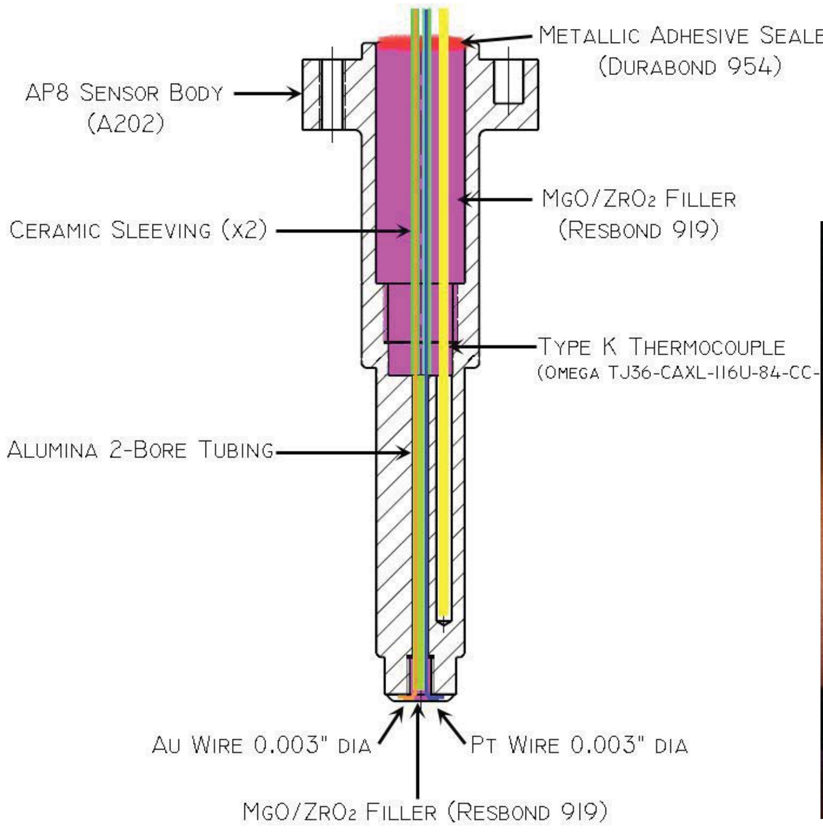
- VIPR (Vehicle Integrated Propulsion Research)
  - On-going ground-based engine test venture (since 2011)
  - Utilizes a Pratt & Whitney F117 turbofan engine
  - Maturing Engine Health Management (EHM) technologies
- VIPR2 (2013) Objective O13.0 — acquire data from a thin-film thermocouple probe installed 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

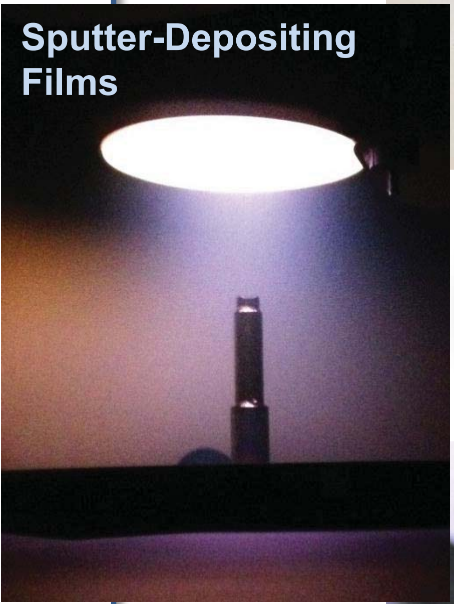


Thermocouple Probe Fabrication

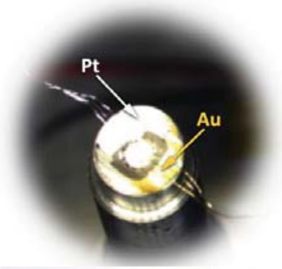


Fabrication Diagram showing wires and potting cement

Sputter-Depositing Films



Machined Sensor Probe Body



Au-Pt Films on Probe Tip with Crown

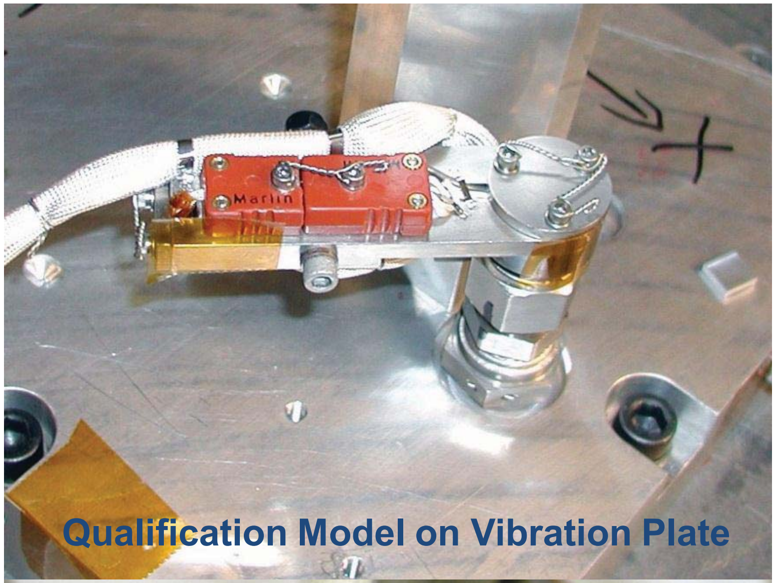
- Sensor probe components designed, fabricated and assembled at NASA GRC

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

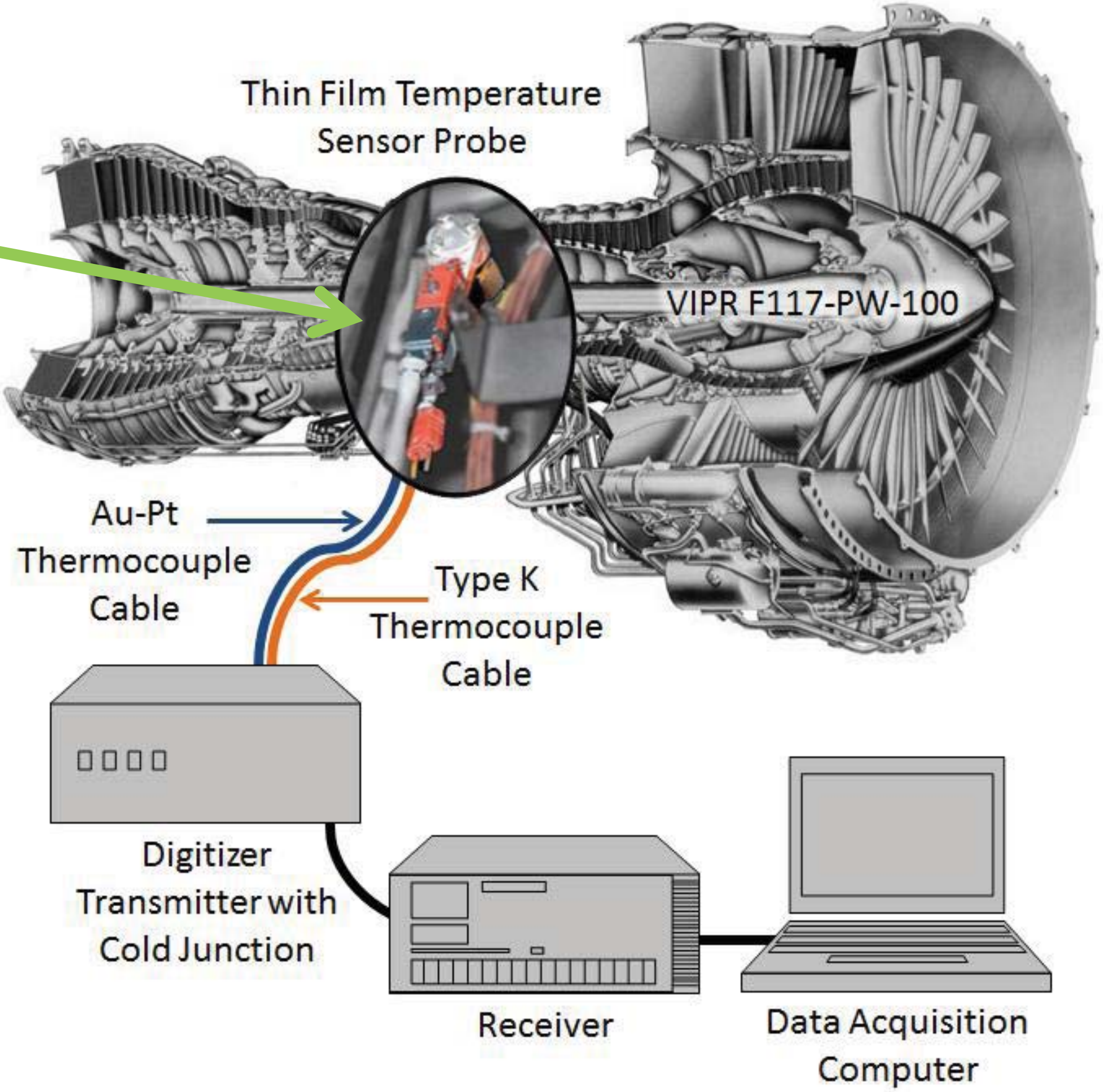
- Sensor Probe underwent a Qualifying Test Protocol as prescribed by VIPR requirements
- Qualifying Conditions:
  - Survivability after 20g shock
  - Operation at 5357 kPa (777 Psia)
  - Operation at 633°C
- Bench test operational unit in 150°C Box Furnace
  - Verified operation
  - Thin Film Au-Pt thermocouple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



Qualification Model on Vibration Plate

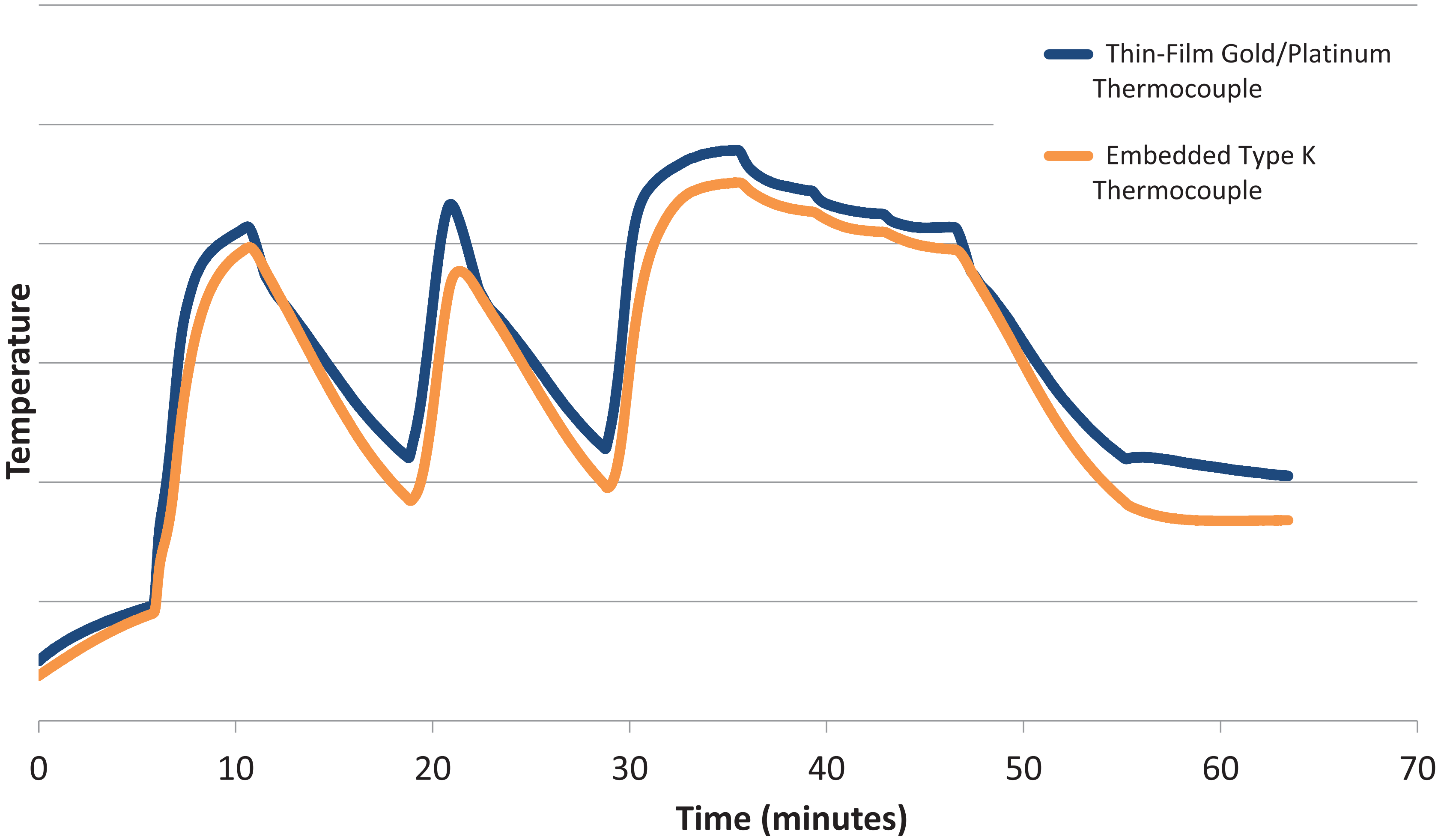
Qualification Model after Qualifying Tests

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

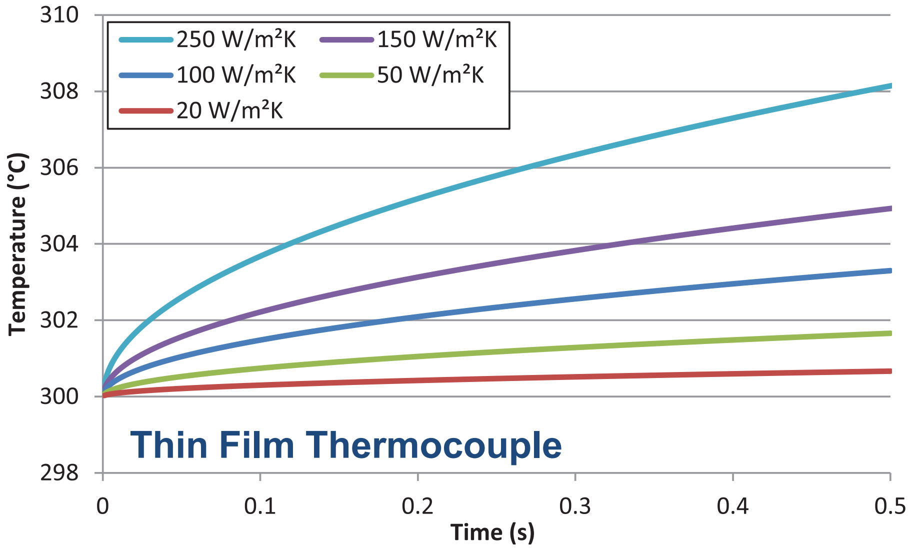
- Determine temperature with time based on the rate of heating :

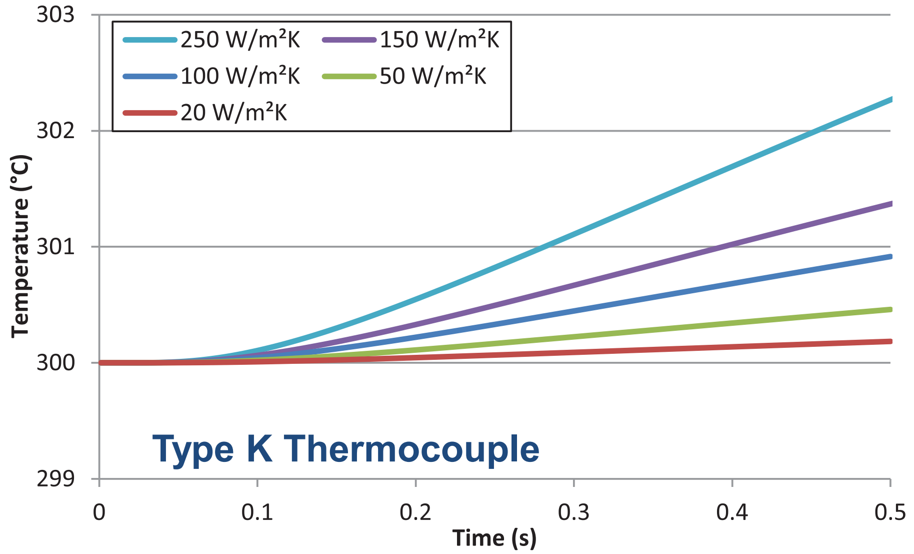
$$\partial T/\partial t = \alpha \cdot \partial^2 T/\partial x^2$$

- 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:

  $\tau = (\mathrm{d}T/\mathrm{d}t)^{-1} \cdot \{T_g(t)\text{-}T(t)\}$
  - $t = 0.25$ s
  - $dt = 0.5$s
  - $T_g = 600°\text{C}$
- Very different results compared to data fit

Heat Transfer Coefficient ($\mathrm{W/m^2K}$)	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?

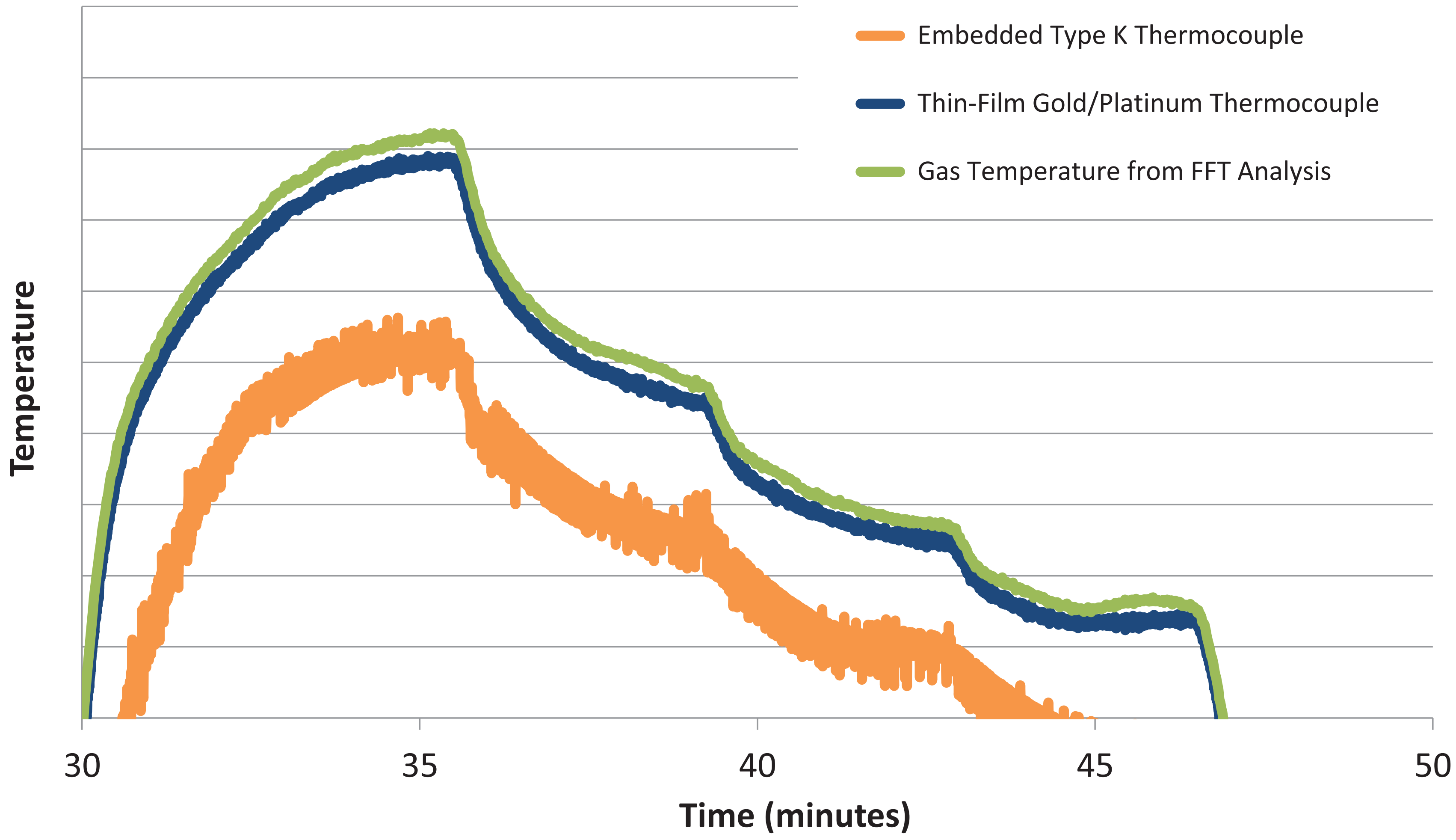
Comparison to Derived Temperature

- 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

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
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- **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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