Hybrid Optical Sensors for Power Generation Systems

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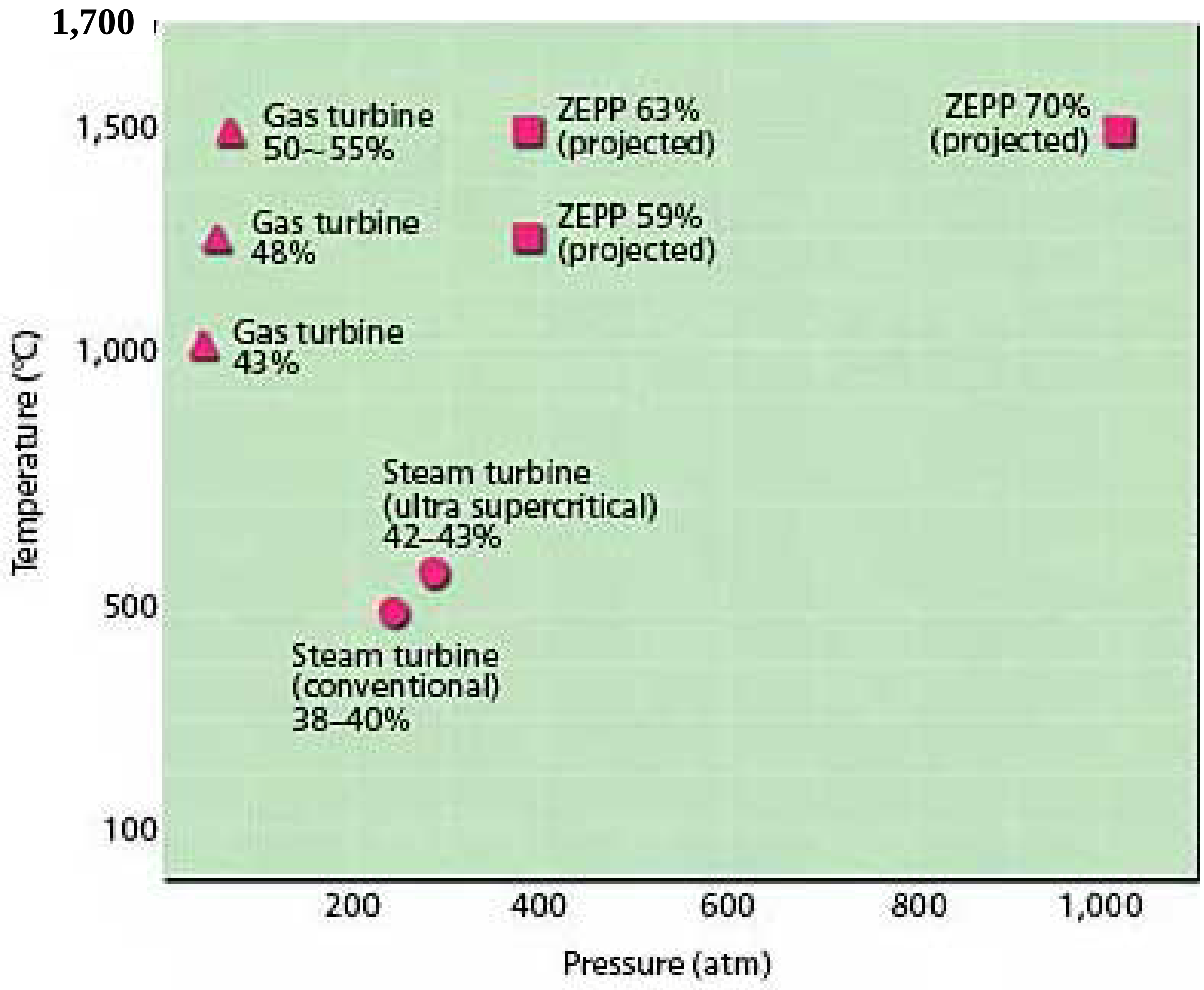
Sponsor: US Department of Energy (DOE)

Why is Extreme Temperature Sensing Needed --- Greener & More Efficient



Ultimate Goal--ZEPP: Zero Emission Power Plant

Burn Less Fuel

↓

Less Hazardous Waste & CO_2

Higher Pressures

↓

Liquify CO_2 -Easier To Transport/Store Waste

↓

Greener Plant

* J. H. Ausubel, “ Big Green Energy Machines,” The Industrial Physicist, AIP, pp.20-24, Oct./Nov., 2004.

GE's H system Gas Turbine

System Test had 3500 gauges and sensors

Uses Firing Temperature of 1430   C

R. Matta, et.al, " Power Systems for the 21st Century," GE Power Systems Publication GER3935B, Oct. 2000.

THE NEED:
PRECISION RELIABLE SENSORS for GAS Temperature and Pressure Measurement to Keep Plants at Operating at Super Critical Conditions

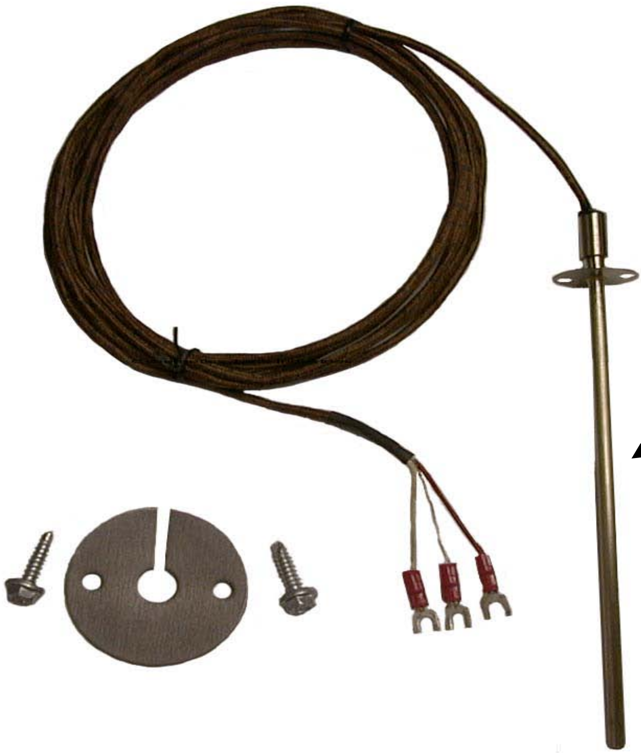
Any Options?

-- ALL Electronic Sensor Chips ?   Fail after ~ 500   C (Insulation Breakdown)

-- Silica/Glass Fiber Optics (Single Mode) – Fail after ~ 900 °C (Grating Erasure)

How does Extreme temperature Measurement get done today?

Platinum/Rhodium High Temperature Thermo-Couple (TC) All-Electrical Technology is used to Measure Extreme Temperature



Note:
Need to Encase in Custom Magnesia (MgO) or Alumina Insulating Ceramics – Can Reach 1900 C

Image courtesy: Cybernetics Technical Industries Inc.

What are the limitations of the Best TC Technology?

Present **TC Technology** under extreme engine conditions are:

- Structurally unreliable (develop cracks in the ceramic insulation – moisture retention making it conductive, can explode)
- Give inaccurate and erratic readings
- Readings intrinsically depend on a % of measured extreme temperature, i.e., gets worse at higher temperatures- caused by Compositional variations in wire alloy – varying EMF properties along length

Type	Combination		Working Temperature Range/°C			Tolerance/°C
	-ve	+ve	Bare wire only		Metal Clad form	
			Continuous use	Intermittent use		
S	Pt	10% Rh/Pt	200-1500	200-1650	200-1300	IEC 584-2 Class 1or 2
R	Pt	13% Rh/Pt	200-1500	200-1650	200-1300	IEC 584-2 Class 1or 2
B	6% Rh/Pt	30% Rh/Pt	200-1600	200-1750	200-1450	IEC 584-2 Class 1or 2
	20% Rh/Pt	40% Rh/Pt	200-1700	200-1850	200-1450	8.0
	Iridium	40% Ir/Rh	1000-2100	-	N/A	10.0
	0.03% Fe/Au	Chromel	1-300K	-	N/A	-

Tolerance Classes
Class 1 = +/- 1°C or +/- {1 + (t - 1100) x 0.0003}°C
Class 2 = +/- 1.5°C or +/- 0.0025t°C
Class 3 = +/- 4°C or +/- 0.005t°C
Whichever is the greater and where t is temperature in °C

Availability

Type	Class 1	Class 2	Class 3
S	x	x	
R	x	x	
B		x	x

The temperature scale used in ITS-90 for which the fixed points are as follows:-
Zinc point = 419.53°C
Gold point = 1064.18°C
Palladium Point = 1553.5°C
Platinum Point = 1768.1°C

~ +/- 0.2 %

Table of tolerance values

Temperature °C	Class 1 +/- °C	Class 2 +/- °C	Class 3 +/- °C
0 - 600 incl.	1.0	1.50	4.0
700	1.0	1.75	4.0
800	1.0	2.00	4.0
900	1.0	2.25	4.5
1000	1.0	2.50	5.0
1100	1.0	2.75	5.5
1200	1.3	3.00	6.0
1300	1.6	3.25	6.5
1400	1.9	3.50	7.0
1500	2.2	3.75	7.5
1600	2.5	4.00	8.0
1700	-	4.25	8.5

2009 Table : JM Noble Metals Inc. www.noble.matthey.com

Who does TC Probes?

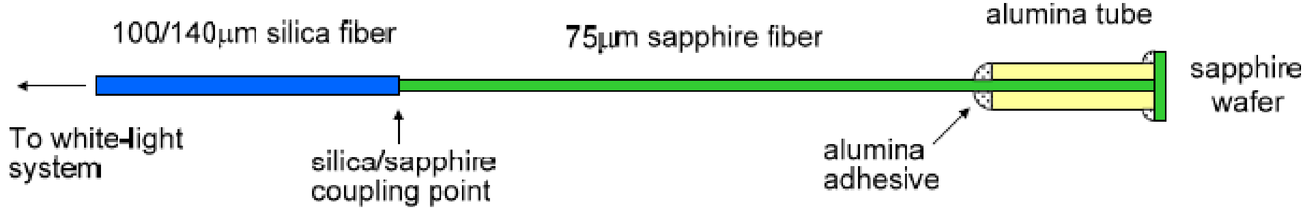
Engine/Turbine Manufacturers design custom Temperature Probes based on Highly Packaged / Protected TC Technology

Image courtesy: L&L Kilns Inc.

Fiber-Optic Probes?

Same Packaging Problem as TCs – Protect the Flexible and Thin/Brittle Optical Fiber and related frontend optics generally requiring a mix of packaging materials-CTE Mismatches

Multi-Mode Fiber-Optics for Robust Coupling – Causes Multi-Mode Interference/Noise



Ref: Virgina Tech, SPIE 2007.

Is There An Extreme Temperature Sensor Design Without the TC & Optical Fiber Probe Packaging & Reliability Issues?

What is new about our approach?

Wireless + Wired Optics

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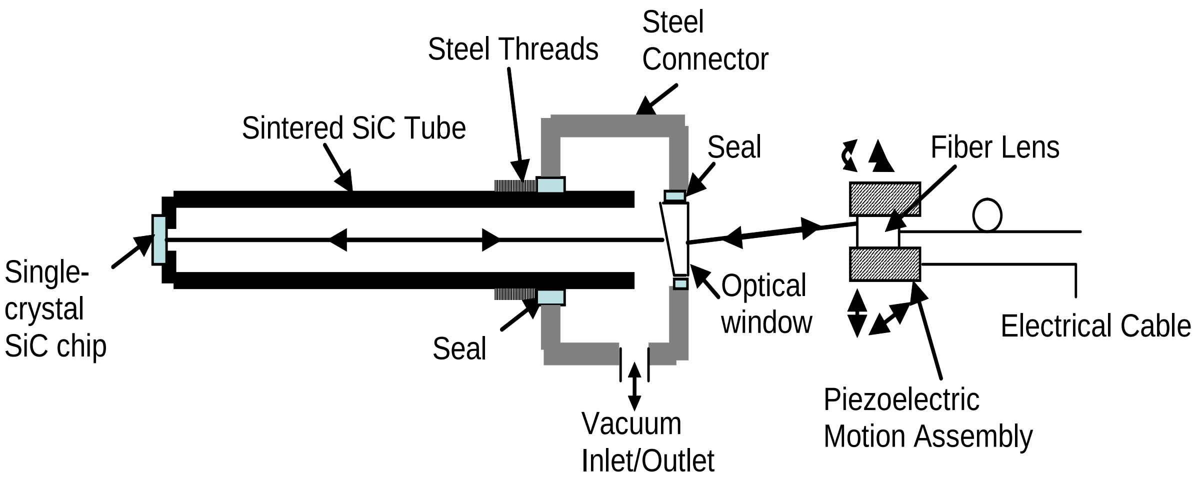
Extremely Hot | Thermal Isolation | Cool Section



What is new about our approach?

- Single Crystal SiC + Sintered SiC Probe
- Single material (CTE matched) – Robust frontend for extreme zone
- Temperature Reading Independent of Intrinsic % Increasing Temperature Error

Eliminated Fundamental TC Limitations

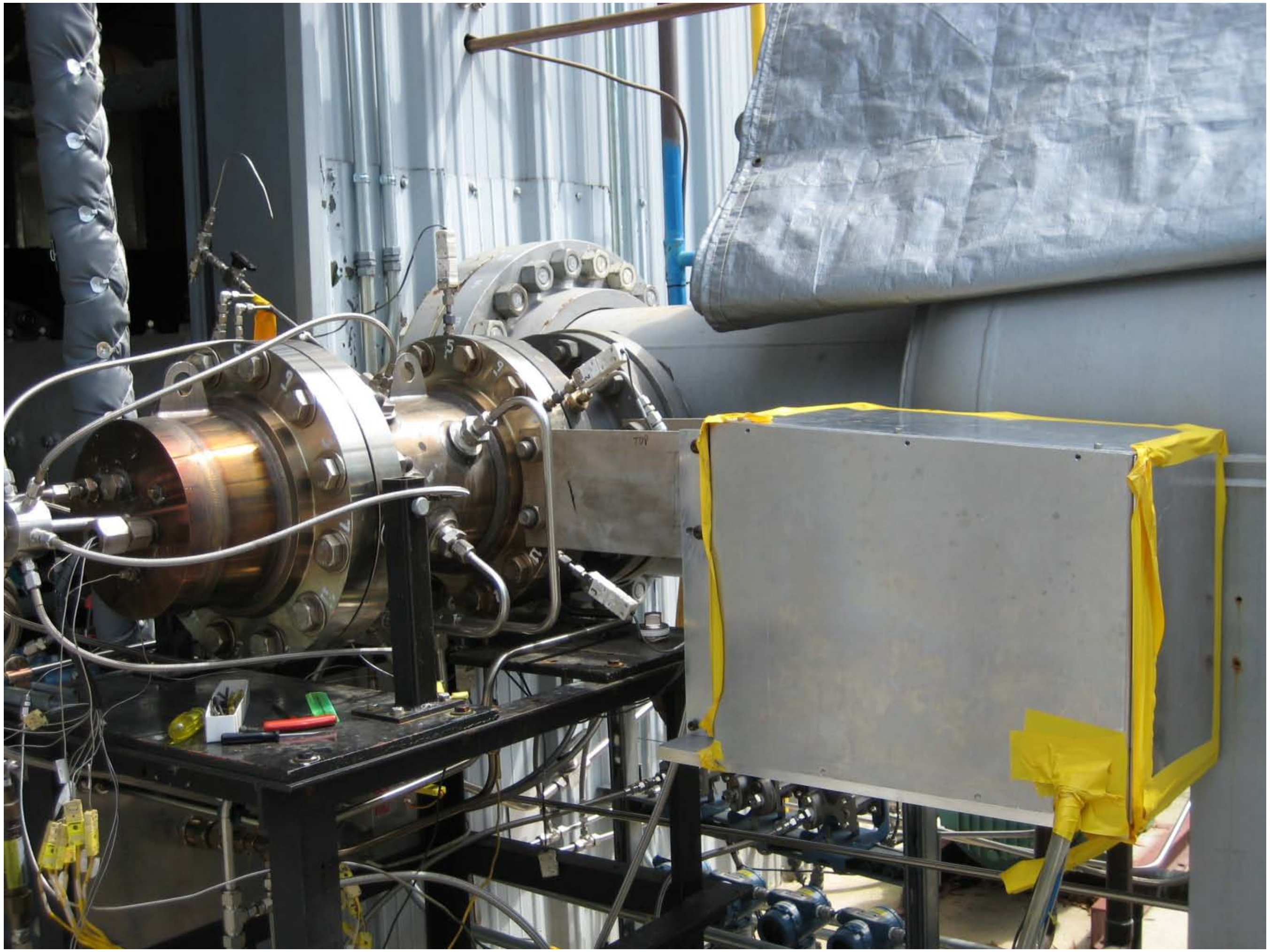
Front-End Probe

Unassembled

Assembled

Images courtesy: Nuonics, Inc.

INSTALLED OPTICAL SENSOR AT GAS TURBINE TEST RIG



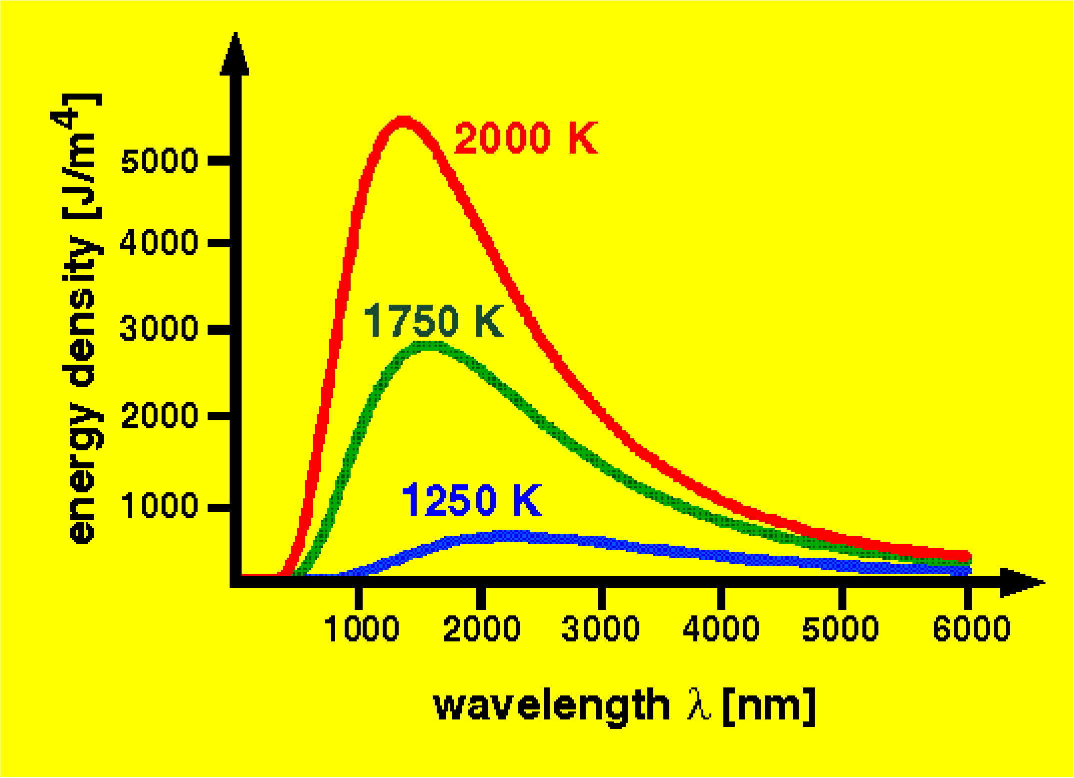
6 Thermo-Couples (TCs) Placed in Circular Ring Format At Exit of Combustor

Optical Probe about 6 inches From TC positions in Combustor Exhaust Section

GAS TURBINE RIG TESTING SUMMARY

COMBUSTION RIG FLAME ACTIVE OPERATION	**6 DAYS**
NO. OF TIMES PROBE EXPERIENCED FLAME LIGHT AND THERMAL SHOCK (TEMPERATURE RAMP OF 1000 DEG-C IN 3 SECONDS)	**8 (1 DAY 3 FLAME LIGHTS, 5 DAYS 1 FLAME LIGHT/DAY**
OPERATION WITH FLAME ON	**26 HOURS**
OPERATION WITH FLAME OFF AND BLOWER ON	**13.5 HOURS**
NUMBER OF COMBUSTION HEAT AND COOL CYCLES	**8**
DAYS IN EXTERNAL RIG ENVIRONMENT	**28 DAYS**

+100 years of Blackbody Radiation & Temperature Dependence



Max Planck

$$I(\lambda,T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1}\cdot\varepsilon(\lambda,T)$$

Radiation Thermometry - Pyrometers

- Options:
---Direct View of Near BB radiation – <u>Problem</u>- Changing Gas/Combustor Wall Emmissivity Issue

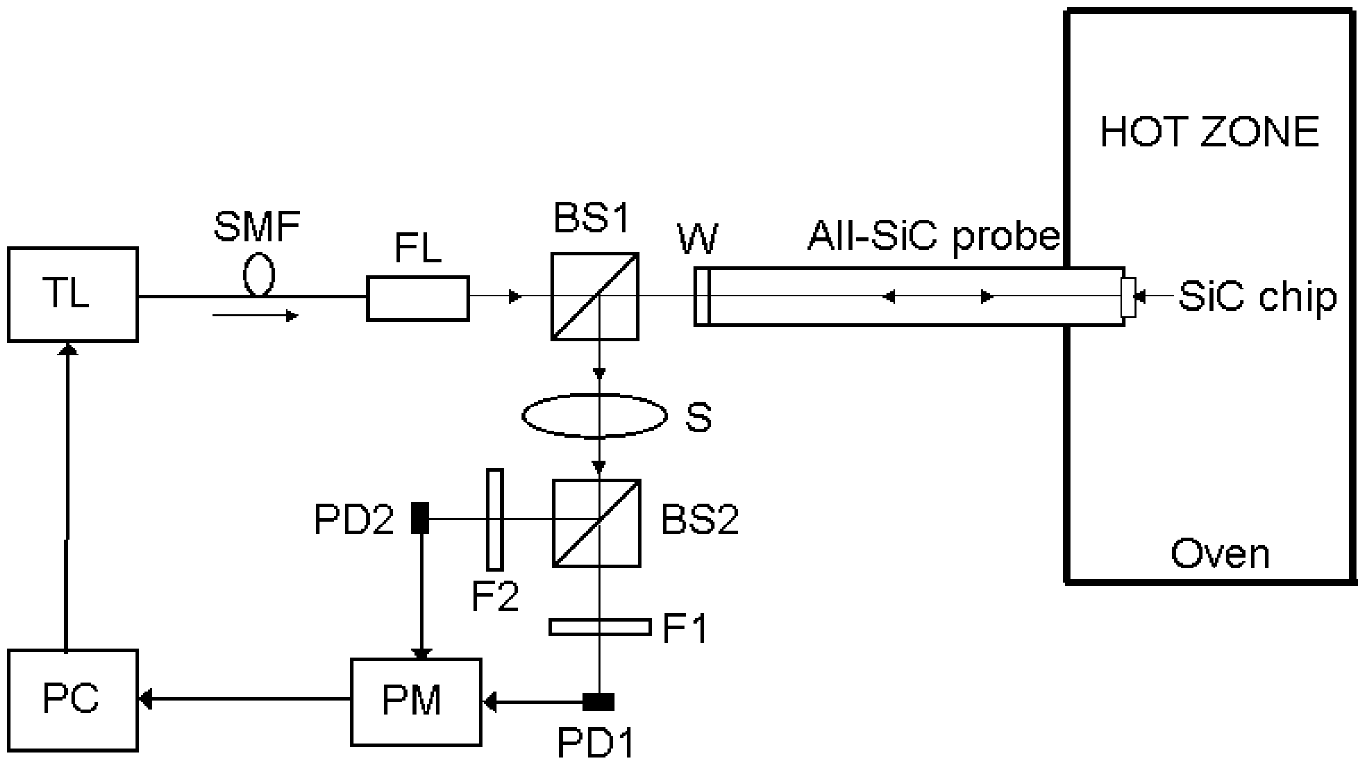
-Emmissivity Calibration via 2-wavelength – <u>Problem</u> – Optical Window Dirty
-OK for fixed clean material production- Steel Melts Production Factory
(Pioneer: Prof. of Chemical Engg. Hoyt Hottel- 1924-68 at MIT)

--- Indirect View of Protected Target Material BB radiation
- OK as No window and changing emmissivity issue BUT <u>Problem</u> of light coupling and Multi-material issue (couple light to optical fiber – NASA– <u>Coarse Temperature Resolution and Multi-Material Design</u> – Mechanical Breakdown issues)

Can Pyrometry Positively Impact The Proposed All-SiC Hybrid Sensor?

Proposed Dual-Signal Processing-Mode Sensor Design

A First Hybrid Design:
Pyrometry + Laser Interferometry



F1, F2: Optical Bandpass Filters

Two-Color Pyrometer

- Measure radiation power at two wavelengths and take the ratio

Wein Approximation $$I(\lambda,T)=\frac{2hc^2}{\lambda^5}e^{-\frac{hc}{\lambda kT}}\cdot\varepsilon(\lambda,T)$$

$$R=\frac{P_{\lambda_1}}{P_{\lambda_2}}=A_S\left(\frac{\lambda_2}{\lambda_1}\right)^5\frac{\varepsilon(\lambda_1,T)+a(\lambda_1,T)}{\varepsilon(\lambda_2,T)+a(\lambda_2,T)}\exp\left[-C_2\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)\frac{1}{T}\right]$$

A_s: system-specific constant – takes into account optical and detection components

$a(\lambda,T)$: specific emissivity of the background

$C_2 = hc/k$

Hoyt Hottel, MIT, 1932

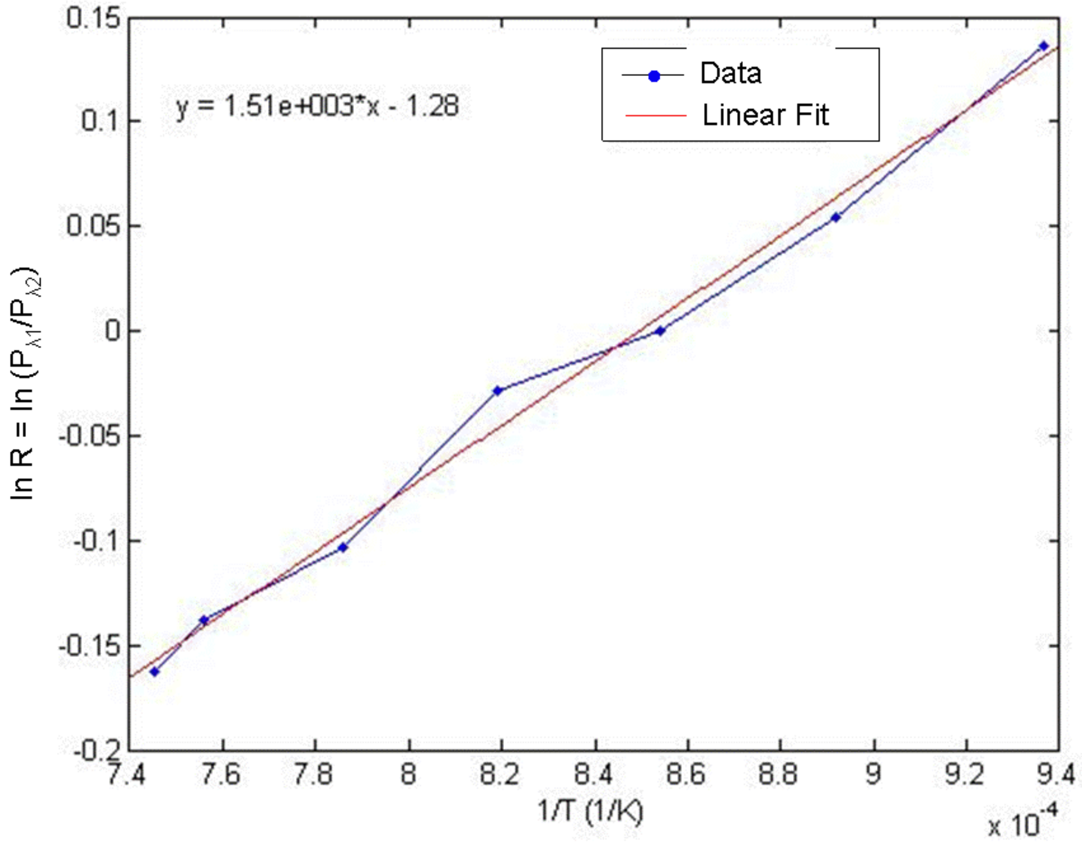
Two-Color Pyrometer

- Specific emissivity has a weak dependence on wavelength
- If the two wavelengths are selected close to each other, then the emissivity ratio can be approximated to a constant

$$R = \frac{P_{\lambda_1}}{P_{\lambda_2}} = A_S \left(\frac{\lambda_2}{\lambda_1} \right)^5 \frac{\varepsilon(\lambda_1, T) + a(\lambda_1, T)}{\varepsilon(\lambda_2, T) + a(\lambda_2, T)} \exp\left[-C_2 \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \frac{1}{T} \right]$$

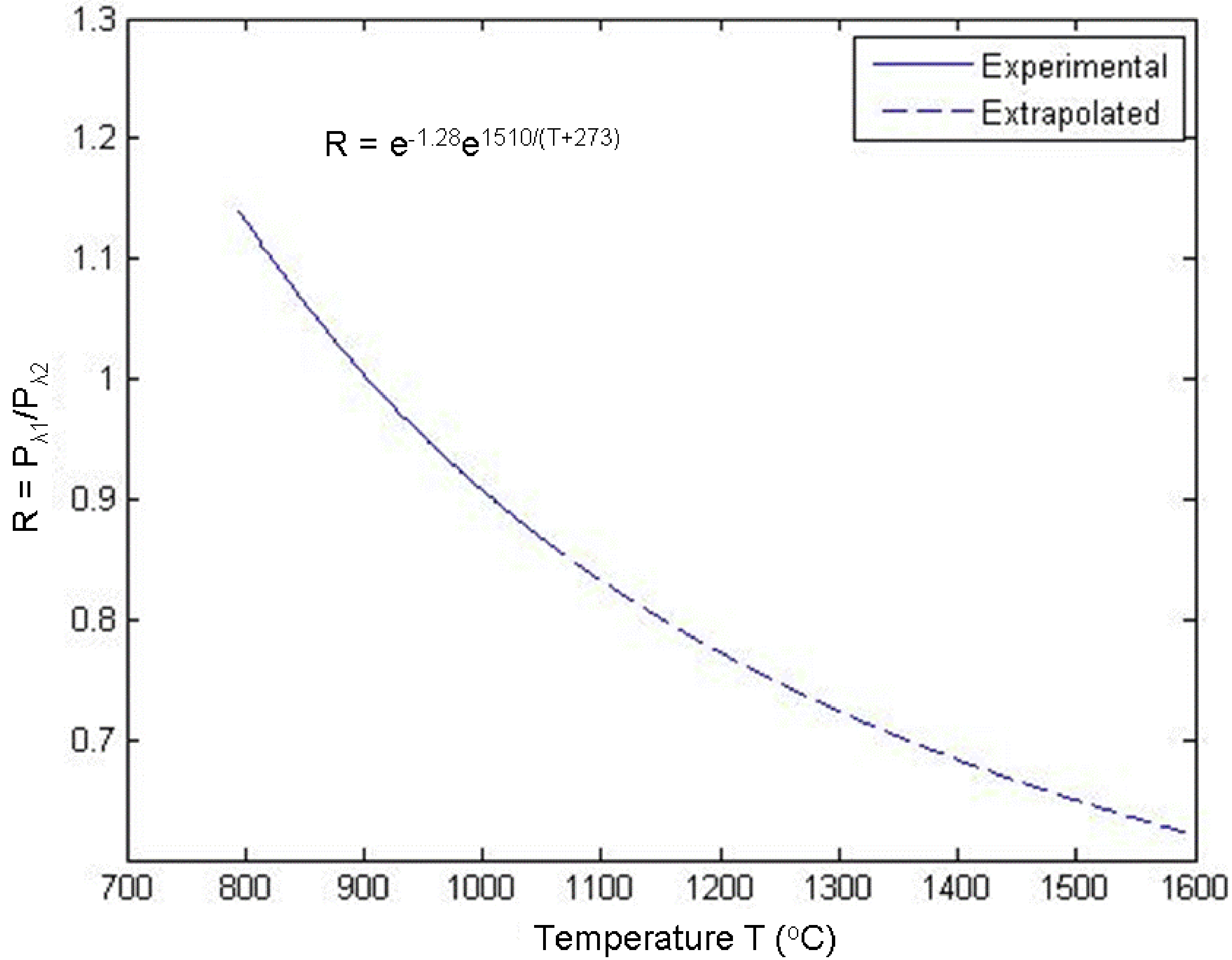
$$\ln R = \alpha + \frac{\beta}{T}$$

Proposed SiC Sensor Calibration Experimental Results



F1: Center wavelength: 1550 nm, FWHM: 30 nm
F2: Center wavelength: 1300 nm, FWHM: 30 nm

Calibration Curve from Data



Discussion on Results

- Works best beyond ~800 °C
- Resolution depends on the smallest change in radiation power that can be detected
- Estimated resolution varies between 5.8 °C at 795 °C to 2.7 °C at 1077 °C
- Can be used to give a coarse value of temperature

Proposed Fine Temperature Sensing Technique using Fixed Wavelength Power and Power Slope Measurement

Classic Fabry-Perot Etalon Reflectance

$$R_{FP} = \frac{R_1 + R_2 + 2\sqrt{R_1 R_2}\cos\varphi}{1 + R_1 R_2 + 2\sqrt{R_1 R_2}\cos\varphi} \qquad \varphi = \frac{4\pi}{\lambda} n(\lambda, T) t(T)$$

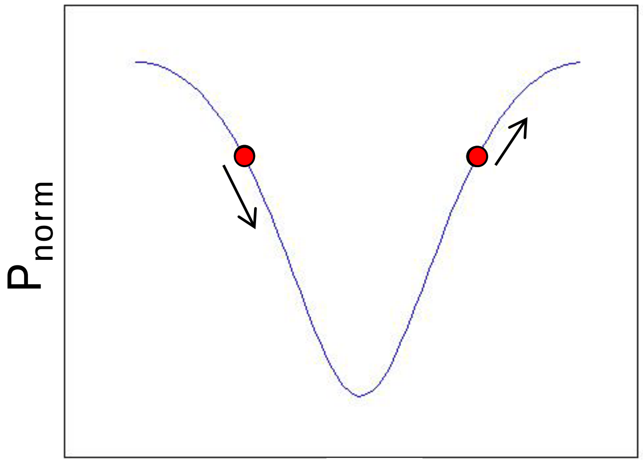
Detected Power $\quad P \propto R_{FP}$

$$P_{norm} = \frac{P - P_{\min}}{P_{\max} - P_{\min}}$$

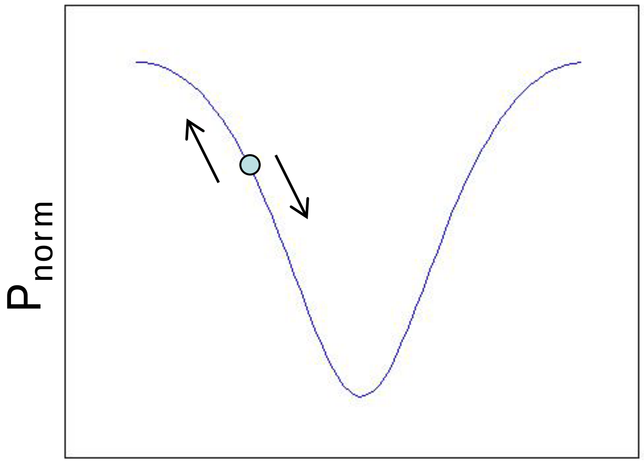
$$\frac{dP}{d\lambda} = \frac{dP}{d\varphi}\frac{d\varphi}{d\lambda} = -\frac{4\pi}{\lambda^2} n(T) t(T) \frac{dP}{d\varphi}$$

- If dP/dλ ☐is positive, then dP/dφ would be negative and vice versa
- φ at a fixed wavelength changes only because of temperature

Normalized Power vs. Temperature Curve



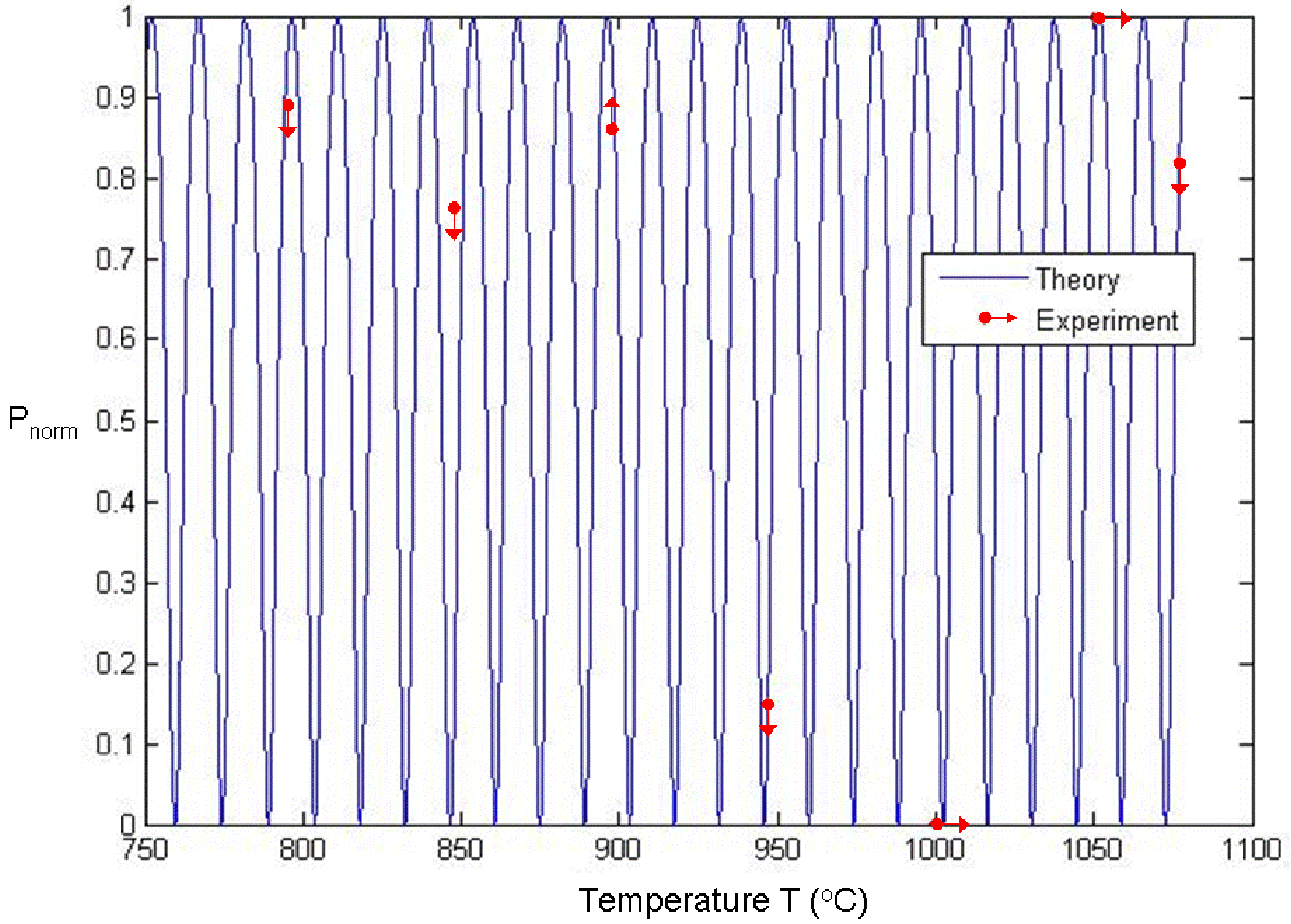
T
Fixed λ



λ
Fixed T

Within each cycle, for any P_{norm} value, there are two possible values of temperature

Experiment



Fixed Wavelength λ : 1550 nm
Arrows denote the sign of dP/dλ

Summary of Hybrid Temperature Sensing Approach

- Find a coarse value of temperature using two-color pyrometry
- Measure laser reflected power
- Measure P_{max} and P_{min} by tuning the wavelength and use these to find P_{norm}
- Find the sign of $dP/d\lambda$ to find which half of the 2π cycle is the temperature
- Resolution is 0.1 °C
- Comparable to TC

N. A. Riza, M. Sheikh, "Silicon Carbide-based High Resolution Extreme Environment Hybrid Design Temperature Sensor using Optical Pyrometry and Laser Interferometry," IEEE Sensors Journal, Feb. 2010.

Conclusion- Technology has Potential for Success

- Both single-crystal SiC and sintered SiC are tried and tested materiald
- Single-crystal SiC is used by US DoD for all high temperature power electronics
- Sintered SiC is used by NASA / ESA as a lightweight material for space platforms and for giant mirrors for telescopes

Ref: Seme Lab

Ref.: ESA