Concepts and Materials Needs for Condition-Monitoring Sensors

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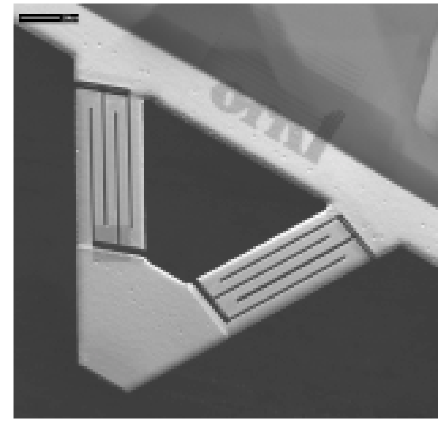
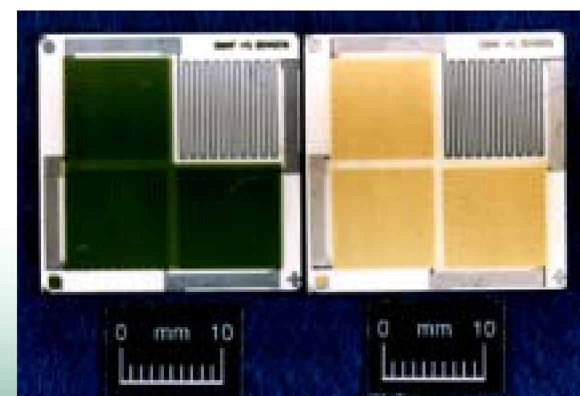
Outline of Presentation



- Sensor uses, functionality, and priorities
- Sensor requirements and material needs
- Commercially available measurement systems
- Next generation technologies and material development areas
- Summary



Sensors Required for High Performance, Improved Reliability and Control

- **Goals for Sensor and Controls**
  - **Increase operational efficiency**
    - **Higher yield**
    - **Less energy used**
    - **Less waste generated**
  - **Reduce emissions**
  - **Lower operating costs**
  - **Safety and equipment protection**

Sensors Functionality

- Rugged & robust
- Reliable – quality data, low maintenance, and survive at least one year
- Preferred non-intrusive or embedded in structures
- On-line and real-time
- Self-calibrating and self-diagnostics
- Cost is important

Measurement Priorities

- **Flame Imaging (species, uniformity, shape)**
- **Combustion efficiency (CO and O_2)**
- **Particulates (size, concentration, velocity)**
- **Emissions (NOx, SOx, Hg, CO_2, HCl)**
- **Air/fuel Ratio**
- **Temperature (surfaces and gas)**

Diagnostic Needs (NDE techniques)

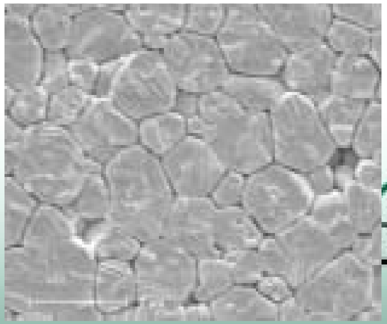
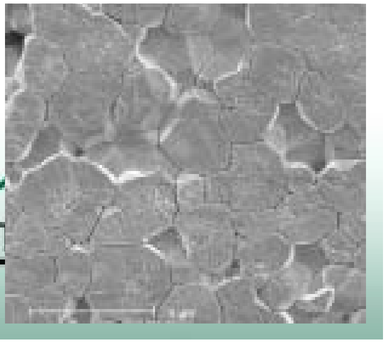
- Monitoring of corrosion
- Monitoring of coatings
- Refractory contouring
- Equipment component degradation
- Sensor self-diagnostics

Sensor Measurement Requirements Are Very Challenging

- **Temperatures: 700^{0} C to 2500^{0} C**
- **Pressure: 100 - 500 psig**
- **Oxidizing and Reducing Atmospheres**
- **Particulates (fly ash)**
- **Slagging (hot, sticky, heavy)**

Material Needs Are Many and Varied

- **Thermowells for thermocouples**
  - **Corrosion and erosion**
- **Non-fouling optical windows/ports**
- **Optical fibers for high temperatures**
- **Fusion of high temperature materials and sensors (embedded)**
- **Nanomaterials (high temperature gradients, high mechanical stresses, modeling)**
- **Lifetime prediction and reliability models**
- **SiC cost, metal oxides/ceramics, catalysts and electrolytes**

High Temperature Fossil Measurements

- NGK zirconia O_2 probe with ceramic sheath
- Rosemount and Ametek CO catalytic bead sensor (yttria-stablized zirconia)
- Tunable diode laser (TDL) technology for CO and O_2
  - Unisearch and Boreal

In-situ Probe

TDL

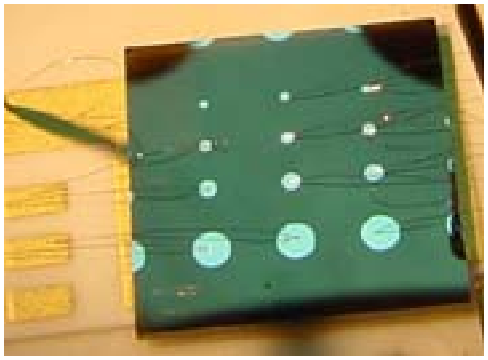
Across a duct

Non-contact Thermometry for Gasifiers

- Texaco has developed an infrared ratio pyrometer
  - Fast response
  - More reliable than thermocouples
  - Materials developed for optical access port
  - Testing soon to be underway in a power station
- Acoustic thermometry by STOCK/CSI and SEI Boilerwatch
  - 2-D profiles across entire scanned area
  - Non-intrusive, reduces material issues

Current Research in High Temperature Sensing

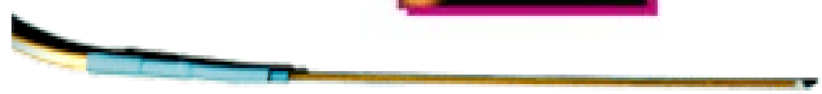
- **Flame Temperature sensor (GE/Sandia/NETL) – high bandgap semiconductor photodiode (AlGaN) and SiC UV photodiode: Tracks flame dynamics**
- **Coating life odometer – taggants detect incipient coating loss (GE/Sandia/NETL)**
- **SiC based gas sensors (> 900^0C) – Michigan State and West Virginia Universities**
- **Metal oxide-based sensors for gases (NO, CO, CO_2, NO_2, NH_3, and SO_2) – Sensor Research and Development Corp.**



Fiber-Optic Thermometry Offers Highly Reliable, Accurate Temperature Measurements

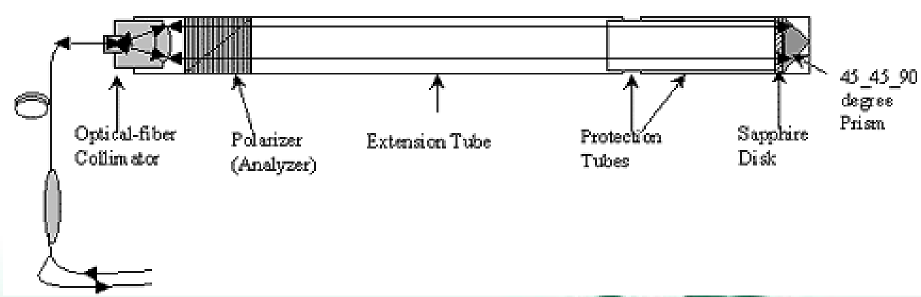
- Non-contact phosphor thermometry has been demonstrated by ORNL, Fluoroscience, and others for turbine, steel processing, and automotive diagnostics over the past 10 years
- Temperatures measured to 1700^0 C using laser and phosphors
- VPI has developed single crystal sapphire shown effective to 1600^0 C in harsh environments
- Zirconia prism and alumina extension tubes used to 1500^0 C
- Needs include window materials and sheathing for fibers

Phosphor luminescence



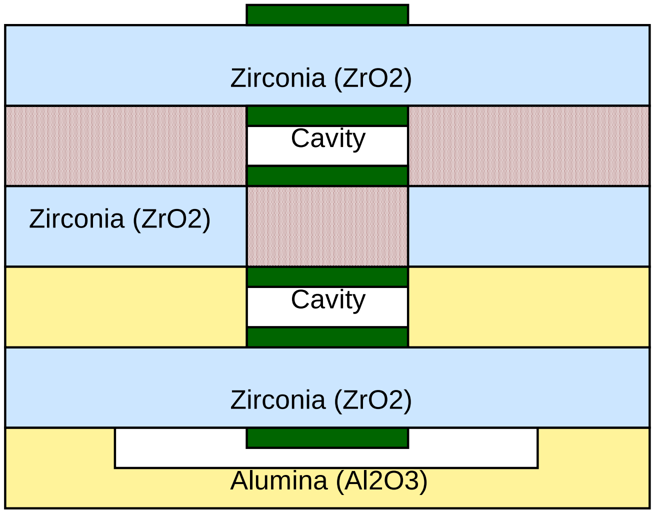
Micro-optic temperature sensor

Figure 1: Configuration of PLIS System



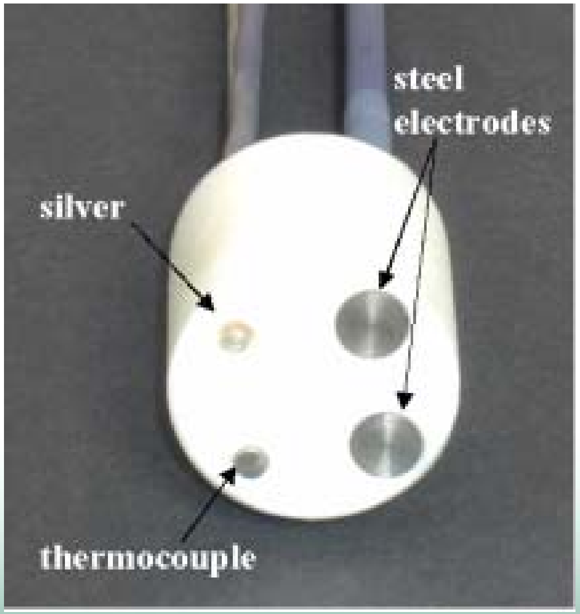
ORNL Sensor Development for High Temperature, Harsh Environments

- NO_X, O_2, and NH_4 sensor development in progress
  - planar O_2 sensor developed with output proportional to partial pressure; response time diffusion barrier/geometry dependent, demonstrated to 1100^0 C
  - low-cost NO_X demonstrated to 700^0C; commercialization partner on board
  - resistive mixed potential sensors for NO_X, NH_4, H_2S, hydrocarbons with potential for lower cost and easier to produce



Real-time Corrosion Sensors

- Electrochemical noise principle
- Dual working electrodes representing the material under evaluation
- Monitors fluctuation in potential & current noise
- Assesses general corrosion (pitting, etc.) and relative intensity
- Need high temperature insulator

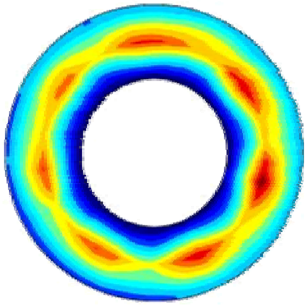


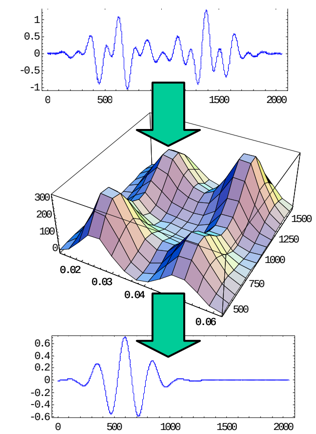
Thermowell Material Development

- Wells needed to protect thermocouple from aggressive environment
- Current materials degrade in weeks
- Need to develop appropriate metallic and ceramic phase chemistry/evolution
- Consider dispersed reservoir (DR) approach
- May be possible to design a composite alloy structure with capability to resist oxidation, sulfidation, carburization, and/or molten salt/slag attack

NDE for System Diagnostics

- Condition monitoring of thermal barrier coatings (TBC)
  - ANL's IR imaging and laser scattering
  - ORNL's TBC doped with phosphors in layers
- Advanced signal processing (chaos, neural nets, etc.)
  - Pressure signals, gas concentrations, flame qualities (B&W's Flame Doctor)
  - Better sensors (materials) will result in improved diagnostics
- Robots that can withstand high temperature/corrosive environments – platform for visual and physical measurements for tube surfaces and thickness, coatings, refractories



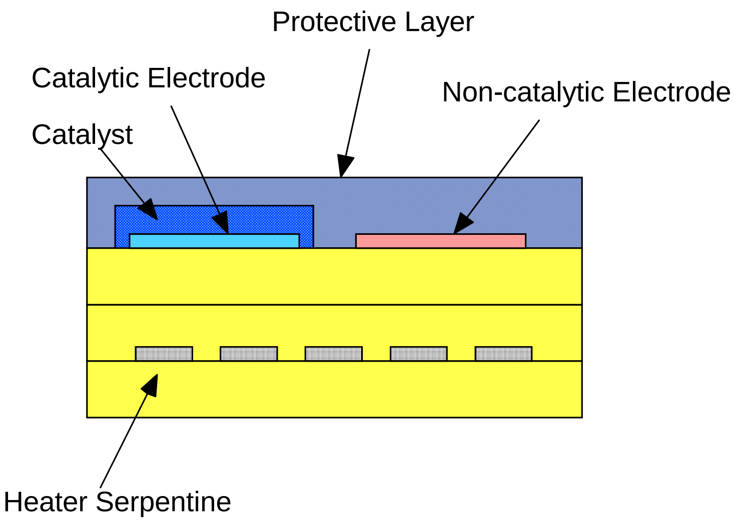


Thermomechanical Reliability and Life Prediction of Sensors

- Sensor design needs understanding of thermal-chemical-mechanical stress state coupled with potential thermomechanical performance of sensor materials
- Thermal expansion mismatches, residual stresses, thermal transients effects minimized by design
- Validated models require theory, material characterization, and experimental data (corrosion, environmental, etc.)

Next Generation High-Temperature Multi-Species Gas Sensors

- Built on multilayer ceramic sensor demonstrated concepts
- Simultaneously measure O_2, NO_x, NH_3, and SO_2 for example
- Development of catalyst, diffusion barriers, species specific materials, electrodes
- Kinetics at catalyst surface (influence of electric potentials)
- Incorporate reliability/life prediction models



High Temperature MEMS Sensors

- **SiC MEMS array for multiple gases – H_2O, *Hg*, NO_x, *CO*, *S*, H_2**
- **Microcantilever technologies with coatings for multiple gas species**
- **Potential to 1200^0C and low-cost**

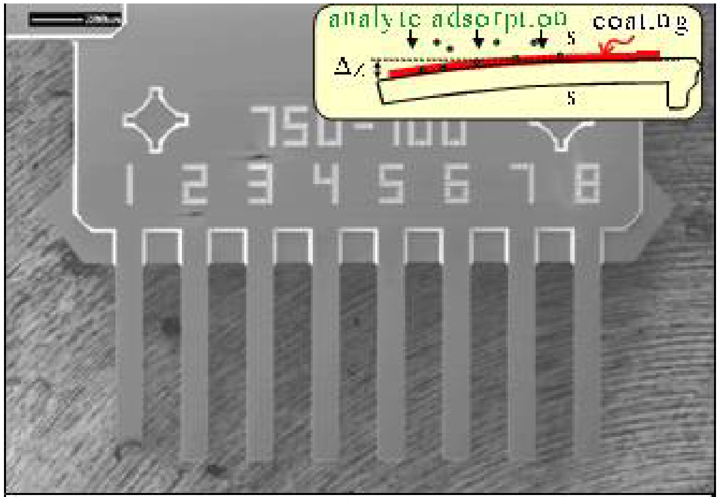
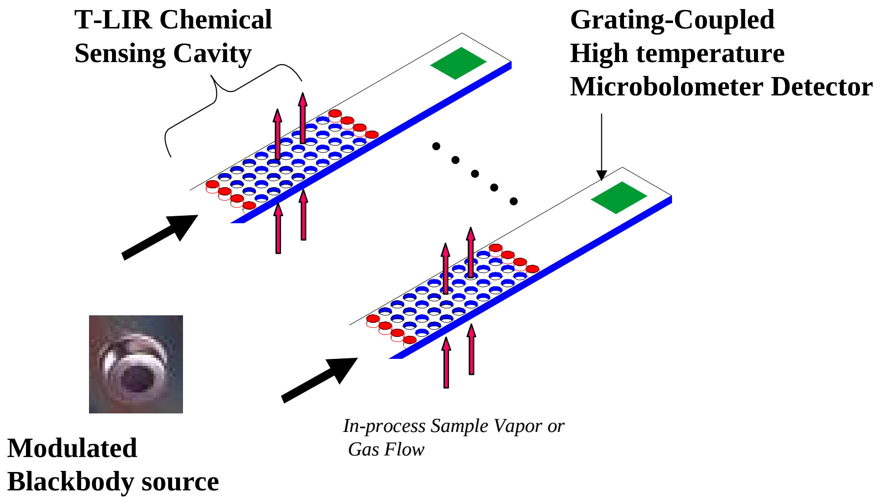


Figure 1. A typical Si *MC* array used in previous studies to monitor analyte adsorption on the MC surface. Analyte-induced deflection, Δz, is depicted with inset.

Next Generation High-Temperature Multi-Species Gas Sensors

- Couple MEMS with micro-optics
  - Micro-scale Midwave IR sampling cell on a chip
  - Integration of miniature black body source and off-chip detector
- Measure H_2, NO_x, S, CO, and Hg simultaneously
- Develop and characterize high temperature IR materials and blackbody source



Integrated TLIR Array Chemical Sensor

Robust Light Source for High Temperature Corrosive Environments

- Approach based on electroluminescence (EL) of ceramic phosphor materials in the UV range
- EL device comprised of high temperature materials – quartz, ceramics, and metal
- Uses ultraviolet emitting phosphors under AC excitation
- Testing and modeling needed to evaluate durability, operability at high temperatures, thermal cycling, and corrosion resistance
- Potential to be embedded in structures

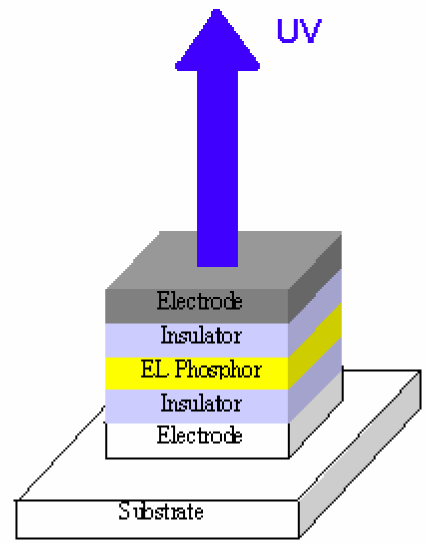
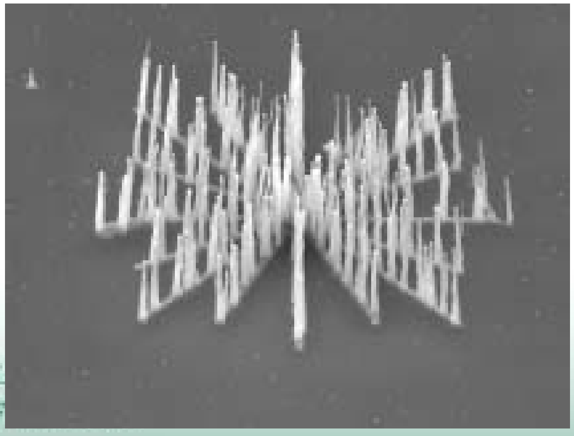


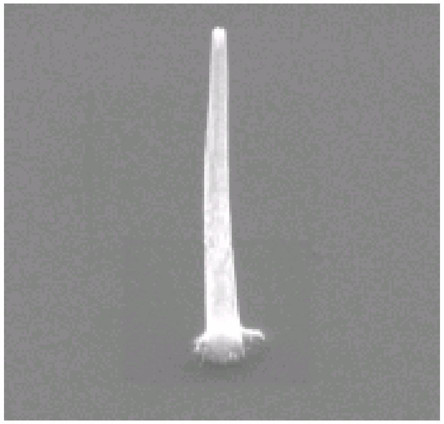
Figure 1. Typical EL device configuration.

Nanosize Sensors for Harsh Environments by NASA and ORNL

Carbon Nano-tubes for high Temperature Sensing

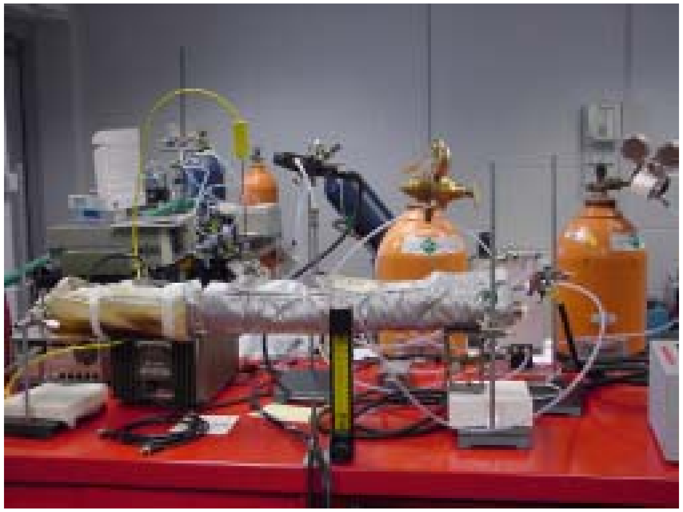
- Nanotubes can be deterministically sized and located
- Withstand high temperatures, up to 2000^{0}C
- Very robust
- Needs include material characterization, synthesis, and automated fabrication techniques





Sensing for FE Processes is Very Challenging - Multidisciplined Approach Is Needed for Sensor Development

- Expertise in material synthesis, various transduction methods, high temperature electronics, packaging, and advanced signal processing
- Experience in harsh environments (high temperature, toxic/corrosive, particulates)
- Facilities for developing, prototyping, testing, and characterizing sensor concepts, robustness, and sensitivities



Multidisciplined Approach Is Needed for Sensor Development

- Material characterization technologies
- Theory, modeling, and simulation of thin films, interfaces and boundaries, defects, material synthesis, nanoscale particles and interactions
- Massively parallel software & hardware
- Excellent opportunity for teaming with National Labs, Universities, and Industry