Concepts and Materials Needs for Condition-Monitoring Sensors

J. E. (Jim) Hardy
Leader, Sensor and Instrument Research Group
Oak Ridge National Laboratory
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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 O₂)
- Particulates (size, concentration, velocity)
- Emissions (NOx, SOx, Hg, CO₂, 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° C to 2500° 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-stabilized zirconia)
- Tunable diode laser (TDL) technology for CO and $O_2$
  - Unisearch and Boreal

In-situ Probe  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°C) – Michigan State and West Virginia Universities
- Metal oxide-based sensors for gases (NO, CO, CO₂, NO₂, NH₃, and SO₂) – 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°C using laser and phosphors.
- VPI has developed single crystal sapphire shown effective to 1600°C in harsh environments.
- Zirconia prism and alumina extension tubes used to 1500°C.
- Needs include window materials and sheathing for fibers.

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$^\circ$ C
  - low-cost NO$_x$ demonstrated to 700$^\circ$ C; commercialization partner on board
  - resistive mixed potential sensors for NO$_x$, NH$_4$, H$_2$S, 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, $\Delta z$, 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 H₂, NOₓ, S, CO, and Hg simultaneously
- Develop and characterize high temperature IR materials and blackbody source
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
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°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