UT-BATTELLE

Novel Sensor Technologies Improving Energy Performance

J. (Jim) E. Hardy

Leader, Sensor & Instrument Research Group

Oak Ridge National Laboratory

Brown Bag Luncheon Seminar

November 1, 2004

Presentation Outline

- **Need for Sensors & Controls**
- **ORNL experience & expertise**
- **Examples of Impact from S&C**
- **Future Science in Sensors & Controls**
- **Summary**

Sensors and Controls Enable Process Optimization That Leads to Efficient Energy Use and Waste Minimization

- **Process control to maximize throughput and yield**
- **Monitoring to reduce product variability**
- **Measure, control, and monitor emissions**
- **Process and equipment diagnostics for productivity, safety, and waste reduction**
- **R&D and prototyping new processes and products – evaluation and characterization**

Why is Sensor R&D Needed?

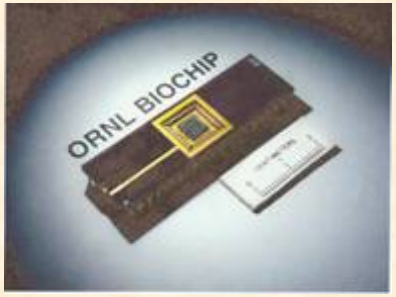
- **Almost all roadmaps list Sensors and Controls as the top 1 or 2 priority**
- **Numerous vendors and products available BUT - the needs persist**
- **Often the measurement science is understood — technologies R&D is crucial link**
  - **System integration and packaging**
  - **Embedded intelligence**
  - **Connectivity**
  - **New materials**
  - **Reducing cost through miniaturization**

What we Do: Conceive, Develop, and Build Prototypic, Advanced Sensor Systems for Nationally Important Problems

- **Very diverse expertise and experience in all aspects of measurement science and systems integration**
- **R&D integrated into working prototypes**
- **Teaming across laboratories, universities, other government agencies and industry**

Diversity and Multi-program Nature Results in Excellent Resources for Sensor Development

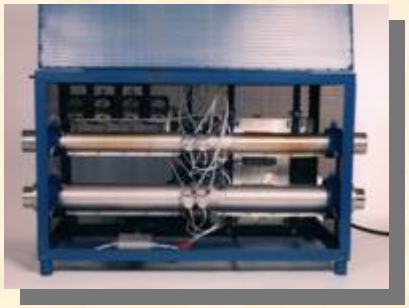
- **Over 200 professionals in measurement science**
- **Physical, chemical, biological, radiation sensing**
- **Advanced analog and digital electronics**
- **Signal and image processing**
- **Material synthesis & characterization for harsh environments**
- **Systems engineering for packaging, miniaturization, integration, and sensor networks (optical and wireless)**
- **$80M in R&D across the Laboratory**



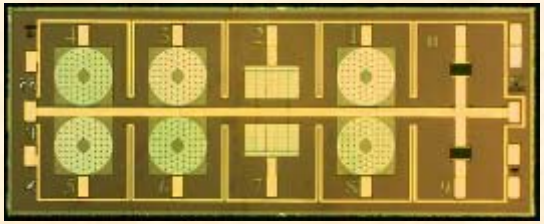
Sensor R&D to Advance Science, Improve Energy Efficiency, and/or Enhance National Security

- **Sensor Development for Physical Properties**
  - **Low-cost, uncooled IR imaging; hydrazine calibration; low-cost, low-power, wireless microsensor arrays; hydrogen pipeline leak detectors**
- **Sensors for Harsh Industrial Environments**
  - **Non-contact, no drift Johnson noise for high temperature, Flow (single/two-phase), Fuel cell sensors (temperature, humidity)**
- **Optics, Electro-optics, and diagnostics including micro and nano sensors**

High Temperature Vehicle Exhaust Flow



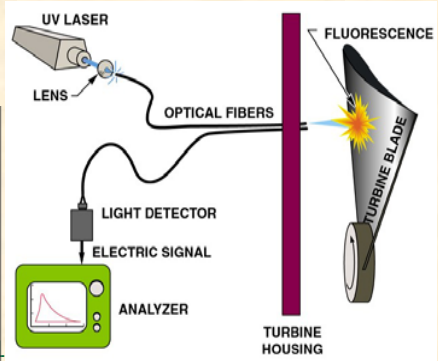
Microcantilevers



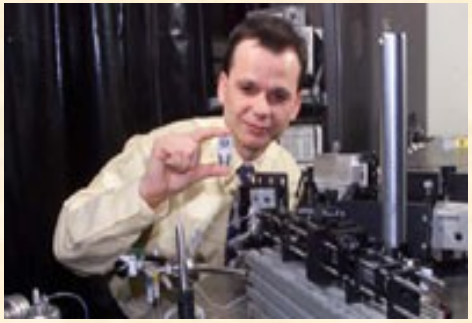
Non-contact inductive temperature sensor

Microsensor Array & readout

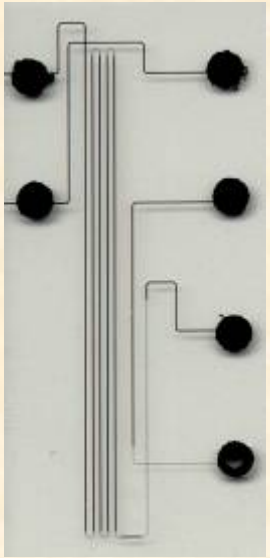
Fluorescence-based temperature



Micro/Nano Electro-Optics

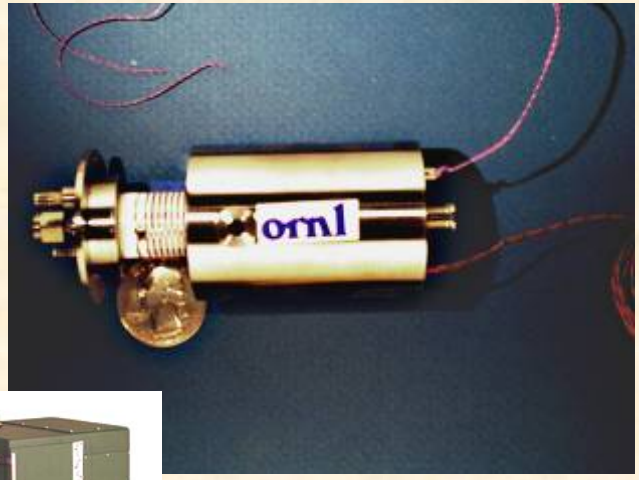


Sensors and Platforms IV
Miniaturized Versions of Larger Instruments



Lab-on-a-chip: Micro-fluidics for a variety of applications

Micro Ion mobility spectrometer or potential applications in explosives, CW agent, or drug detection



New mass spec and sample introduction system developed by four directorates at ORNL. Pre-production units manufactured by commercial partner.

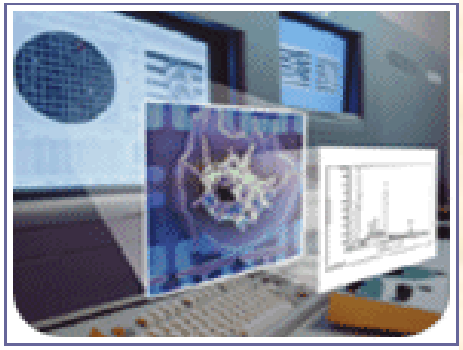
Micro-ion trap mass spectrometer

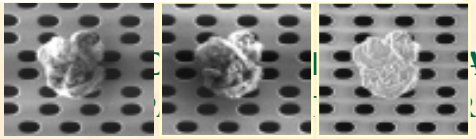
Entire system to be integrated into Fox Recon vehicle

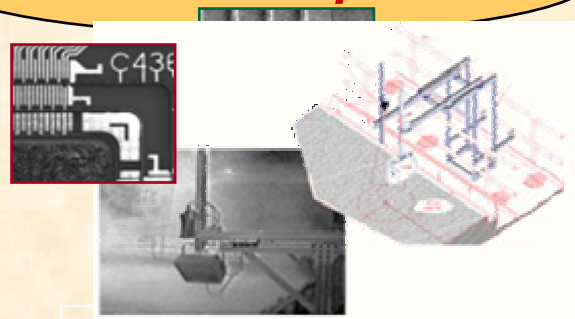
Signal Processing/Controls Solutions

- **Developed real-time data acquisition systems and remote access via web applications for information and control**
- **Developed human-like visual and decision making capabilities via real-time image processing - occupant(s) movement/activity**
- **Supervisory and distributed controls for robust, intelligent systems**
  - **fault-tolerance, degradation consequences, robust**
  - **Intelligent agents for adaptive control and optimization**

Industrial Inspection







- semiconductors
- technical ceramics
- forest products
-textiles
-automotive

Advanced Signal Processing Helped Develop the Technology to "Hear" the SSN-21 (Seawolf)

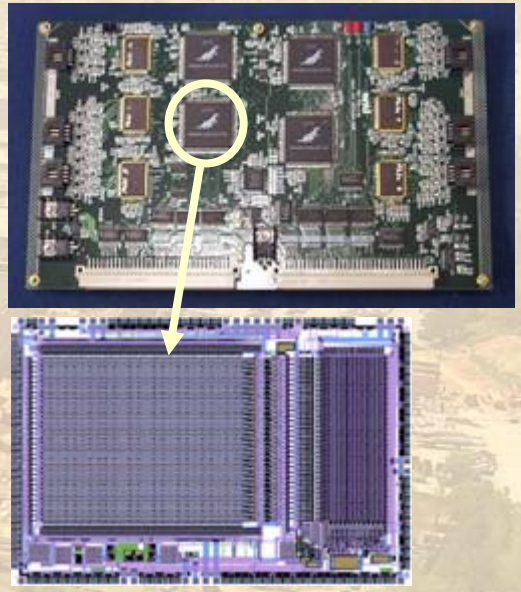
"Measuring the Undetectable"

System Features:

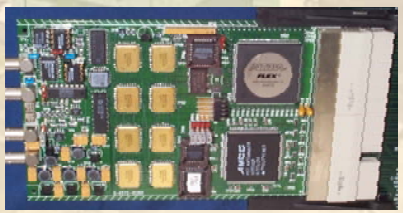
- ✓ **Two high-gain acoustic Beamforming measurement systems**
- ✓ **40 Gflops of computational power for beamforming and spectral estimation**
- ✓ **Dual-stage, frequency domain beamformers**
- ✓ **Highly accurate and steerable measurement beams and image beams**
- ✓ **Each array has 1,328 acoustic sensors (1,120 processed continuously)**
- ✓ **1,600 Custom PCBs**
- ✓ **GaAs digital multiplexer technology, aggregate data rate of 160 Mbytes/sec**
- ✓ **Underwater electronics, with fiber-optic telemetry of data to ship**

Advanced Analog and Digital Electronics Focuses on Low-power, low-cost, hybrid chip and PC board solutions

Analog, Digital, & Mixed-Signal Application-Specific Integrated Circuit & Systems R&D



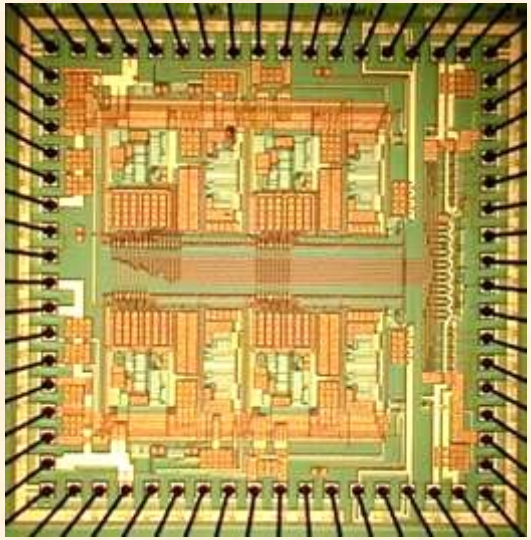
- **Custom electronics design**
  - Analog circuits
  - Digital circuits
  - Programmable devices
  - Low-power systems



- **Software tightly-coupled to hardware**
  - Embedded microprocessors
  - QNX, Windows NT drivers
  - LabView

Experience, Innovation, Sophisticated Tools and Access to State-of-the-Art Foundry Services Enable The Use of Application Specific Integrated Circuit (ASIC) Technologies

- Expertise spans from discrete analog design to sophisticated mixed signal ASIC
- 30+ Full-time Staff & Students
- Dedicated ASIC Design, Development & Testing Infrastructure
- Multiple Electronics Development Labs
- Specialized Facilities (Bio-Instrumentation Labs, SEM Lab, Cleanroom)
- Fabrication Agreements with Multiple Foundries (prototype quantities up to full-wafer runs)



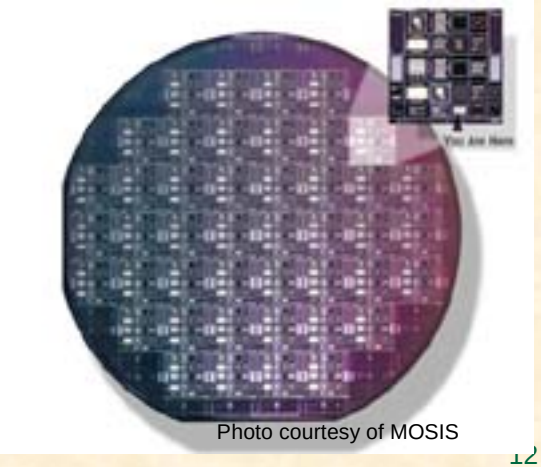
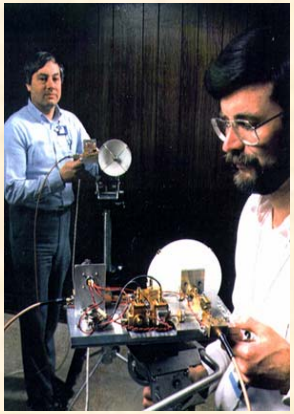


Photo courtesy of MOSIS

The RF & Microwave Systems Group

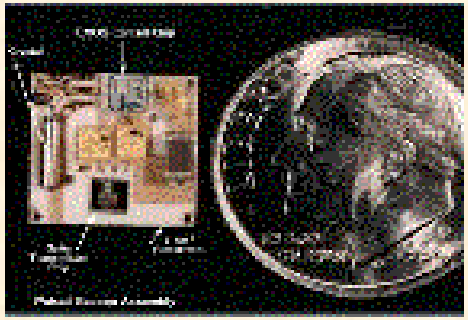


94 GHz Reflective-Environment Communication System

Core R&D

- RF & Microwave Communications and Wireless Systems
- RF Measurements and Diagnostics
- Electromagnetic Environmental Effects

Magnetic Spectral Receiver

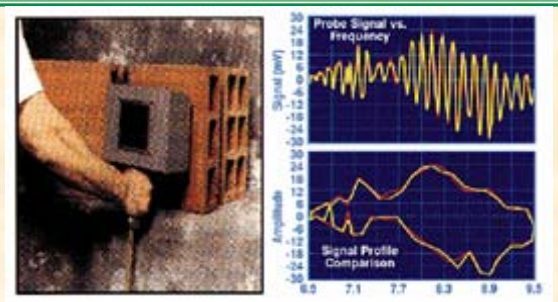


16 GHz Microtransmitter

Market Areas

- Energy
- National Security
- Science
- Environmental Quality

The RF & Microwave Systems Group provides RF and Microwave Solutions for Demanding and Nationally Important Instrumentation Problems



Microwave Diagnostic Probe

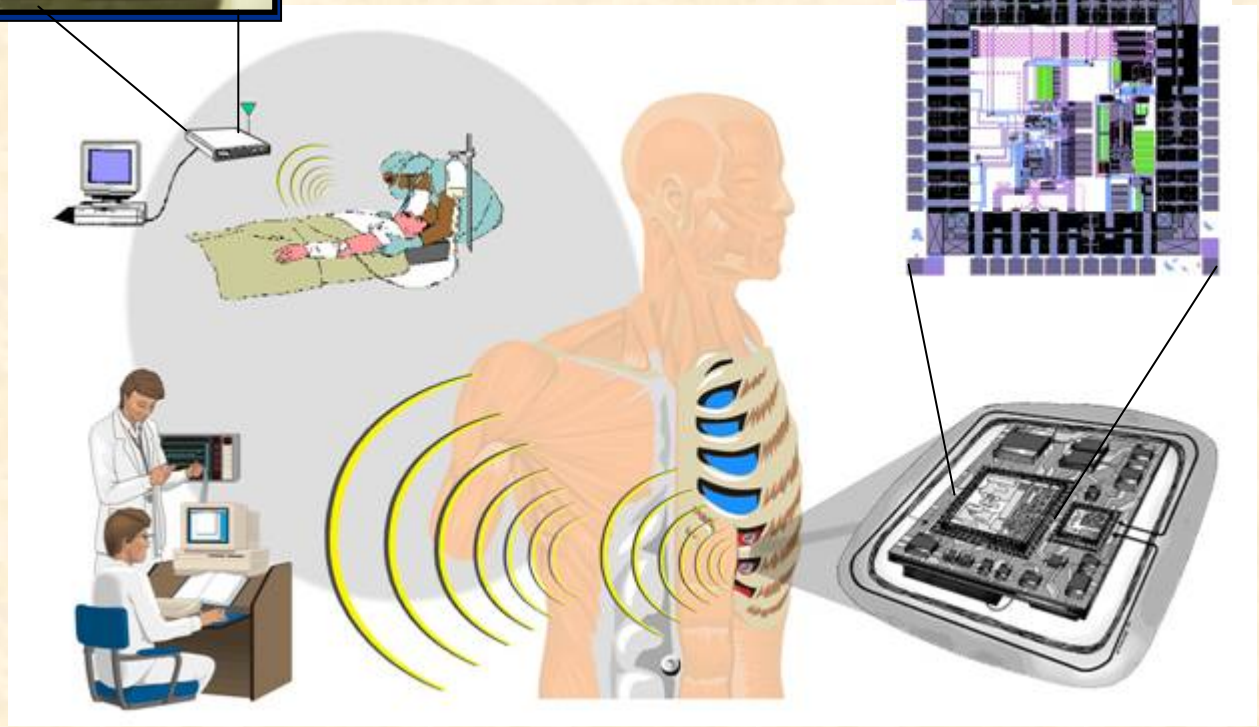
915 MHz Wireless Sensor

Video Intercept Receiver

ORNL Team Develop Wireless Patient Monitoring System – Based on Portfolio of 20+ patents and Various Partners

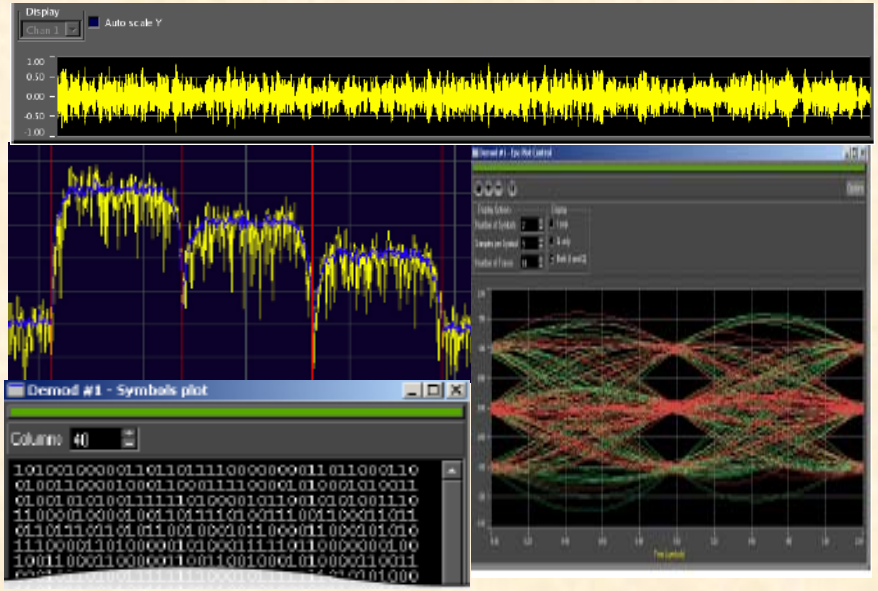
Field-tested wireless system in DOE project

ASIC Developed with Internal Funds



Integrated system developed with CRADA and NIH funding

Extreme Measurement Communications Center (EMC^2)



Operational Capability

The DoE EMC^2 provides modeling, simulation and characterization support for industrial wireless networks.

This facility is equipped with parallel computing resources as well as state-of-the-art measurement equipment for high performance wireless and wired network characterization from the physical layer to the application layer

Broadband RF record and playback instrument can simulate and generate characteristic waveforms to help in-lab study of the wireless device's behavior in harsh industrial environments

EMC^2 Program Benefits:

- EMC^2 formalizes the testing of industrial wireless networks to quantify the latency, throughput, security and fault-tolerance (Interference and Noise)
- Wireless Industrial Networking Alliance (WINA) has accepted EMC^2 as its product testing and characterizing center to member companies
- Currently supports exhaustive modeling and simulation of the communication infrastructure for future electric grid
- Help develop or improve existing standards in industrial wireless networks to include measurement, verification and reliability of network and device parameters
- The center is being developed both as a user facility and an on-site testing provider using portable test equipment

Milestones, Deliverables, & Contact:

Key Milestones: Alliance with WINA and member companies for technology assessment and characterization; Provides modeling and simulation support for developing fault-tolerant electric-grid communication infrastructure

Deliverables: Standards-based report generation for different wireless devices and network layouts; Software development for characteristic network testing;

Contact Information:
Wayne Manges
mangesww@ornl.gov, 865-574-8529

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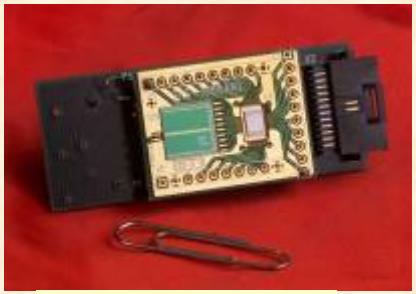
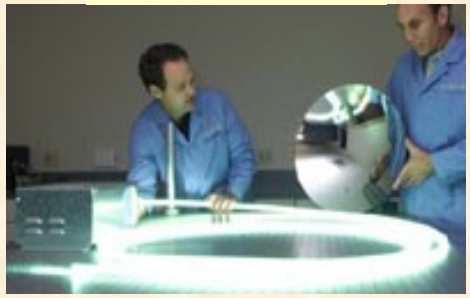
Sensors and Controls - Enablers for Improving Energy Technologies

- Measurement in harsh environments
  - **Non-contact temperature, flow, NO_X, O_2, direct sampling mass spectrometry, CO_2, and H_2**
  - **Steel, FreedomCAR, Fuel Cells, Solar (Hybrid Lighting)**
- Advanced electronics and wireless sensors/networks
  - **Very low power, mixed signal ASIC, spread spectrum, power management, self calibrating**
  - **Buildings, Distributed Energy, Hydrogen, Steel, Biomass**
- Inspection/diagnostics
  - **Image processing, pattern recognition, auto defect classification, yield improvement**
  - **Automotive, Forest Products, Semiconductors**
  - Modeling, simulation, controls for process optimization (yield, energy efficiency, throughput)
  - **Steel Making, Building HVAC, DEER, Fuel Cells**

Wireless micro-sensor arrays



Hybrid Lighting

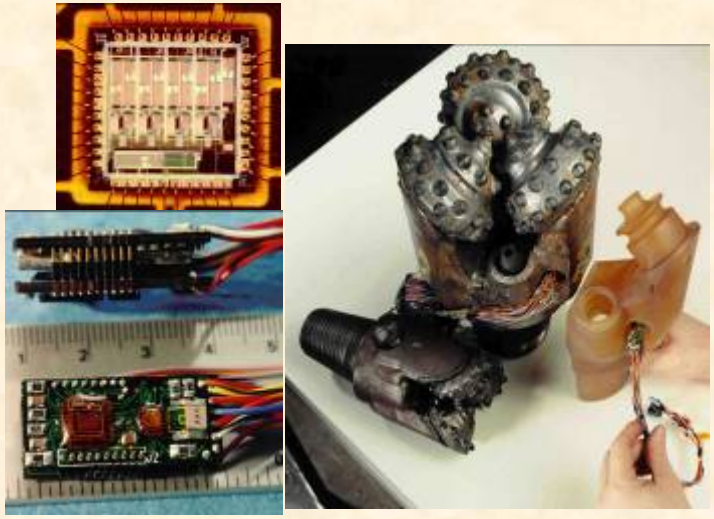


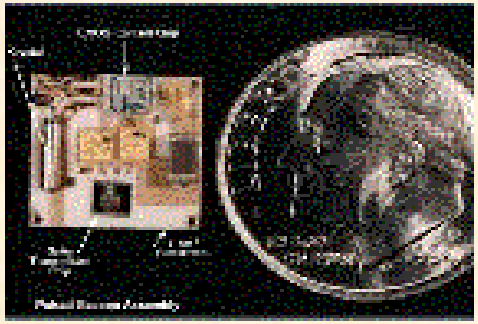
Yield Improvement via Material Inspection

Vehicle Emission's Reduction

Sensors for Harsh Environments

- **Sensors and electronics for high temperature/harsh environments**
  - Rail-to-rail high temperature electronics
  - High-Temperature High-Resolution ADC Chipset (0.5µm SOS-CMOS)
  - Drill Bit Monitor/Diagnostics
- **Low cost, low power, wireless microsensor arrays and Rf Tags for Tracking and Location**
- **Automated defect detection**
- **Diagnostics and Process Control**
  - **Non-contact temperature measurements**
  - **Flow and film thickness**
  - **Emissions monitoring**





16 GHz Microtransmitter

ORNL Has Developed High Temperature Sensor Systems (Sensor, Materials, Packaging, Electronics)

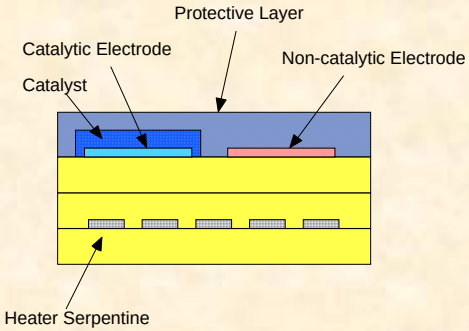
- **Vehicle exhaust gas flowmeter (650^{0}C, 100 to 1 range, fast response, low DP)**
- **Two-phase flow & liquid film thickness probes (800^{0}C, severe thermal shock)**
- **Non-contact phosphor thermometry has been demonstrated for turbine, steel processing, and automotive diagnostics over the past 10 years for temperatures -100^{0}C to 1700^{0}C**
- **Multilayer ceramic sensors demonstrated to 1000^{0}C for O_2, 700^{0}C NO_x**
- **Coupled MEMS with micro-optics spectrometer (Integration of miniature black body source and off-chip detector**
  - **Micro-scale Midwave IR sampling cell on a chip – Concept viable to >500^{0}C**
- **Carbon Nanotubes for high Temperature Sensing to 2000^{0}C**

Vehicle Exhaust Flow

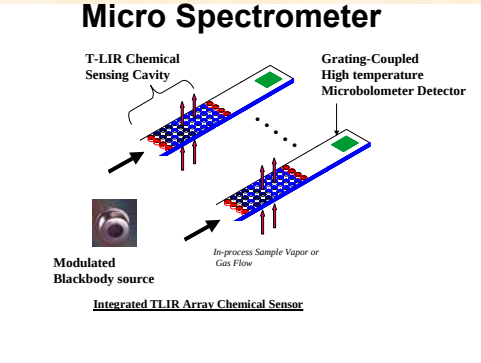
Liquid film probe

Phosphor thermometry

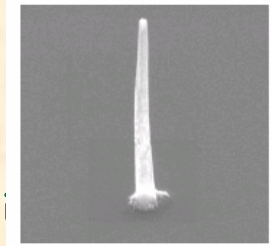
Ceramic Gas Sensors



Micro Spectrometer



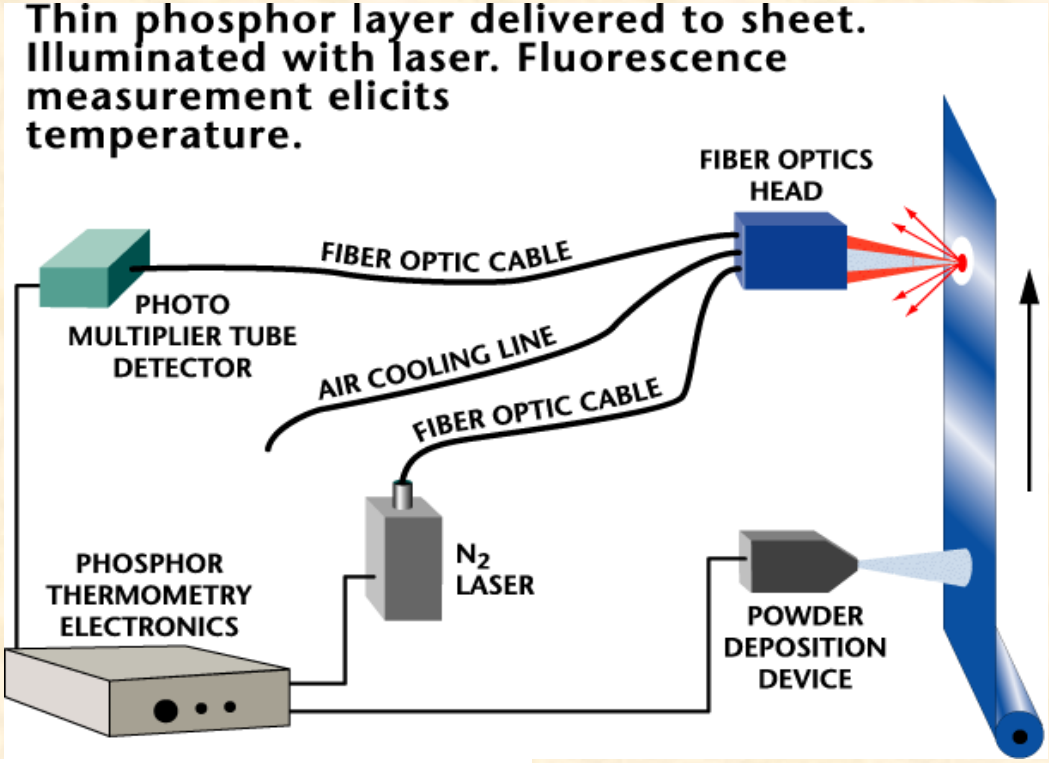
Carbon Nanotube

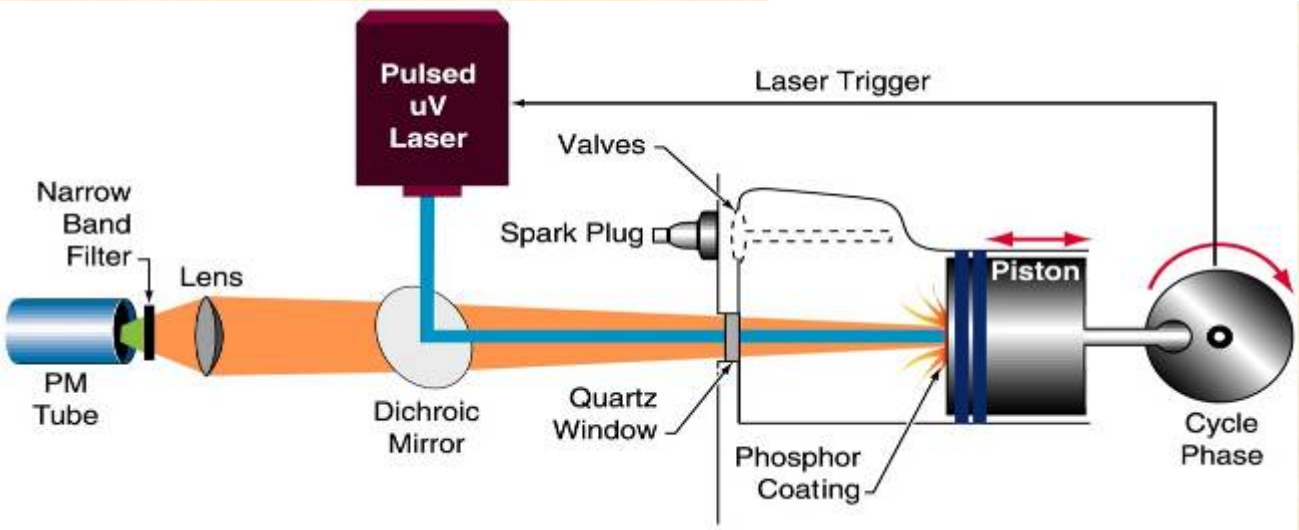


Thermometry with a Thermographic Phosphor Systems

Accuracy to 1^0C
Temperature Range -100 to 1700^0C
Millisecond response time
Non-contact measurement
Originally developed for turbine blade measurements

Galvaneal temperature measurement at high velocity/temperature

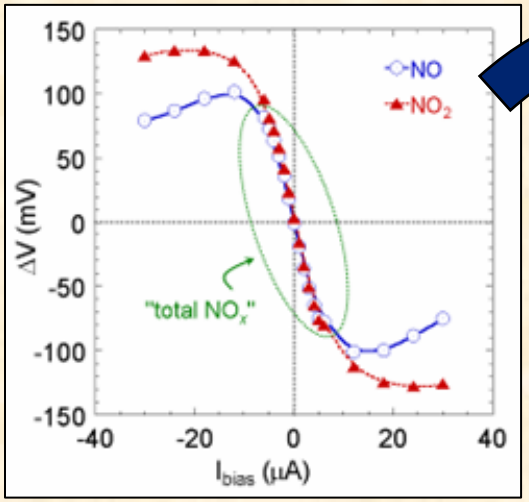


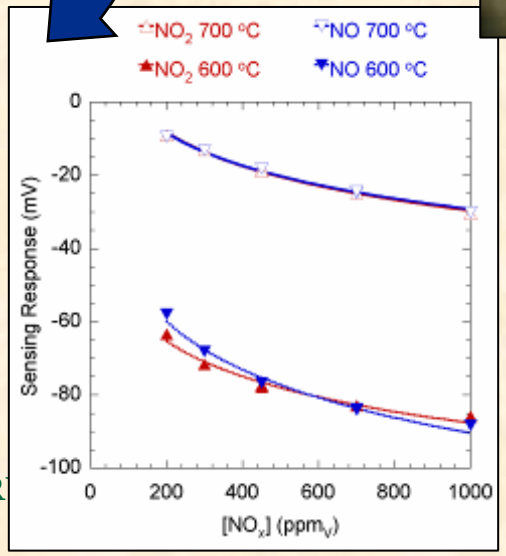


Piston temperature measurements during engine operation

High-Temperature Gas Emission Sensor Development

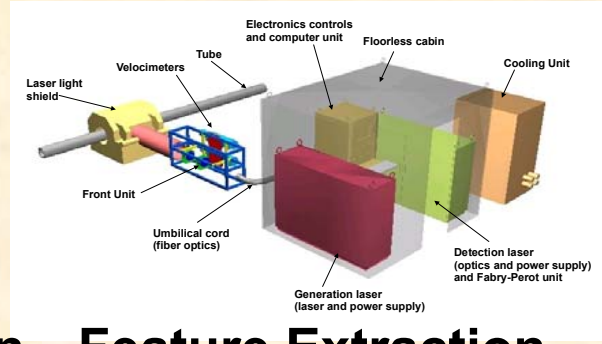
- Developing multilayer oxygen sensors for monitoring gas emissions at temperatures <1000°C
  - Current work targeting NO, NO_2, "total" NO_x (NO+ NO_2), NH_3, and SO_x sensors
- Developed processing methodology for planar oxygen sensor
- Developed porous protective layer that prevents fouling
- Demonstrated first functional NO sensor





Use of novel catalysts and electrode designs allow "total NOx sensing up to 700°C.

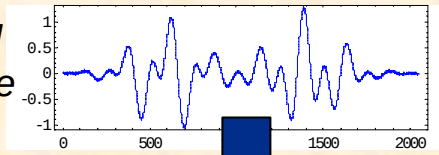
ORNL Provided Technology to Timken Laser-Based Ultrasonic Thickness Measurement Project



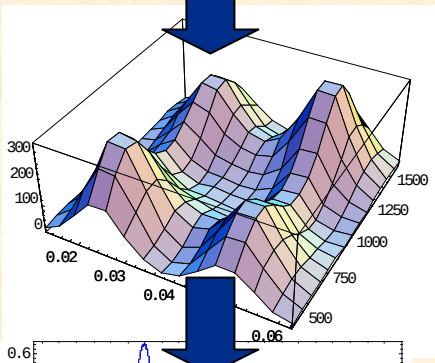
Signal Recovery

Wavelet filtering recovered ultrasonic reflection signals out of high noise

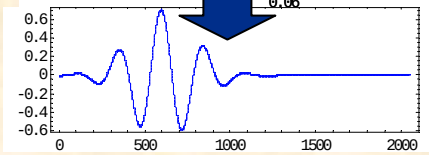
Signal & Noise



Filtering



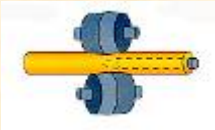
Signal



Wireless Tube Detection

Tube detected and signal transmitted by RF to receiver

Tube Detector Transmitter

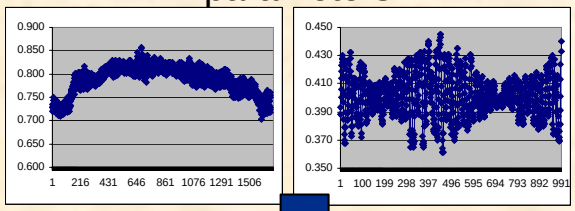


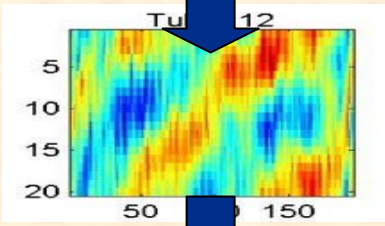
Repeater

Receiver and Interface

Feature Extraction

Patterns in tube thickness related to other system parameters





Identify the plant component causing production part problem

Example of IT Program Success: Laser Ultrasonic Tube-Wall System – *Energy Impact/Commercialism*

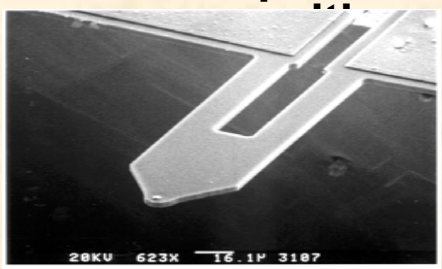
- **A project cost-shared by DOE's Industrial Technologies Program and the Timken Company** (LEVERAGING)
- **Successfully developed and implemented laser-generated ultrasound to measure the thickness of hot seamless steel tubing.**
- **The project has shown that this measurement can be accomplished routinely in a mill setting under ordinary working conditions.** (ENTIRE SYSTEM APPROACH)
- **Since production commenced in March 2002, over 1M tubes have been measured and savings–including reduced scrap metal– exceed projections. Annual energy savings have been estimated at five percent, or 2.3×10^{10} BTUs.** (METRICS/IMPACT)
- **Commercialization efforts are underway.** (VERTICAL TEAM)
  - End User, Instrument Supplier, National Lab, University

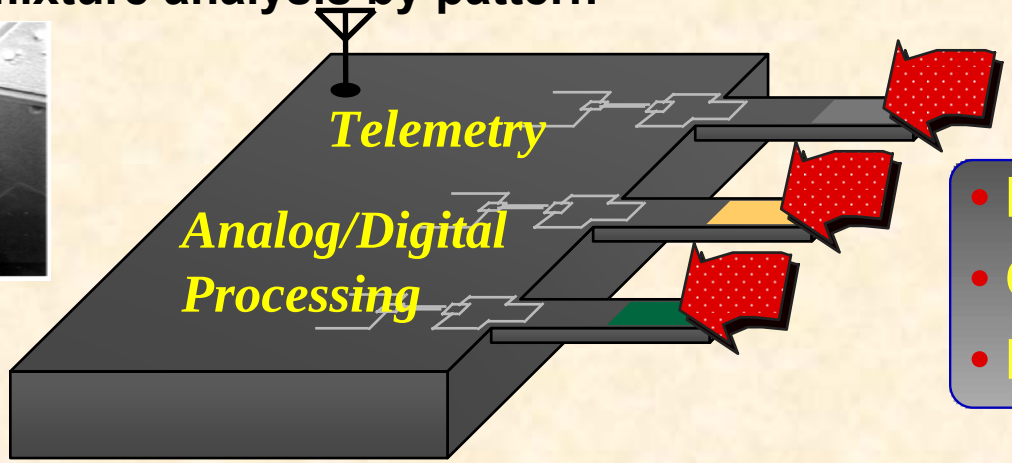
Low-cost, zero-net power, wireless micro sensor arrays poised to make big impact on energy efficiency, productivity, and personnel health

- **Enabling technology for energy reduction in buildings**
- **Improvement of employee productivity and health through better indoor air quality**
- **Staff, experience, and facilities to create a technology development path for robust, low-cost ($10s) sensor systems**
  - **micro sensor arrays, very low-power electronics**
  - **bi-directional wireless communications**
  - **zero-net power technologies**
  - **integration and controls to optimize performance**

Wireless Nose-On-A-Chip

- **MEMS Sensor Arrays**
- **Selectively coated for physical, chemical and biochemical sensing**
- **Pico-gram detection sensitivity**
- **Antibody-antigen: Parts-per-trillion sensitivity**
- **Complex mixture analysis by pattern**





- **Physical**
- **Chemical**
- **Biochemical**

Micro-cantilever Sensors (MEMS)

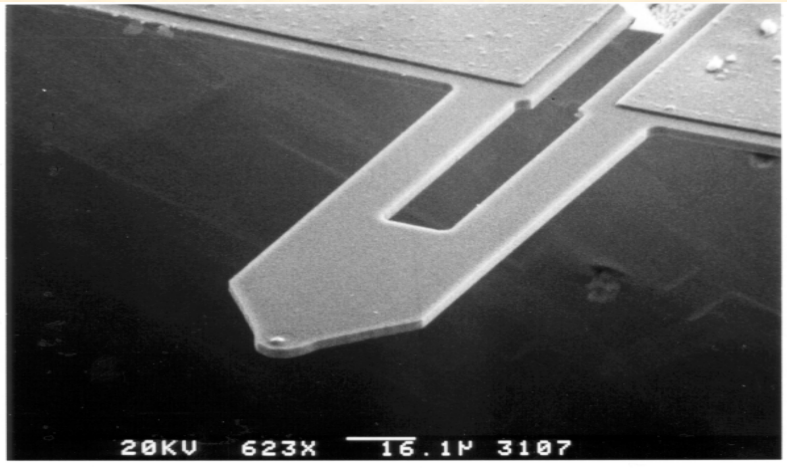
Dimensions:

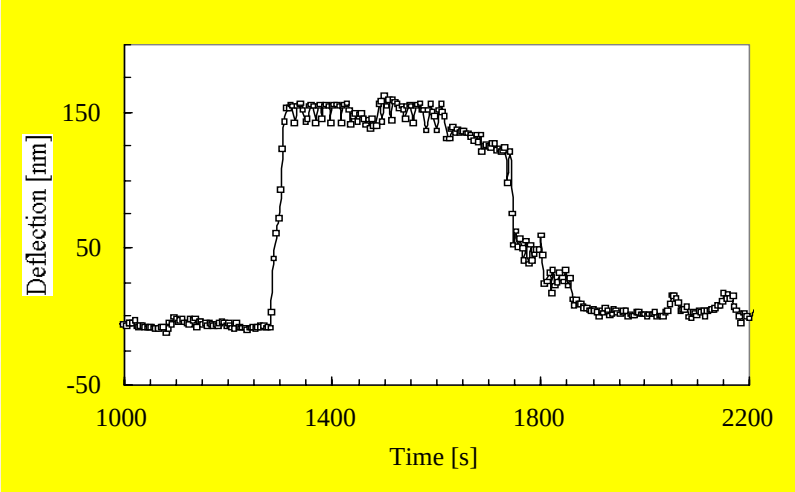
- **100µm long**
- **20µm wide**
- **0.3µm thickness**
- **Nanogram mass**

Gives 5 types of signals:

- **Amplitude**
- **Frequency**
- **Bending**
- **Phase**
- **Q-factor**

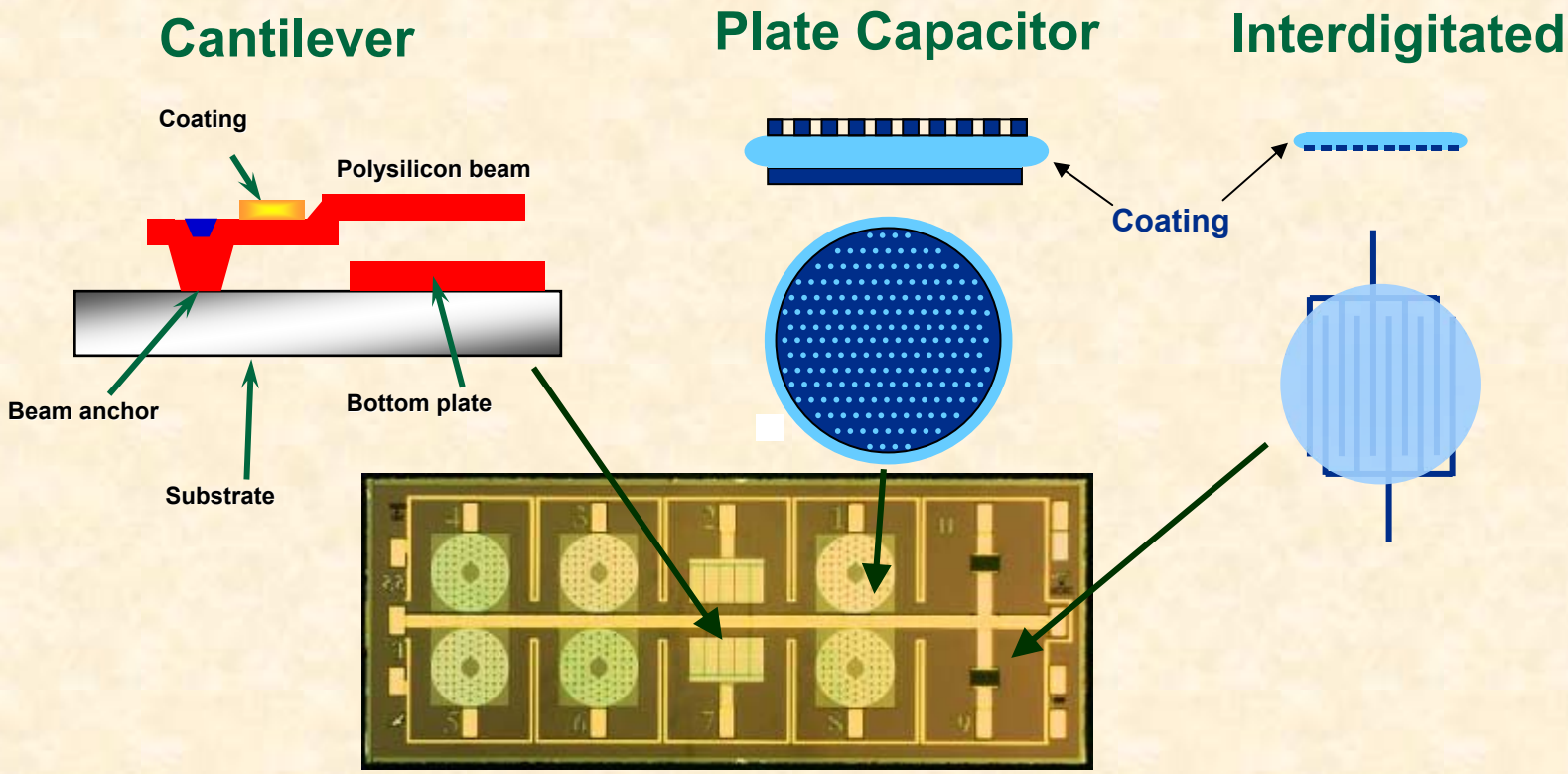
Pico-gram detection sensitivity; nanometer deflection





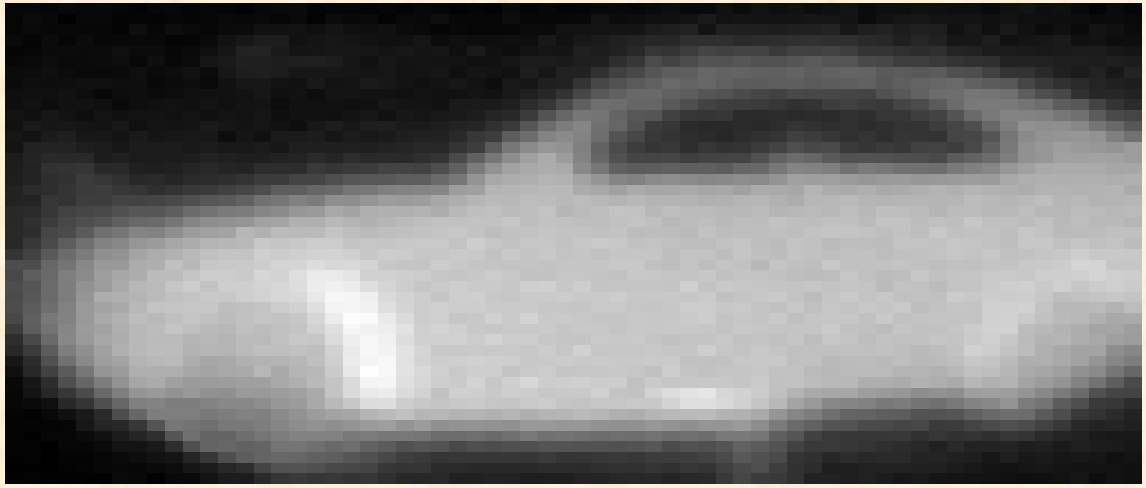
Antibody-antigen: Parts-per-trillion sensitivity

Microsensor Arrays for Very Low-level Gas Detection

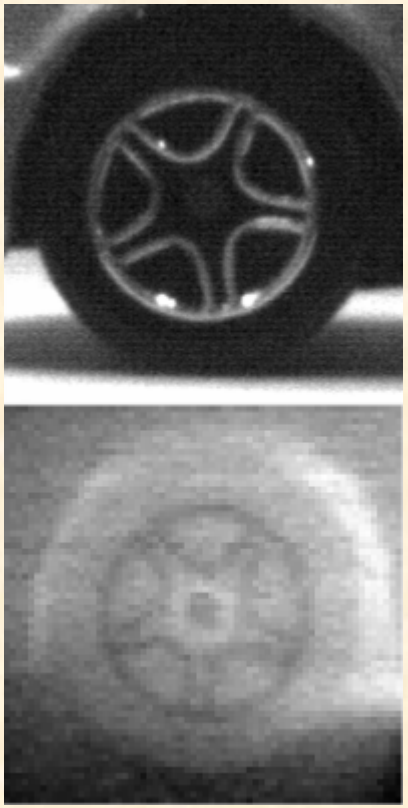


Infrared Imaging Using Uncooled MEMS

64x45 IR Image (Using Optical Readout)



Car Wheel



IR Image of Car Wheel

Integrated Sensor Array with Carbon Dioxide, Temperature, Humidity, and Occupancy as well as Communications

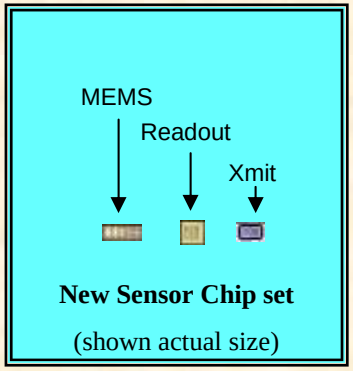
Communications

MEMS Array

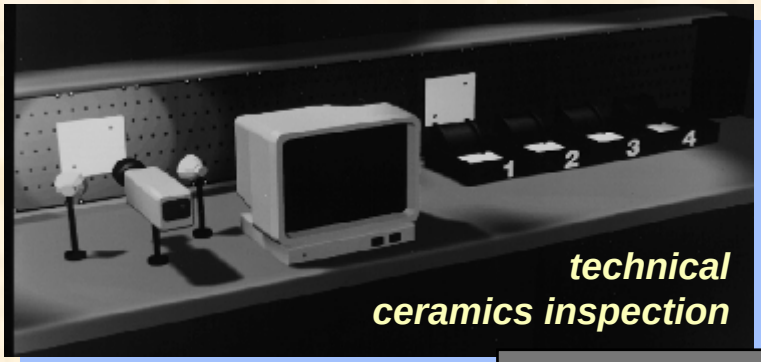
µprocessor

Vision for Sensor Systems: Ultra-low power, low-cost, wireless sensor arrays

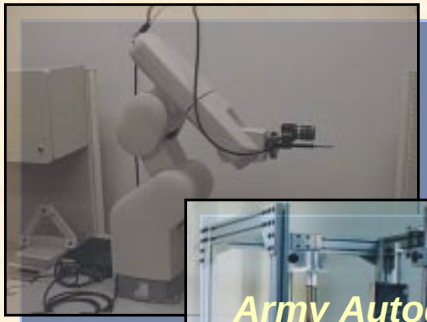
- **Micro sensor arrays and smart materials**
  - **Gases, room occupancy, energy consumption, national security, etc.**
- **Ultra low-power signal conditioning and readout electronics**
- **Communications using existing wires or wireless …bi-directional**
- **Self-diagnostic, self-calibrating**
- **Ultra-low power**
  - **<5 mW continuous use/100 μW in sample mode**
  - **scavenging power from environment**
- **Integration into robust measurement system for vision of "peel-stick-and-forget" deployment**



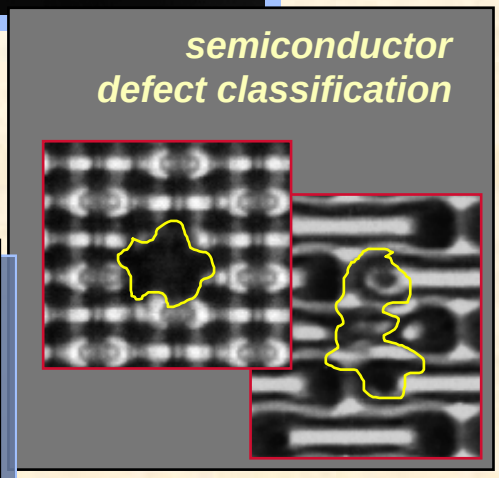
Machine Vision For Real-Time Inspection & Automation



technical ceramics inspection



Army Autodocking and Vision ID



semiconductor defect classification

On-line Machine Vision Inspection for:

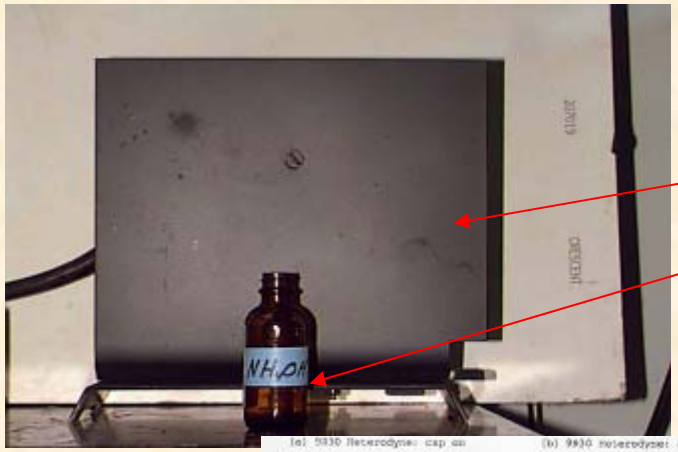
- ***defect detection and classification***
- ***improved process understanding***
- ***process feed-back and control***
- ***improved product quality***
- ***inventory control***
- ***instrument alarm***

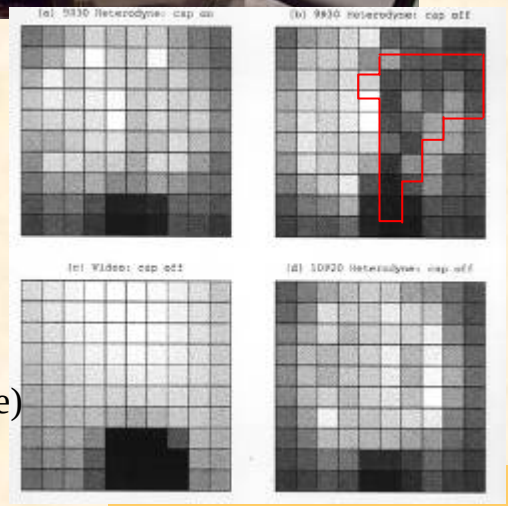
American Textile Partnership: quality control, product improvement

Coherent Infrared Imaging Camera (CIRIC)

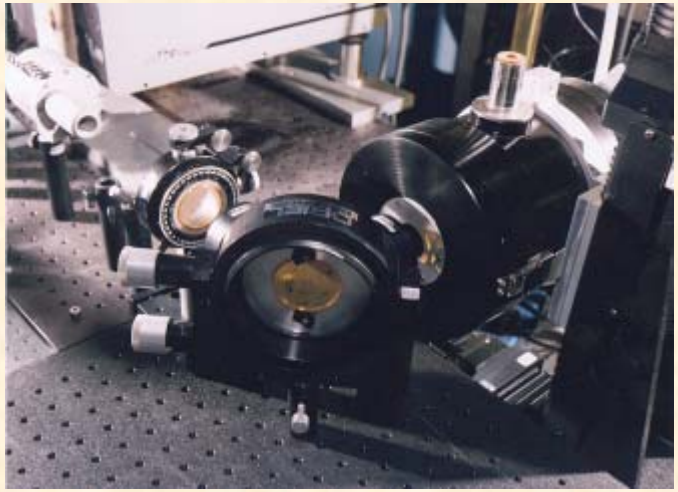
Features:

- Each pixel is an independent laser radar receiver
- Long-range chemical detection
- Hard-body and aerosol capability
- Active or passive measurements
- Range > 10 km
- Velocity measurement
- Detection in inclement weather





CIRIC Receiver Prototype



US Patent Number: **5,751,830**
Issued: **May 12, 1998**

Applications:

- Chemical plume detection & tracking
- Wake vortex measurements
- Target velocity & range

Compact FM-CW Lidar Measurement of Airborne Particles from Diesel Truck Exhaust

- **Uses laser diode and RF component technology**
- **Employs unique signal processing and inversion technique to potentially reduce size to a hand-held unit**
- **System adaptable to an array detector and could eventually provide 3D information on diesel exhaust and other type aerosol plumes**

Laser Scanning System for Item Monitoring – International Safeguards

- **Developed based on the need to monitor multiple stored items where there is reluctance to use RF for several reasons, security of information transfer being high on the list**
  - **Laser scanning of retro-reflective tags provides an alternative option for detailed monitoring of the status of stored materials**
- **Using an optical transceiver and retro-reflecting targets, items can be continuously monitored with high resolution and low cost.**

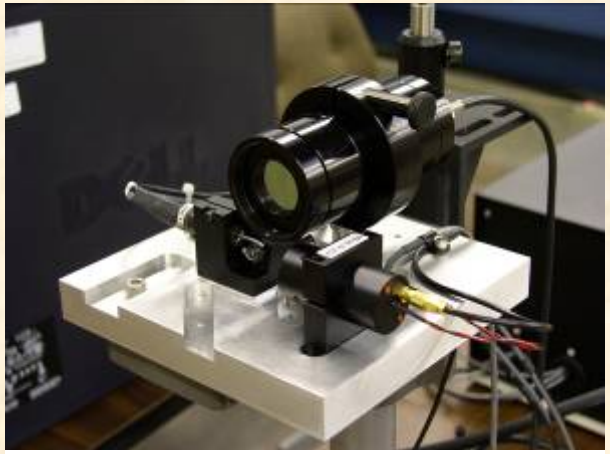


Figure . Master transceiver - consists of laser, scanning system and photodetector

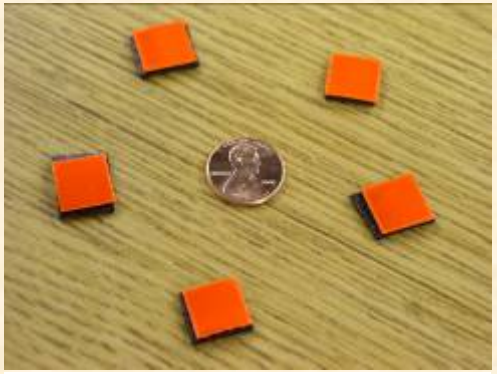
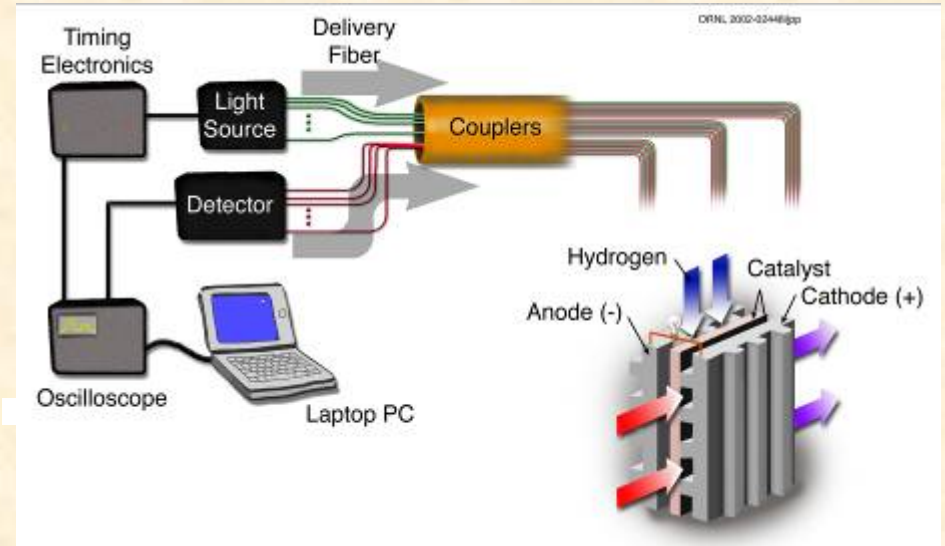


Figure . Retro-reflecting targets - return light to transceiver for analysis

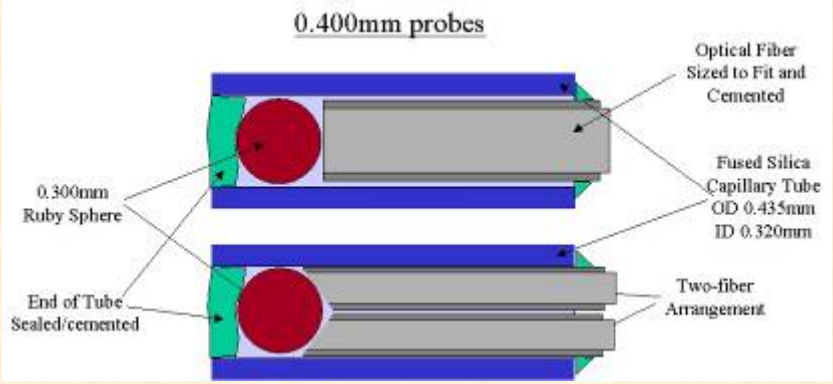
Fiber Optic Temperature Sensors for PEM Fuel Cell Monitoring

Sponsored by the DOE Office of Hydrogen, Fuel Cells and Infrastructure



Problem: the fuel cell developers need to map/optimize the internal thermal environment of operating and developmental PEM and solid oxide fuel cells.

Solution: ORNL led research team is developing extremely compact, low-cost and accurate fiber optic temperature sensors for measurements within the membrane-electrode assembly of operating fuel cells.



Luminescent ruby micro-spheres tell temperature!

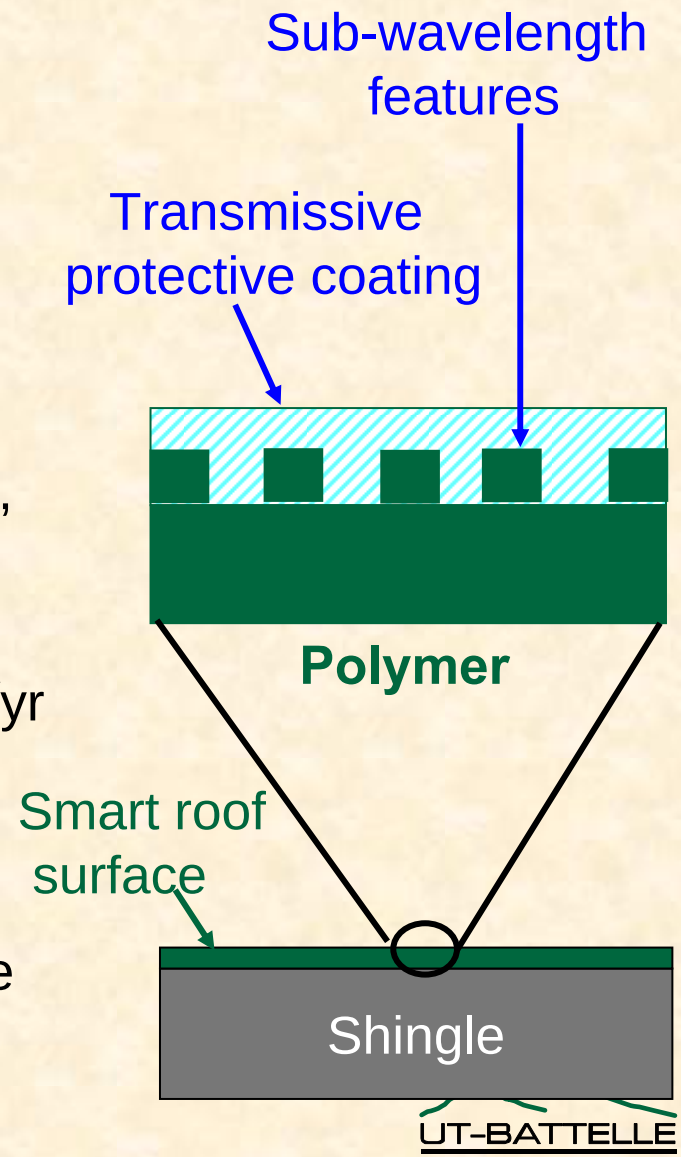
We See the Future of Sensors and Controls as:

- **Low cost, very low power, autonomous, robust sensor systems**
- **Highly integrated, intelligent control**
- **Dynamic wireless networks & sensor systems - the sensors are the network**
- **R&D Funding for the "infrastructure" technologies**

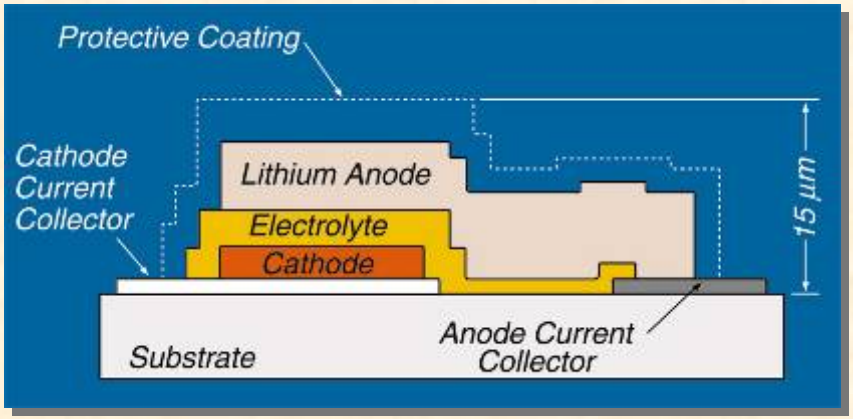
Leading to adaptive, robust manufacturing processes that improve yield, reduce energy consumption, and minimize waste generation/emissions

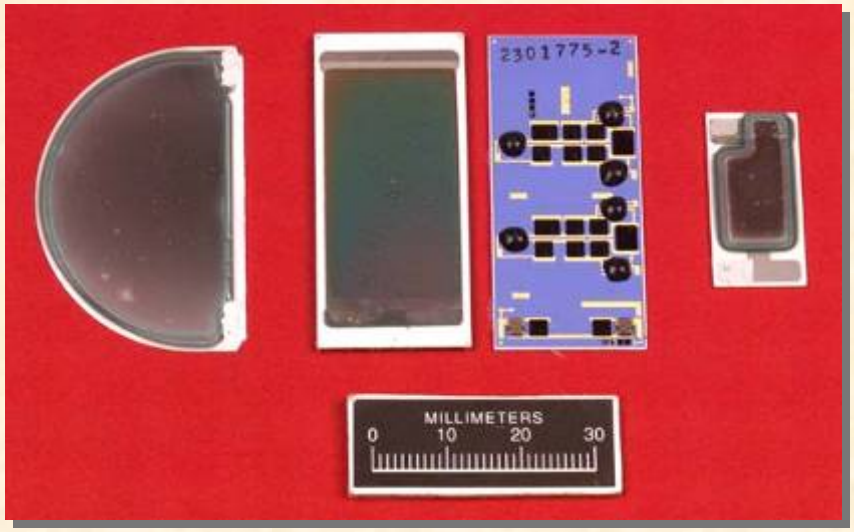
Smart Roof - Substantial Energy Savings Technology

- Leverages DOE investments in polymers, roofing and building materials, and micro and nano-optical devices
- The temperature-sensitive polymers exhibit a material phase change at a specific temperature and change in optical properties.
- Integrated with the sub-wavelength structures, the combination provides the variation for building heat/cooling loads.
- Estimated Energy Savings of \$0.05 - \$0.20 ft^2/yr (Simulations have shown a roof with a reflectivity of 85% above 65 ^{0}F and 5% below 65 ^{0}F)
- Protective coating for durability and imprint-like manufacturing for cost-effective production



Integrating Power with Thin-Film Batteries and Then to Scavenging Power



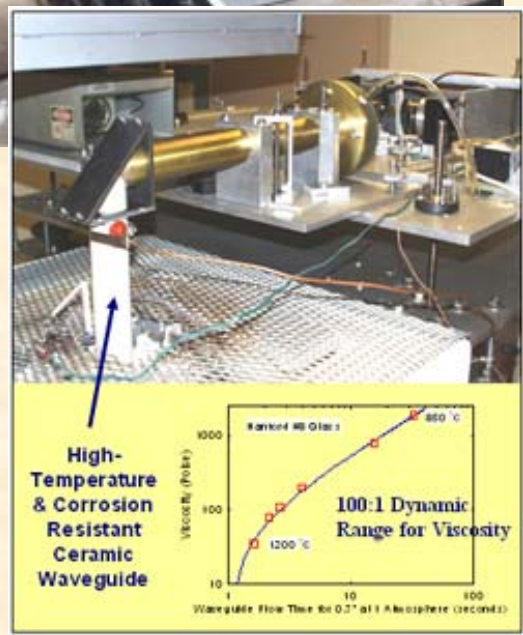


Li-LiCo0_2 cells

- Capacity 250 µAh/cm^2
- Energy >1 µWh/cm^2
- Wide operating temperature rate (-25 C to 250 C)
- 1000's of cycles
- Long shelf life: years
- Rapid Charge rate <20 min.
- Fabricated in arbitrary shape and only 15 microns thick

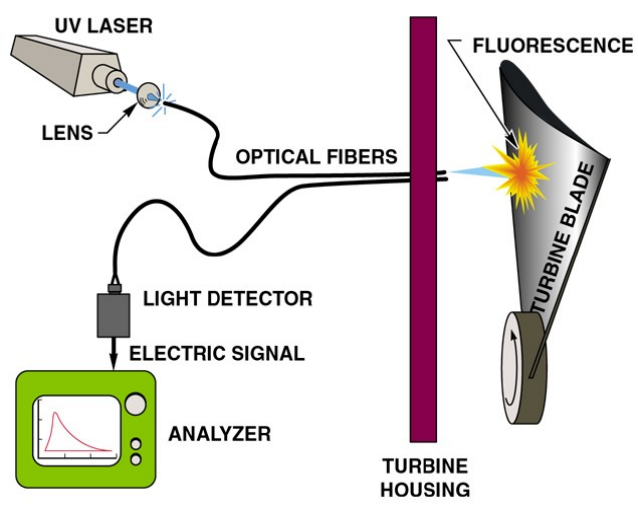
EERE Investment in Sensors & Controls Has Created Successes

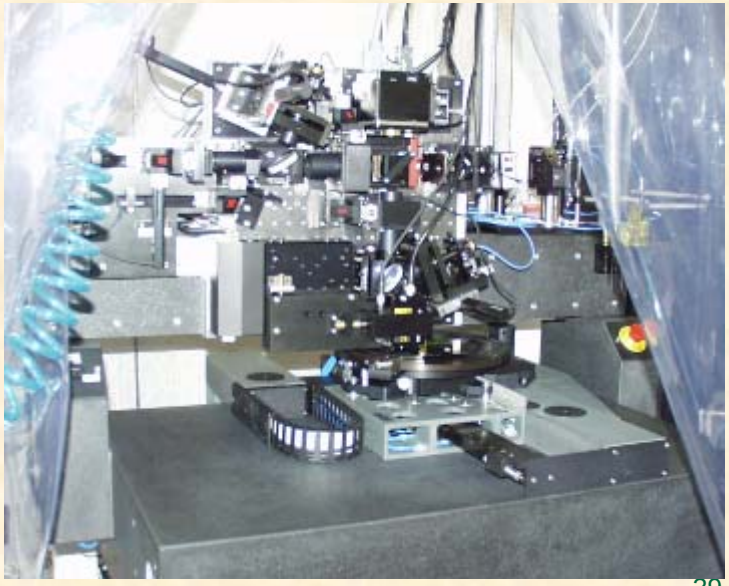
- **High Temperature NOx and O2 sensors for engine performance and emissions control**
- **Measurement Firsts**
  - **Fast-response, direct-sampling mass spectrometry for emission control diagnostics (SpaciMS)**
  - **In-line characterization of exhaust particles**
  - **Intra-catalyst temperature transient profiles – thermal phosphors**



Successes Continued

- **Inspection system for head box to improve paper quality**
- **Non-contact temperature applied to steel and engines for yield improvement and performance enhancement**
- **Robust, secure wireless communications and networking**
- **Collaborated on with industry for new product development**





Sensors & Controls Providing Impact

- **Solving important problems for DOE, DOD, DHS, and industry**
- **15 R&D 100 awards since 1995, 50 overall**
- **20 Federal Laboratory Excellence in Technology Transfer Awards - 3 of which were National Winners**
- **Innovative Technologies: ~10 patents awarded per year, 30 licenses granted**
  - **Patent Portfolios in wireless, microsensors, nanoscience, and inspection technologies**
- **DOE/ORNL technology has started up several companies (examples: IPIX, nLine, Calipher, Sarcon, Tarallax, CSI)**