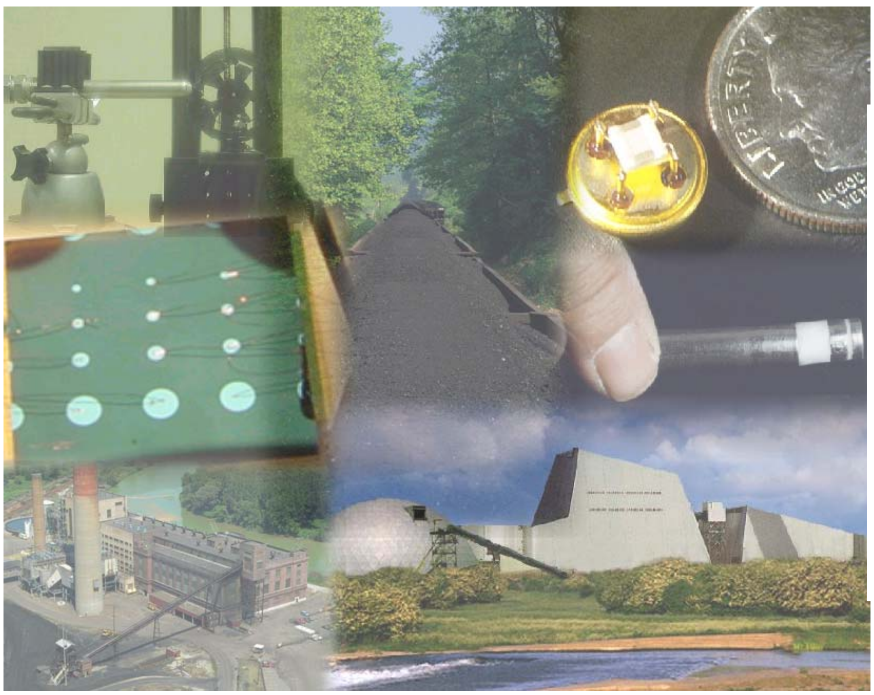
The 2002 NETL Sensors and Control Program Portfolio Review and Roadmapping Workshop: *Gas, Emissions, and Process Monitoring*



Workshop Proceedings

October 15-16, 2002
Pittsburgh, PA

The 2002 NETL Sensors and Control Program
Portfolio Review and Roadmapping Workshop:
Gas, Emissions, and Process Monitoring

WORKSHOP PROCEEDINGS

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EXECUTIVE SUMMARY

As performance requirements for fossil-energy systems become more stringent, new approaches to systems monitoring and control are required. For fossil energy to remain the backbone of a secure, affordable energy supply, improved efficiency and lower emissions will be required. Advanced sensor and control systems provide a promising pathway to achieve this critical national benefit.

The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) of the Office of Fossil Energy (FE) held a Sensors and Controls Program Portfolio Review and Roadmapping Workshop in Pittsburgh, PA on October 16-17, 2002. The purpose of the workshop was twofold.

- Review progress to date of the NETL Instrumentation, Sensor and Control Systems (ISCS) Program's research portfolio.
- Elicit stakeholder perspective and insights on opportunities for innovative technologies and techniques.

The workshop was conducted in three sessions, an initial plenary session and two small-group breakout sessions. The plenary session provided an overview of the ISCS Program and perspectives from industry and National Laboratory researchers on novel approaches and applications for sensors and controls. The balance of the workshop was conducted in three breakout groups, running in parallel.

- Gas Sensors and Measurement: Improving System Performance
- Emissions Measurement: Assuring Regulatory Compliance
- Condition Monitoring: Improving Reliability, Availability, and Maintainability

The first breakout sessions were for the portfolio review, and the second for brainstorming on technology opportunities and pathways.

Plenary Session

There were four presentations and associated question and answer periods in the plenary session. Following an overview of the ISCS Program, guest speakers provided perspectives on basic-science developments, industry and National Laboratory approaches to new sensors and devices, and current and emerging targets in industrial, security, and energy applications, including fossil energy.

Overview of ISCS Program – Robert Romanosky, NETL

The Product Manager for the FE Advanced Research Program at NETL, Bob Romanosky, provided an overview of the ISCS Program, its relationship to the FE Vision 21 Programs, the current ISCS research portfolio, and future activities. The Advanced Research Program, with a FY 2002 budget of $28 million, supports research in materials, modeling and simulation, bioprocessing, CO_2 sequestration, coal science and sensors and controls. The ISCS Program is a new component of the portfolio, and targets innovative solutions that address the following criteria:

- Low cost and high benefit,
- Capability for retrofit in the nation's large asset base of coal-fired electric generation plants,
- Capability to enable FutureGen and other advanced plants, including combustion, gasification, gas turbines, fuel cells, and hybrid systems, and
- Ease of integration at all levels, encompassing device, unit, process, system, plant, and facility.

There is great potential for innovation in control systems, including both entirely new techniques and the adoption or adaptation of tools and techniques used in other applications. Key barriers already known include materials limitations, the difficulty of overcoming interferences from non-target chemical species, and problems in assuring the accuracy and reliability of sampling under typical plant operating conditions.

Four key questions to guide the workshop were posed.

- Why can't we build these systems today?
- What is the state-of-the-art and major technology-development trends?
- What are the materials issues?
- What is the role of government support in order to provide public benefits?

Overall, sensors and controls offer one of the most promising pathways to meeting fossil-energy requirements. The workshop results will help guide visionary planning and effective implementation of the ISCS Program.

Nanoscience: The Expanding Boundaries of a Shrinking World – John Miller, DOE Office of Basic Energy Sciences

Developments at the nanoscale level are moving rapidly to the point where the prospect for breakthrough, high-payoff applications are compelling. John Miller of DOE's Office of Basic Energy Sciences (BES) discussed the challenge of extending capabilities from the microscale engineering level to the nanoscale level. Three overall goals to achieve this are 1) attaining the understanding and prediction of materials properties and behavior at the nano-scale (in contrast to known bulk-material properties, 2) exploring and elucidating mechanisms for fabrication and manufacture of materials and components, and 3) examining the methods and processes to achieve effective interfaces between nano- and macro-scale objects. Considering that "mother nature got there first," biotechnology and biomimetics are expected to play a major role in innovative processes and systems. In composite, future applications will merge nanotechnology, materials, and sensors. To achieve this will require large-scale, dedicated facilities, including the research infrastructure of such tools as synchrotron light sources; the reality is that big facilities are needed to study small things, and BES is sponsoring five Nanoscale Science Research Centers in the DOE National Laboratory complex.

Chemical Sensors Based on Carbon Nanotubes – John Cumings, Nanomix, Inc.

Nanomix, Inc. is a small nanotechnology firm in Emeryville, California. John Cummings, a Nanomix researcher, presented a review of the company's capabilities and work in nano-materials, specifically the design and synthesis of nanotube-based devices. The company core competencies are in three primary areas: the computational design of novel materials, the development and refinement of synthesis methods for nanomaterials, and working with product development to demonstrate applications of the novel materials. The two primary market targets are chemical sensors and hydrogen-storage devices. Functionalization and other structural manipulation of nanotubes and related structures are expected to yield both near-term product applications such as sensors and longer-term applications such as hydrogen storage.

Recent Development in Sensors an Micro-Analytical Systems – Ronald Manginell, Sandia National Laboratories

Integration of advanced sensors with on-chip electronics and separations can provide advanced systems for field-deployable monitoring systems. Ron Manginell, Principal Member of the Technical Staff at the Micro-Analytical Systems Department, Sandia National Laboratories, described the development of tools for applications including national security, and their potential for fossil-energy applications. "Micro-Chemlab" and "Micro-Robot" are two new tools developed by Sandia for security applications. Micro-Chemlab, by integrating collection, sampling, separation, and detection at a micro-scale level, provides the capability for hand-held devices usable in field applications. Many of these same attributes can potentially be applied to *in situ* monitoring and control of fossil-energy processes. For example, remote chemical sensing capabilities could be applied to gas-stack measurement or to support condition-based maintenance programs.

Portfolio Review

Following the plenary session, the meeting was broken into three parallel sessions. The sessions began with review of twelve representative projects supported by the Advanced Research Program. These projects are a part of NETL's program on sensor development, and were selected because they were directly related to the subject areas to be discussed in the workshop.

From a program-portfolio perspective, the reviewers generally thought most of these projects were relevant to the DOE needs for developing advanced sensors for power systems. The reviewers endorsed the idea of using sensors to improve control of power systems, and paid close attention to the response times of many proposed sensors. There were two projects that addressed using multiple sensing to measure gas components to help control the combustion process. These projects were directly responding to the findings of the previous workshop indicating that control of air:fuel ratio is critical for improving combustion performance, and that moving sensors closer to the combustion zone is desirable.

With respect to research barriers, the reviewers raised most concerns about practical issues, such as particulate contamination, the interface with electronics, and packaging. These areas need to be improved. For example, although SiC materials can operate at elevated temperatures, reviewers had concerns about whether the wiring and packaging will function well at such high temperatures. The H_2O effect on SiC at high temperature is another practical issue.

The reviewers suggested NETL pay special attention to the "real-world" application issues such as particulate contamination, system-interface issues such as extraction and sampling systems and optical windows, and packaging that will allow advanced sensors to survive in harsh environments over useful time-frames. Some suggested that NETL establish a test protocol that will encompass these concerns, and thus aid developers in targeting and achieving critical fossil-energy system goals. Reviewers also suggested that NETL support other emerging and competing technologies, including nanotechnology, silicon-on-insulator, wave-based, and optical measurement technologies.

Breakout-Group Sessions

Previous workshops sponsored by NETL have highlighted the potential gains from advanced sensor and control systems. Improved efficiency, lower costs, and improved environmental performance are high-payoff–and achievable–outcomes. The harsh conditions (high temperature, high pressure, corrosive environments, and presence of particulates) are indeed challenging. Systems must be robust, accurate, reliable, and cost-effective over life spans for power-plant applications that may be measured in decades.

Equally important is the ease of integration of new capabilities into both currently deployed systems (targeted by FE's innovations for existing plants program) and new systems (targeted by FE's Vision 21 Program). System logic, algorithms, actuators, and networks must be able to apply sensor data to best effect in "real life" operating and maintenance regimes. Such systems can help foster the implementation of new power generation technologies as well as enhancing plant control in the existing fleet of fossil-fueled power plants.

In facilitated brainstorming sessions, three groups (Gas Sensors and Systems, Emissions Measurement, and Condition Monitoring), working in parallel, addressed a series of questions.

- What are key barriers (technical, regulatory, institutional) to achieving the FE goals?
- What are the R&D areas of opportunity to overcome these barriers?
- What are the highest-priority R&D pathways?
- What are the action plans needed to implement these high-priority pathways, including tasks, resources, and opportunities for collaboration?

While the majority of the results are specific to the individual topics, there were notable common elements that crosscut the groups. Many of these relate to requirements definition and implementation issues.

- Systems integration: achieving best results can only be achieved by making integration a priority design and operating requirement.

- Test standardization: assuring that the end user can evaluate options and select the best one(s) with confidence is necessary for widespread technology deployment.
- Economics and market opportunity: defining clear user needs that constitute a viable market target for technology developers is necessary to attract new ideas and players.
- Performance specifications: highly detailed, system-specific design requirements should be readily available to bridge the gap between plant owners/operators and technology developers. The vast array of fossil-energy systems of concern (combustion, gasification, gas turbines, fuel cells, hybrids, new Vision 21 plants versus retrofit applications at pulverized coal-burning plants) constitute a complex target, *particularly for those not currently involved in FE programs*.
- Regulatory versus other drivers: While in general, regulatory requirements are seen as the major near-term driver, focusing on the potential for efficiency enhancement and cost is critical. This encompasses reductions in both capital costs and operations and maintenance costs, and applies to both new and retrofit applications.

There was also significant conformance across the groups in many technical areas. For example, the Emissions Measurement group considered the highest-payoff options to be those associated with “moving up the pipe” to process control. Accordingly, many key findings underscore those of the Condition Monitoring group. Another theme was to explore cheap, multiple sensors that do not require extreme durability; redundant multiple sensors may be a valuable option. A related topic was sensor packaging; coatings, sealants and package integration are concerns.

A set of high-priority R&D topics was selected by each group through participant voting. These topics are summarized in the accompanying table. For each topic, an action plan was prepared. These plans identify potential applications, specific R&D products and characteristics, critical steps, integration issues, critical resources, and collaboration opportunities.

SUMMARY OF HIGH-PRIORITY TOPICS

Barriers	High-Priority Topics
Gas Sensors and Systems Group	
• Systems integration: sampling, communications, packaging, interfaces • Improved economics: the need for market pull • Standardized testing: common testing protocols • Design architecture: changing old approaches by introducing new paradigms • Materials: uncertain, changing requirements • Systems-specific: critical needs are different for combustion, gasification, fuel cells, gas turbines, and hybrids	• Materials development coupled with standard reference data and modeling of mechanisms • Shared test-bed for sensors to enable realistic evaluation under EPA (and other) requirements • Database repository for sensor performance: clear performance targets and applications • High-temperature packaging development: integrated sensor and electronics • SiC substrate and device processing for long-term stability: cheap substrate, new epitaxy techniques • Establish pool of users for diode lasers
Emissions Measurement Group	
• Basic technology: innovative, alternative approaches • Emissions reporting requirements: uncertainty and changing requirements • Applications issues: packaging, testing, sampling, accuracy and repeatability • Commercialization issues: market entry and opportunity	• Materials technology for sensors: fundamental studies and mechanisms • Test facilities for standardized testing: pilot-scale facility and open test ports at utilities • Targeted program on sampling interfaces: optical access and other approaches • *In situ* measurement of O_2, unburned carbon, NO_x, CO • Novel concepts for sensing: wave technologies, acoustics, electromagnetics, nuclear-magnetic resonance
Condition Monitoring Group	
• Interface limitations: sensors with controls, controls with operators • Integration: point measurements relative to the big picture • Materials limitations: high-temperature, harsh environments • Lack of measurement capability: flow, combustion stability, temperature/emissions, strain • Performance testing: lack of facilities/protocols for test and validation	• Flame monitoring and characterization methods: combustion stability and efficiency • Enabling materials for sensor development and development of engineered high-temperature materials • Low-cost test facilities: at sufficient scale to provide reliable and validated results • Pyrometer measuring and monitoring for thermal barrier coatings

The Path Forward

For fossil-energy systems to thrive as the nation's preeminent choice for affordable, secure, and clean power and fuels, improved performance must be attained at costs less than current systems. This workshop, along with ongoing exchanges of ideas and perspectives with stakeholders, will provide a balanced technical and analytical base to focus the ICSC Program's technology roadmapping and R&D implementation efforts. The results will guide technology *innovation* as well as *integration* with FE's Vision 21 and Innovations for Existing Plants Programs.

For More Information

For information on the Advanced Research Program and related programs visit the NETL web site for Coal and Environmental Systems http://www.netl.doe.gov/coalpower/index.html.

Section **1.0**

WORKSHOP OVERVIEW

1.1 INTRODUCTION

The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) conducted a Sensors and Control Program Portfolio Review and Roadmapping Workshop, held on October 15-16, 2002 in Pittsburgh, Pennsylvania. The workshop's purpose was to review progress to date in the program's research portfolio and to elicit stakeholder perspectives and insights on research needs and opportunities that could be applied to program planning. Drawing over 70 experts from industry, the National Labs, and universities, the workshop's theme was new paradigms for sensors and controls that could revolutionize power systems. It builds on the findings of NETL's first workshop on Sensors and Control technology, held in April of 2001. These workshops, along with other interactions with stakeholders, provide a balanced technical and analytical base to focus the program's technology roadmapping and R&D implementation efforts.

There is an established consensus that advanced, integrated control systems will be essential to achieving the cost and performance targets of high-efficiency, low emissions fossil-fuel plants. The workshop was sponsored by the Instrumentation, Sensor, and Control Systems (ISCS) Program, part of the Office of Fossil Energy's (FE) Advanced Research Program, which targets novel research opportunities for fossil-energy systems. In the manner that engine control systems have optimized efficiency, power, and emissions performance for motor vehicles, the ISCS program explores similar approaches that could revolutionize power systems.

1.2 BACKGROUND

ISCS Vision Statement

Enabling, improving, and protecting power systems and related infrastructures through the development and application of innovative sensor measurement and control technologies

NETL is the nation's largest fossil-fuel research laboratory and leads DOE's efforts in developing cleaner, more efficient, and cost-effective technologies for fossil fuel uses. Sensors and controls are an essential enabling technology for advanced power generation, including efforts such as DOE's FutureGen plant to test technologies for producing hydrogen and electricity with extremely high efficiency and near-zero emissions.

The ISCS Program provides support for the crosscutting needs of FE's advanced-technology development programs. The ultimate goal of these programs is to effectively eliminate, at competitive costs, the environmental concerns associated with the use of fossil fuels for producing electricity, hydrogen, transportation fuels, and other products. Advanced coal-based systems may incorporate combustion, gasification, fuel cells, turbines, or hybrid combinations of technology.

The operating environment for these coal systems is extremely harsh. Some generic system conditions are shown below.

Power Generation Technology	Upper Temperature Limit	Upper Pressure Limit	Other
Gasification	3,000°F/1650°C	600 psi	Slagging and reducing environment, particulates present
Turbine (gas path)	3,200°F/1,760°C	400 psi	Oxidizing environment
Turbine (surface)	2,500°F/1,370°C	400 psi	Oxidizing environment
Combustion	1,500°F/800°C	100 psi	Oxidizing environment, particulates present

The ISCS program explores and develops innovative sensing and control capabilities to serve three primary objectives.

- Improve the performance of existing power systems through increased efficiency, availability, and reliability, and reduced emissions with a high level of cost competitiveness by providing critical measurements and advanced control that allow the conversion of fossil fuel for power generation to be optimized in real-time.
- Support FutureGen and other advanced systems by developing innovative sensing capabilities and advanced control systems that enable the full-scale deployment of advanced power generation technologies.
- Strengthen the protection and security of interdependent infrastructures that are critical to power generation including fuel supply, water, and transmission by furnishing the monitoring capability for optimized management.

The timing requirements for the ISCS Program reflect the market-driven strategy of the FE coal programs. There are three primary market targets.

- Develop environmental control and efficiency improvement technologies for existing fleets of coal-fueled power plants by 2005.
- Develop next-generation technology for retrofit and re-powering markets by 2010.
- Integrate advanced enabling technologies into FutureGen and other advanced systems by 2015.

1.3 Workshop Structure

The workshop consisted of an initial plenary session followed by concurrent small-group breakout sessions. The plenary session provided an overview of the ISCS Program along with perspectives from industry and DOE on novel approaches and R&D opportunities for sensors and controls. Following the plenary session parallel workshop sessions convened for three technical areas.

- ***Gas Sensors & Measurement: Improving System Performance***

  In advanced power-generation systems, gas compositions need to be measured or monitored. Temperature tolerance, selectivity, stability, and resistance to particulate contamination are key areas of concern for advanced sensors. Balancing the fuel/air ratio on combustion systems is a key to improving power generation efficiency and reducing emissions. To achieve an optimum fuel/air ratio where thermal NO_x formation is lowest and flame stability is acceptable, several areas of measurement and control are of interest: flame quality, fuel supply, physical conditions, and chemical composition of the combustion zone. Flame-quality data can be extracted by a variety of methods, including acoustic, electrical, and optical technologies. However, the challenge is to transform the data into meaningful information that can be used by the control system.

  In the area of fuel supply, accurate on-line measurement of solid fuel flow needs to be developed. While microwave, electric, and acoustic technologies have been attempted, more work is still needed. In addition to flow rate, feedstock characterization is a long-term need for use with advanced control systems. If alternative fuels are being utilized, this measurement will grow in importance. Accurate on-line feed-stock characterization should help proper mixing of fuels, ensure appropriate heat content, allow predictive control of the combustion process, and manage contaminants appropriately throughout the system.

- ***Emissions Measurement: Assuring Regulatory Compliance***

  Sensors to monitor chemical composition, primarily emission constituents, remain a high priority. On-line, in-situ measurement systems capable of performing near the combustion zone are seen as essential for an active, integrated control system where emission information is used as real-time input for plant-operation adjustments. Examples include on-line mercury measurements, in-situ NO_x sensors, and on-line particulate monitors (for size and concentration). Improvements are required for stack monitoring as well as for use near the combustion zone. The former is needed to measure emissions compliance while the latter can enable improved emissions performance in integrated control systems.

  Mercury and PM 2.5 are two emerging regulatory issues, and developing on-line measurement of mercury and particulates is an urgent task. The capabilities of current CEM equipment are limited. Areas of improvement include, for example, the ability and accuracy in detecting low levels of NO_x and the potential of using sensors in place of analyzers for compliance monitoring and reporting.

- ***Condition Monitoring: Improving RAM***

  Condition monitoring can reduce facility failure and unnecessary maintenance and service. Accurate monitoring of the physical conditions within turbines and gasification systems remains a high-priority need. For the huge generation base of existing combustion systems, measurement and prediction of boiler scaling, corrosion, and other parameters could have widespread benefits in preventing boiler-tube failure. Current on-line technologies cannot withstand the harsh conditions, particularly those found inside gasifiers and turbines.

For example, while the specific applications for gasifiers and turbines differ, the primary need is to develop materials and technologies capable of accurately detecting gas path and surface temperatures (for example, as high as 4500°F/2500°C in turbine gas path) in high-pressure corrosive environments. As system complexity increases, advanced control systems will be required to assure reliability, availability, and maintainability.

Each group reviewed the currently available sensor and control capabilities for fossil systems and representative R&D projects funded by the ISCS Program. Following this review, in facilitated sessions the groups brainstormed on the following topics:

- Key barriers (technical, policy, regulatory, institutional) to achieving FE goals;
- R&D areas of opportunity to overcome these barriers;
- High-priority R&D pathways; and
- Action plans for high-priority areas, including tasks, timing, and resources; and collaborative implementation opportunities among government, industry, and academia.

1.4 Workshop Comments and Suggestions

Participants were asked to provide comments and suggestions on the workshop scope, process, and participants.

- Additional participation from users would provide much-needed insight into specific requirements under real-life operating conditions.
- The fossil-energy systems (combustion, gasification, fuel cells, gas turbines) of concern have some common needs but generally diverge.
- University research and vendors personnel in particular need specific requirements to drive new applications. This would also improve cross-fertilization from other sensor applications (e.g., automotive).

Section **2.0**

PLENARY SESSION

2.1 OVERVIEW OF THE ISCS PROGRAM
Robert R. Romanosky
AR Power Systems Product Manager
National Energy Technology Laboratory
U.S. Department of Energy

2.2 NANOSCIENCE – THE EXPANDING BOUNDARIES OF A SHRINKING WORLD
John C. Miller
Division of Chemical Sciences, Geosciences and Biosciences
Office of Basic Energy Sciences
U.S. Department of Energy

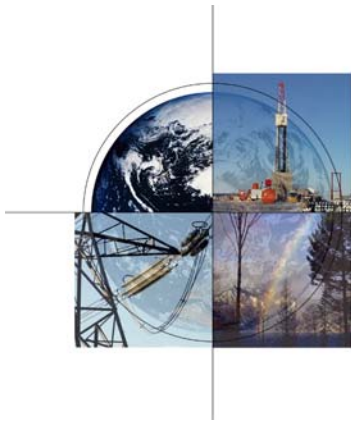
2.3 CHEMICAL SENSORS BASED ON CARBON NANOTUBES
John Cummings
Nanomix, Inc.

2.4 RECENT DEVELOPMENTS IN SENSORS AND MICRO ANALYTICAL SYSTEMS
Ron Manginell
Principal Member of the Technical Staff
MicroAnalytical Systems Department
Sandia National Laboratories

2.1 OVERVIEW OF THE ISCS PROGRAM

Robert R. Romanosky
AR Power Systems Product Manager
National Energy Technology Laboratory
U.S. Department of Energy

NETL's Instrumentation, Sensors and Controls Research Program



NETL Sensors Workshop

October 15, 2002

Robert R. Romanosky, AR Power Systems Product Manager
National Energy Technology Laboratory

www.netl.doe.gov

National Energy Technology Laboratory

- **One of DOE's 17 national labs**
- **Government owned/operated**
- **Sites in Pennsylvania, West Virginia, Oklahoma, Alaska**
- **More than 1,100 federal and support contractor employees**
- **FY 02 budget of $750 million**

Combustion Symposium - Jan. 2002

NETL's Mission

- **Resolve the environmental, supply, and reliability constraints of producing and using fossil resources to provide Americans with a stronger economy, healthier environment, and more secure future.**

Power Systems Advanced Research

- **Extend state of knowledge in fossil energy technology by supporting development and deployment of innovative systems capable of improving efficiency and environmental performance while reducing costs.**
- **Ingenuity, innovation and implementation**

Vision 21

- **Effectively remove environmental concerns associated with the use of fossil fuels for producing electricity and transportation fuels at competitive costs.**

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Advanced Research - Power Systems

Ingenuity, innovation and implementation

Mission

- Extend state of knowledge in fossil energy technology by supporting development and deployment of innovative systems capable of improving efficiency and environmental performance while reducing costs

Advanced materials consortium for ultra- supercritical power plants - NETL/ORNL/EPRI/CURC

Near-term Emphasis

- Advanced materials program development
- Virtual simulation for Vision 21 plants
- CO_2 mineral sequestration
- Bio-process research (sequestration, hydrogen)
- Sensors and controls
- Align UCR to Vision 21 support

Mineral carbonation- NETL /Albany Research Center/LANL/ASU

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Advanced Research Program
Goals and Objectives

- The Fossil Energy's Advanced Research Program is a bridge between basic research and applied R&D.
- The program leads the quest to identify breakthrough technologies or novel applications of existing technologies.
- The Program provides Fossil Energy with a link to Advanced Research programs in National Laboratories, academia, industry, and DOE's Office of Science.

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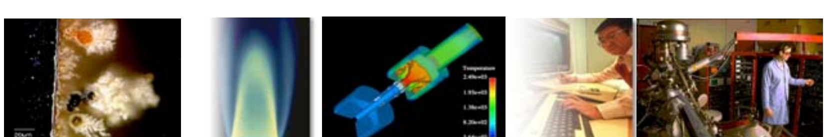
Power Systems Advanced Research

Bridge the gap between fundamental and applied technologies

Reflective of industry needs and responsible for driving new technologies

Ingenuity, Innovation and Implementation



Cross-cutting Technologies and Programs

Modeling & Simulation

SBIR, UCR & HBCU Programs

Materials

Instrumentation, Sensors, & Controls

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ADVANCED RESEARCH PROGRAM BUDGET TRENDS ($Million)

PROGRAM	FY 2001 APPR	FY 2002 APPR	FY 2003 REQ/REV
AR			
• Coal Utilization Science	6.3	6.3	7.9
• Bioprocessing	1.4	1.4	1.4
• University Coal Research	3.0	3.0	4.0
• Materials	7.0	7.0	9.0
• Comp. Energy Sciences	3.0	5.0	5.0
• HBCU	1.0	1.0	1.5
Total AR	**25.5**	**23.6**	**28.8**
Advanced Metallurgical Processes	5.2	5.2	6.0
TOTAL ADVANCED RESEARCH*	30.1	28.0	34.8

*Does NOT include: Coal Export Technology; Environmental Activities; Technical and Economic Analysis; International Program Support; International Capacity Building; Advanced Fuel Cell Research.

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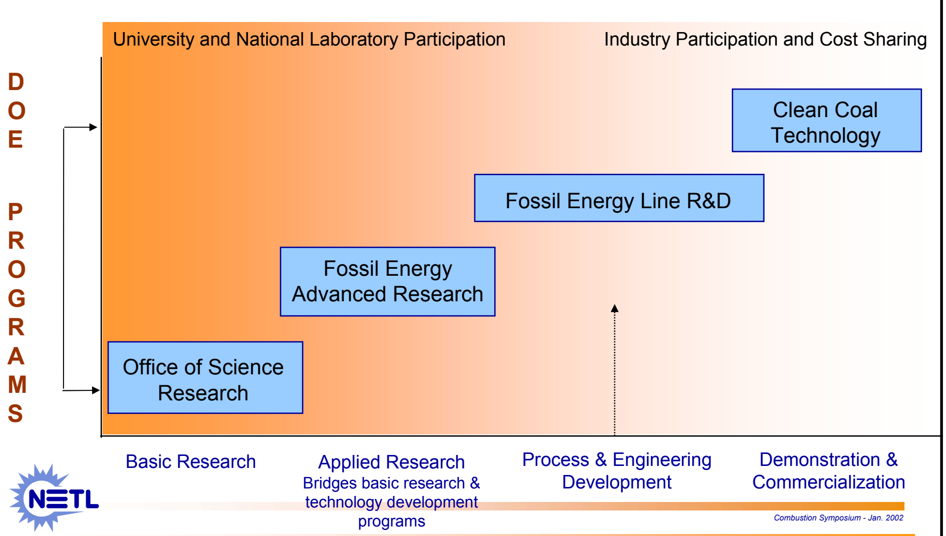
Energy R&D Spectrum



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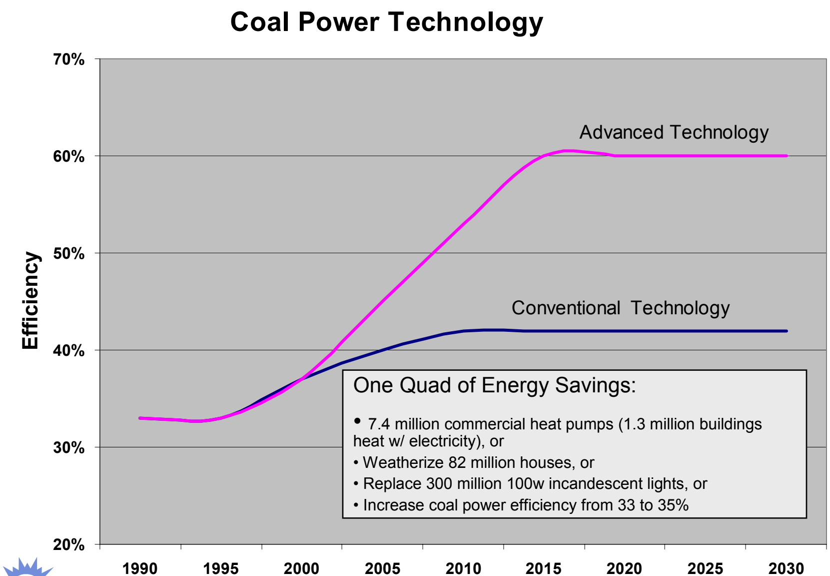

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NETL Power Systems Advanced Research Instrumentation, Sensors, and Control System Program

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NETL's
Instrumentation, Sensors and Controls Program

- Develop novel or revolutionary technology
- Positioned to screen and accept risk
- Capitalize on technology deployment skills
- Support Vision 21 as a concurrent effort
- Maintain stakeholder relationships (developers and users)
- Take a whole system approach

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Need for a Sponsored I,S&C Program

- Current technology not capable of surviving the harsh conditions
- Pervasive and cross cutting technology
- Lost cost / high benefit technology
- Opportunity for existing facilities
- A must for new facilities
- Concurrent development needed for Vision 21 systems

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I,S&C Program Structure

- Basic plan with specific road maps
- Internal and external R&D in both fundamental research and engineering development
- Collaboration with national labs, research centers, universities, small business and industry
- Defined metrics for AR projects
- Technology transfer through line organizations and industry
- Time-phased, results driven program to keep pace with Vision 21 program and industry
- Funding for a defined timeline

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NETL's Interest - Driving Advancements in Instrumentation, Sensors, and Control Technology

- Lost cost / high benefit technology
  - Comparatively small capital investment
  - Lower operating and maintenance costs
  - Enhance efficiency and reduce emissions
  - Increase reliability
- Opportunity for existing facilities
  - Dated systems
  - Deregulation
  - Regulatory emissions monitoring and control
  - Installation and operation of SCR systems
- A must for new facilities
  - High performance and reliability expectations
  - Protect capital investment
  - Minimize operational and maintenance cost

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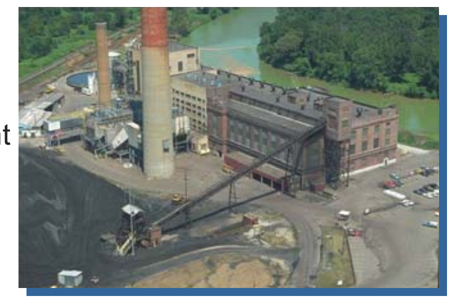
Control Systems

- **Whole system approach**
  - Device, unit, process, system, plant, and facility
- **Simulation of units and entire facilities**
  - Evaluate approaches and options
- **Develop and validate model and algorithms**
  - Dynamic systems
- **Existing facilities**
  - Commercially available systems can offer significant improvement as a retrofit or overhaul



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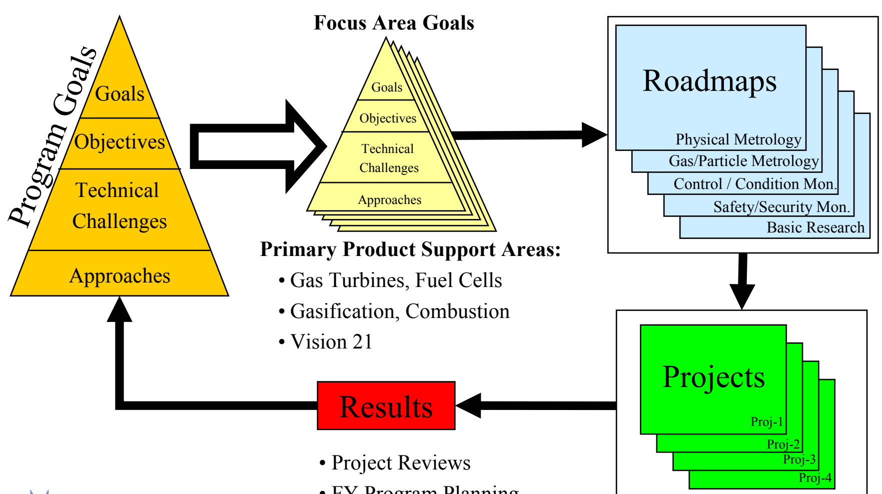
ISCS Program Framework

Program Goals are traceable to projects



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Vision 21

Ultra-Clean Energy Plant of the Future

Energy Plants for Post-2015

- **Use available feeds**
  - Coal, gas, biomass, waste
- **Multiple products**
  - Electricity, fuels, chemicals, steam

Goal:

Absolutely Minimize Environmental Implications of Fossil Energy Use!

Approach:

- **Maximize efficiency**
  - 60% coal-to-electric
- **Near-zero emissions**
  - Option for carbon sequestration

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Vision 21

Ultra-Clean Energy Plant of the Future

- **Flexible feedstock**
- **Electricity and co-products**
- **Maximum efficiency**
- **Near-zero emissions**

Systems Analysis & Systems Integration

INPUT

Fossil-based Feedstocks
- Coal
- Gas
- Oil

Opportunity Feedstocks
- Biomass
- Mun. Waste
- Petcoke

Gasification

Combustion & High Temperature Heat Exchange

Fuel Cells

Turbines

Syngas Conversion to Fuels & Chemicals

Gas Separation

Gas Purification

Environmental Control Technology

OUTPUT

Electricity

Transportation Fuels

Syngas

Chemicals

Hydrogen

Steam

Materials | **Sensors & Controls** | **Computational Modeling & Virtual Simulation**

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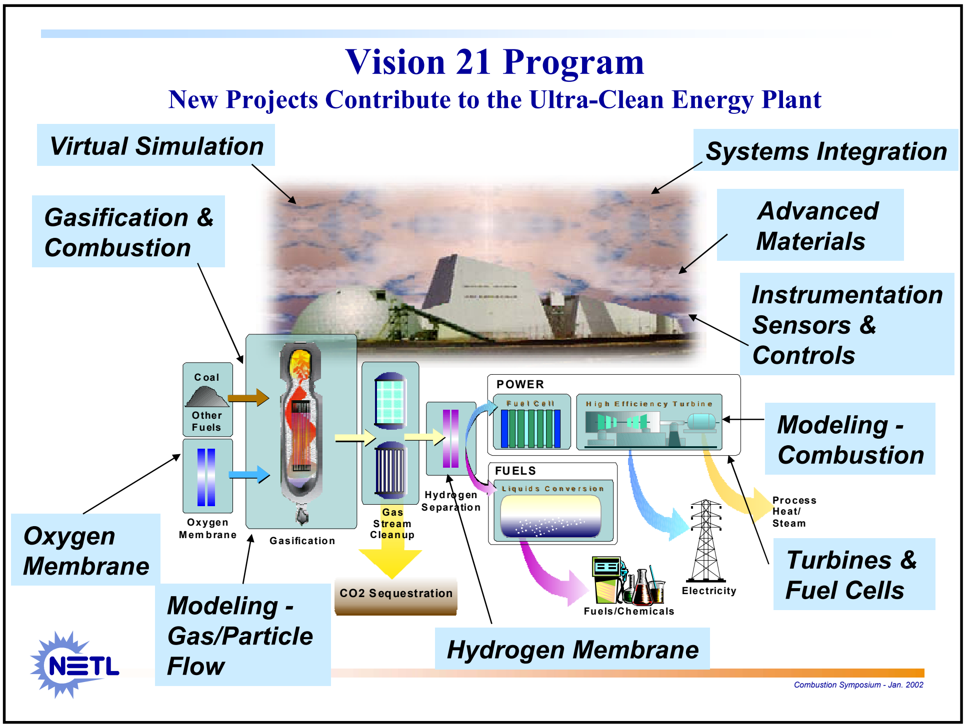
Vision 21 Program
New Projects Contribute to the Ultra-Clean Energy Plant
Virtual Simulation
Systems Integration
Gasification & Combustion
Advanced Materials
Instrumentation Sensors & Controls
Coal
Other Fuels
POWER
Fuel Cell
High Efficiency Turbine
Modeling - Combustion
FUELS
Liquids Conversion
Hydrogen Separation
Gas Stream Cleanup
Oxygen Membrane
Gasification
Process Heat/ Steam
Oxygen Membrane
CO2 Sequestration
Electricity
Fuels/Chemicals
Turbines & Fuel Cells
Modeling - Gas/Particle Flow
Hydrogen Membrane
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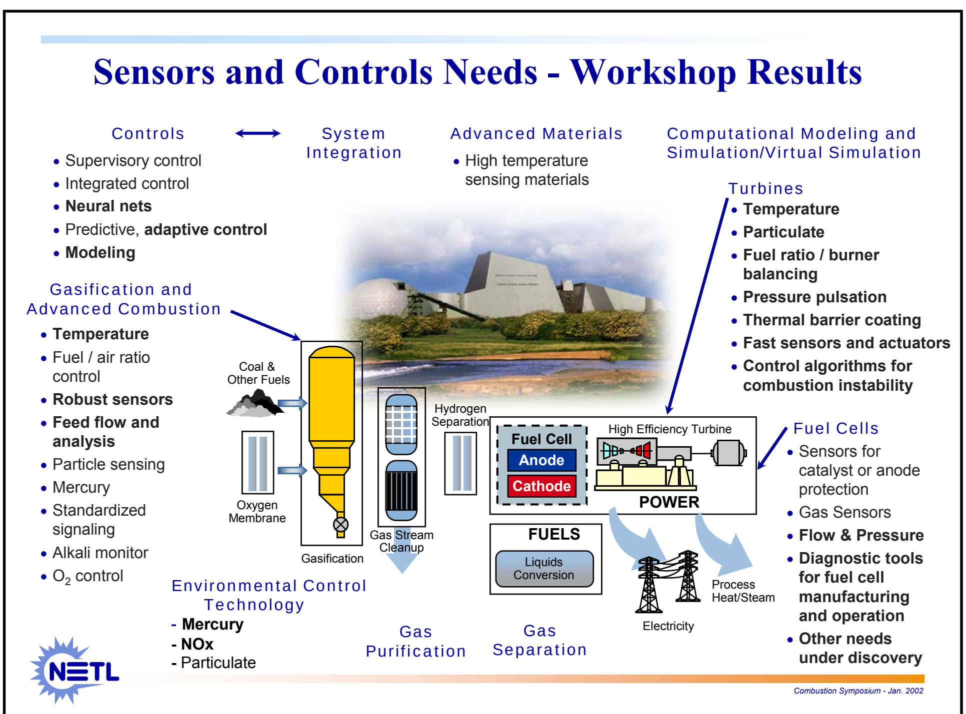
Sensors and Controls Needs - Workshop Results
Controls
• Supervisory control
• Integrated control
• Neural nets
• Predictive, adaptive control
• Modeling
System Integration
Advanced Materials
• High temperature sensing materials
Computational Modeling and Simulation/Virtual Simulation
Turbines
• Temperature
• Particulate
• Fuel ratio / burner balancing
• Pressure pulsation
• Thermal barrier coating
• Fast sensors and actuators
• Control algorithms for combustion instability
Gasification and Advanced Combustion
• Temperature
• Fuel / air ratio control
• Robust sensors
• Feed flow and analysis
• Particle sensing
• Mercury
• Standardized signaling
• Alkali monitor
• O_2 control
Coal & Other Fuels
Oxygen Membrane
Gasification
Gas Stream Cleanup
Hydrogen Separation
Fuel Cell
Anode
Cathode
High Efficiency Turbine
POWER
FUELS
Liquids Conversion
Electricity
Process Heat/Steam
Fuel Cells
• Sensors for catalyst or anode protection
• Gas Sensors
• Flow & Pressure
• Diagnostic tools for fuel cell manufacturing and operation
• Other needs under discovery
Environmental Control Technology
- Mercury
- NOx
- Particulate
Gas Purification
Gas Separation
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Instrumentation, Sensors and Control Active Projects

Controls
- Neural Network-based Intelligent Soot blowing (PPII)
- Distributed Power Sources - Control Requirements

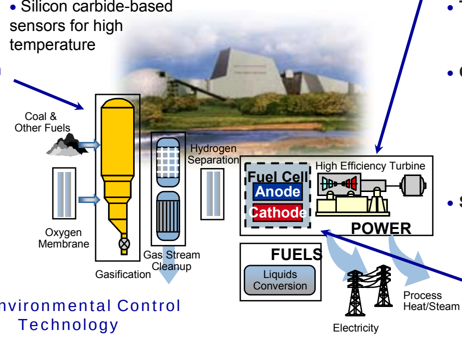
System Integration
- Identify combinations of technology modules (V21)

Computational Modeling and Simulation/Virtual Simulation
- V21 technology module modeling and flow sheet simulation (V21)

Turbines
- **Temperature and Pressure**
  - Embedded thermographic phosphors for temperature and pressure indication
- **Fuel ratio / burner balancing**
- **Thermal barrier coating**
  - Infrared sensor for coating diagnostics
- **Condition Monitoring**
  - Flashback sensor
  - Eddy current sensors and parameter analysis
  - RAM monitoring and control algorithms
- **Smart Power Turbine**
  - NETL, GE, Sandia sensor and control development and integration

Advanced Materials
- Silicon carbide-based sensors for high temperature

Gasification and Advanced Combustion
- Temperature sensors for slagging gasifiers
- Solids Velocity Probe for circulating fluidized beds
- On-line carbon content monitor
- Coal content/Ore grade sensor
- On-line rapid corrosion indicator
- Refractory laser-based contouring technique (PPII)



Environmental Control Technology
- Elemental mercury spectrometer
- Micro gas sensors for NO_X, SO_X, NH_3, H_2S using metal oxides

Gas Separation
- Non-destructive technique to determine candle filter integrity

Fuel Cells
- Micro-valve design for flow control
- Identification of diagnostic tools for fuel cell plate manufacturing

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Vision 21 Technology Roadmap

Goals: Efficiency | Environmental | Cost | Timing

Sensors

- Efficiency / Environmental:
  - Component performance
  - Real time plant performance
  - Equipment health
- Cost:
  - $35/kW
  - Integrated with technology module cost
- Timing:
  - 0-5 year goals
  - 5-10 year goals
  - 10-15 year goals

Barriers

Program & Support
- Fragmented markets
- Treated as add on items

General Technical
- Limited & constrained accessibility
- Harsh operating conditions
- Materials limitations

Approaches

	Program & Support
0-5 Years	• Identify sensor needs and requirements • Extend sensor development program • Assess state-of-the-art sensors and identify gaps
5-10 Years	• Revise priority needs • Demonstrate new sensors technology in operating plants
10-15 Years	• Demonstrate new sensors technology in Vision 21 • Support Vision 21 plant design and operation activities • Assess the payback

	General Technical
0-5 Years	• Focus on in-situ, real time, fast response, field hardened sensors • Develop sensors based on new concepts and technologies
5-10 Years	• Continue supporting development of sensors • Test and incorporate new sensors into advanced control systems
10-15 Years	• Continue supporting development and sensor demonstration projects

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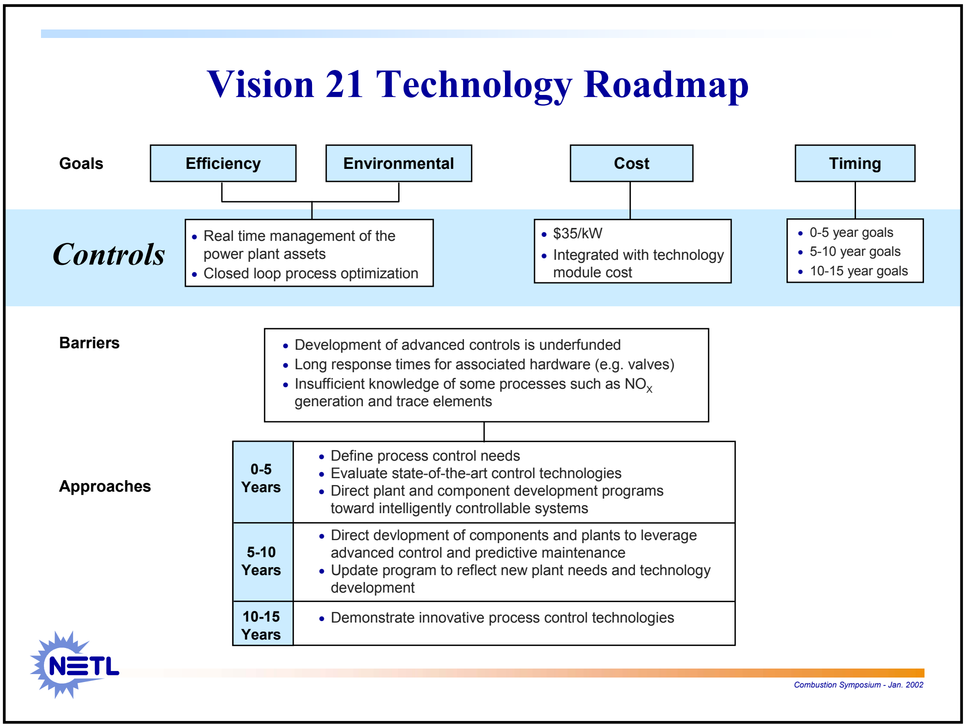
Vision 21 Technology Roadmap
Goals
Efficiency
Environmental
Cost
Timing
Controls
• Real time management of the power plant assets
• Closed loop process optimization
• $35/kW
• Integrated with technology module cost
• 0-5 year goals
• 5-10 year goals
• 10-15 year goals
Barriers
• Development of advanced controls is underfunded
• Long response times for associated hardware (e.g. valves)
• Insufficient knowledge of some processes such as NO_x generation and trace elements
Approaches
0-5 Years
• Define process control needs
• Evaluate state-of-the-art control technologies
• Direct plant and component development programs toward intelligently controllable systems
5-10 Years
• Direct devlopment of components and plants to leverage advanced control and predictive maintenance
• Update program to reflect new plant needs and technology development
10-15 Years
• Demonstrate innovative process control technologies
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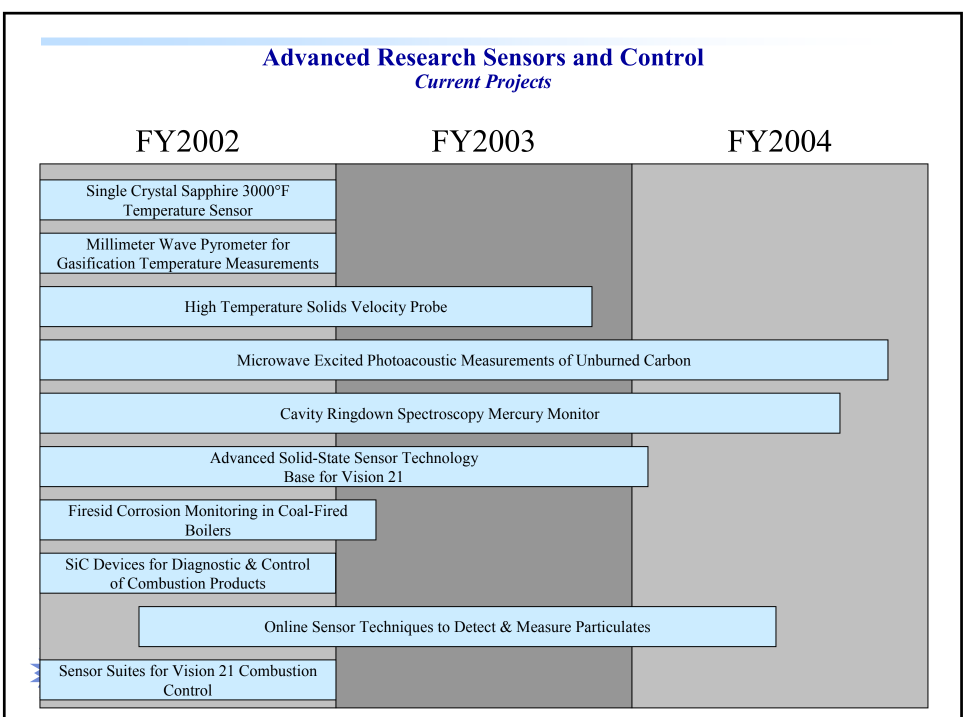
Advanced Research Sensors and Control
Current Projects
FY2002
FY2003
FY2004
Single Crystal Sapphire 3000°F Temperature Sensor
Millimeter Wave Pyrometer for Gasification Temperature Measurements
High Temperature Solids Velocity Probe
Microwave Excited Photoacoustic Measurements of Unburned Carbon
Cavity Ringdown Spectroscopy Mercury Monitor
Advanced Solid-State Sensor Technology Base for Vision 21
Firesid Corrosion Monitoring in Coal-Fired Boilers
SiC Devices for Diagnostic & Control of Combustion Products
Online Sensor Techniques to Detect & Measure Particulates
Sensor Suites for Vision 21 Combustion Control

Advanced Research Sensors and Control

Future Projects

Near-Term	2005	2010
Program Support • Define process control needs • Evaluate state-of-the-art control technologies • Direct plant and component development programs toward intelligently controllable systems	• Direct development of components and plants to leverage advanced control and predictive maintenance • Update program to reflect new plant needs and technology development	• Demonstrate innovative process control technologies
Sensor Development • Identify sensor needs and requirements • Extend sensor development program • Assess state-of-the-art sensors and identify gaps	• Revise priority needs • Demonstrate new sensors technology in operating plants	• Demonstrate new sensors technology in Vision 21 • Support Vision 21 plant design and operation activities • Assess the payback
Control Development • Focus on in-situ, real time, fast response, field hardened sensors • Develop sensors based on new concepts and technologies	• Continue supporting development of sensors • Test and incorporate new sensors into advanced control systems	• Continue supporting development and sensor demonstration projects

Address Product Areas Technology Need and Availability

Gasification and Advanced Combustion
- Temperature
- Fuel / air ratio control
- Robust sensors
- Feed flow and analysis
- Particle sensing
- Mercury
- Standardized signaling
- Alkali monitor
- O_2 control

Turbines
- Temperature
- Particulate
- Fuel ratio / burner balancing
- Pressure pulsation
- Thermal barrier coating
- Fast sensors and actuators
- Control algorithms for combustion instability

Fuel Cells
- Sensors for catalyst or anode protection
- Gas Sensors:
- Flow
- Diagnostic tools for fuel cell manufacturing and operation
- Other needs under discovery

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Other Activities

- **Collaboration and Communication**
  - ISA, EPRI, PIWG
  - National Laboratories, Government Agencies
  - Users and vendors
- **NETL Sponsored Workshop in FY02**
  - Program review & roadmapping
- **Issue Program Plan in FY02**
- **Innovation and Implementation**
  - Seek out new or novel adaptations through focused, industry driven, and time-phased program and project portfolio
  - Strive towards implementation
  - FY03 and FY04 Solicitations

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Future Activities

Collaboration

Communication

Implementation

Solicitation

Innovation

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Conclusion

- Opportunity for improvement and innovation
  - Instrumentation improvement,
  - Sensor development, and
  - New control methodologies
  - Whole system approach
- Technology to overcome barriers
  - Materials, interferences, sampling
- Focused, industry driven, time phased programs
- Internal and external research drives programs

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Power Systems Advanced Research
Future Direction

Advanced Sensors and Instrumentation Research

Advanced Materials Research

Nanotechnology

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Additional Program Information

- **Susan Maley**
  IS&C Project Manager
  NETL
  304-285-1321

- **Robert Romanosky**
  Advanced Research Product Manager
  NETL
  304-285-4721

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2.2 NANOSCIENCE – THE EXPANDING BOUNDARIES OF A SHRINKING WORLD

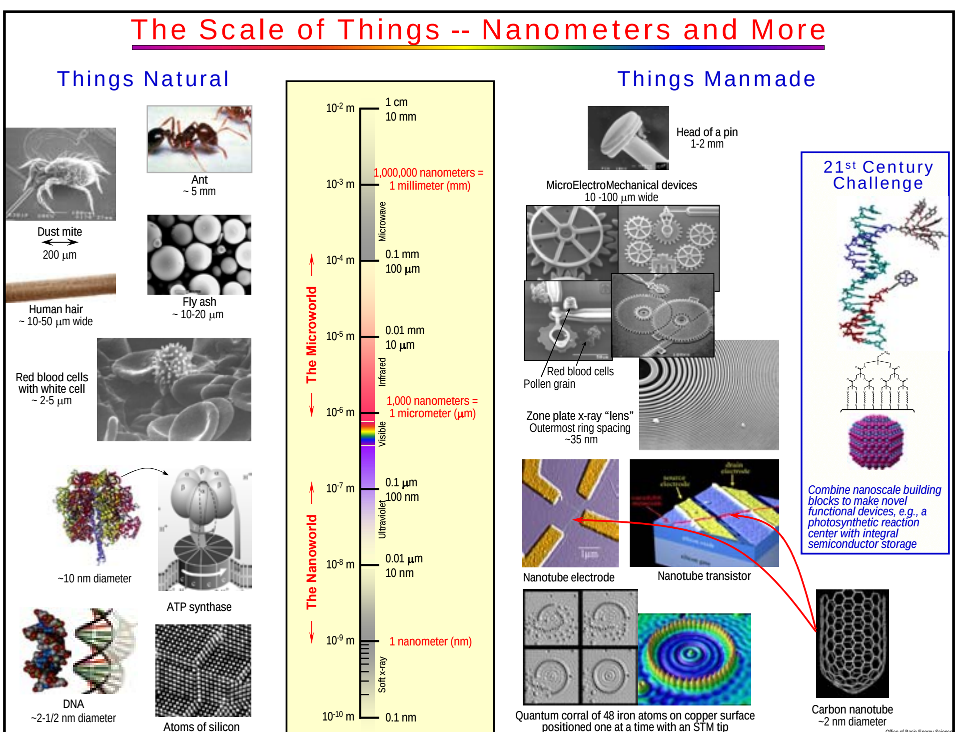
John C. Miller
Division of Chemical Sciences, Geosciences and Biosciences
Office of Basic Energy Sciences
U.S. Department of Energy

BASIC ENERGY SCIENCES -- Serving the Present, Shaping the Future

Basic Research Perspective
Nanoscience
The Expanding Boundaries of a Shrinking World

John C. Miller
Division of Chemical Sciences, Geosciences and Biosciences
Office of Basic Energy Sciences

October 15, 2002



Nanoscience and Nanotechnology

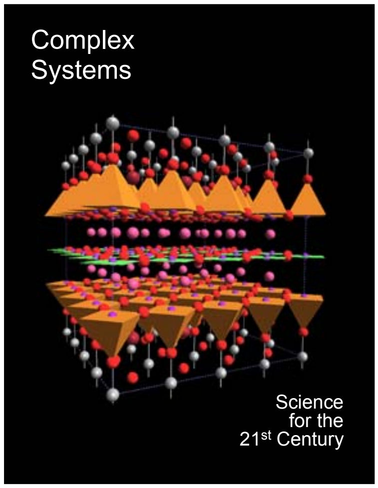
- The nanoscale is not just another step towards miniaturization. It is a qualitatively new scale where materials properties, such as melting point or electrical conductivity, differ significantly from the same properties in the bulk.
  - "Nanoscience" seeks to understand these new properties.
  - "Nanotechnology" seeks to develop materials and structures that exhibit novel and significantly improved physical, chemical, and tribiological properties and functions due to their nanoscale size.
- The goals of nanoscience and nanotechnology are:
  - to understand and predict the properties of materials at the nanoscale
  - to "manufacture" nanoscale components from the bottom up
  - to integrate nanoscale components into macroscopic scale objects and devices for real-world uses

The National Nanotechnology Initiative

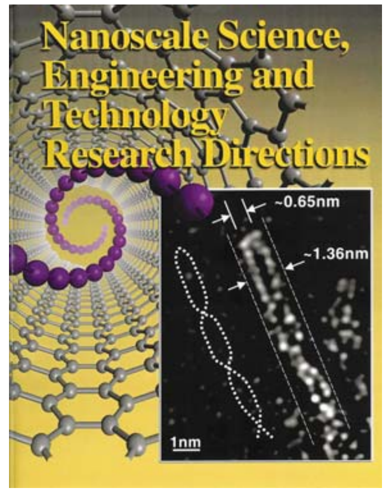
Addressing both scientific frontiers and national needs

Sep 1998	The Interagency Working Group on Nanoscience, Engineering, and Technology (IWGNSET) formed by the NSTC. The IWG meets monthly. Participating agencies: NSF, DOE, DOD, NIH, NASA, DOC/NIST and later also CIA, DOJ, DOS, DOT, DOTreas, EPA, NRC, USDA
Aug 1999	The IWG releases National Nanotechnology Initiative (NNI) report after extensive input from the scientific community
Aug-Nov 1999	BES reports *Complex Systems: Science for the 21st Century* *http://www.sc.doe.gov/production/bes/complexsystems.htm* *Nanoscale Science, Engineering and Technology Research Directions* *http://www.sc.doe.gov/production/bes/nanoscale.html*
Sep-Oct 1999	The six principal agencies brief OMB and a PCAST panel charged to the review the proposed NNI
Feb 2000	The NNI is initiated as part of the FY 2001 budget request
Fall 2001-Spring 2002	National Academy of Sciences reviews the NNI activities

BES Reports



http://www.sc.doe.gov/production/bes/complexsystems.htm



http://www.sc.doe.gov/production/bes/nanoscale.html

NNI FY 2003 Funding Requests

DOE is one of the three lead agencies

National Nanotechnology Initiative

(NNI Coordination Office compilation, as of 1/18/02)

FY 2003
(Dollars in millions)

NSF	221.0
DOD	201.0
DOE*	139.3 + up to $15M in FY02
All other agencies	117.4
TOTAL NNI	678.7

* Excludes funding for synchrotron light source and neutron scattering facility operations and beamlines

National Nanotechnology Initiative Focus Areas

(▪ BES activities shown in bullets)

- Long-term, fundamental nanoscience and engineering research
  - *FY 2001: BES awarded $26.5M in new NNI funds based on peer review -- 76 university grants ($16.1M) and 12 laboratory awards ($10.4M)*
  - *FY 2002: BES may award up to $15M based on peer review*
- Centers and networks of excellence
  - *BES Nanoscale Science Research Centers – the DOE "flagship" NNI activity*
- Research infrastructure
  - *BES supports the synchrotron light sources, neutron scattering facilities, and other specialized facilities in support of nanoscale science*
- Grand challenge areas
  - *1. Nanostructured materials "by design" – stronger, lighter, tougher, harder, self-repairing, and safer*
  - *2. Efficient energy conversion and storage*
  - *3. Nanoelectronics, optoelectronics, and magnetics*
  - *4. National security*
  - *5. Chemical/biological/radiological/explosive (CBRE)detection/protection*
  - *6. Nanoscale processes for environmental improvement*
  - *7. Economical and safe transportation*

  8. Advanced healthcare, therapeutics, and diagnostics

  9. Microcraft space exploration and industrialization
- Ethical, legal, societal implications and workforce education and training
  - *Graduate and postdoc training supported via university grants and lab awards*

Nanoscale Science and Technology …

… in the Bush Administration

Science Based Science Policy

Meeting of the American Association for the Advancement of Science

John Marburger

February 15, 2002

(Excerpts)

The quantum technologies of the chemistry and physics of atoms, molecules, and materials developed rapidly through several generations during the Cold War. By 1991, when the Soviet Union finally dissolved, scientists were beginning to wield instruments that permitted the visualization of relatively large-scale functional structures in terms of their constituent atoms. The importance of this development cannot be over-stated. … The result is an unprecedented ability to design and construct new materials with properties that are not found in nature.

The revolution I am describing is one in which the notion that everything is made of atoms finally becomes operational.

The picture of science I have portrayed -- and I am aware that it is only part of science, but an important part -- has immediate implications and challenges for science policy.

First, there is the need to fund the enabling machinery for exploring the frontier of complexity. Some of this machinery is expensive, such as the great x-ray sources operated by the Department of Energy, or the Spallation Neutron Source. Even the computing power required at the frontier is expensive and not yet widely available to investigators.

Second is the desirability of funding research in the fields that benefit from the atomic level visualization and control of functional matter. They fall into the two categories of organic and inorganic. We call them biotechnology and nanotechnology. I like to think of biotechnology as organic nanotechnology.

Third, there is the very serious problem of the inadequacy of resources to exploit all the new opportunities that now lie before us along the vast frontier of complexity. The need for choice, and for wise allocation of resources to seize the most advantage for society from our leadership in these fields, is a strong motivation for better planning and management of the nation's science enterprise.

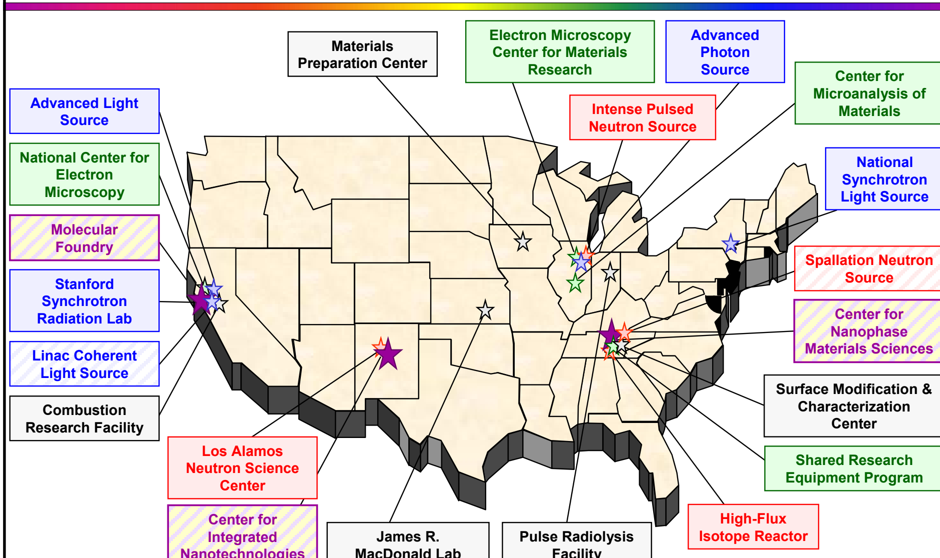
Nanoscale Science Research Centers (NSRCs)

- NSRCs:
  - *Research facilities for synthesis, processing, and fabrication of nanoscale materials*
  - *Co-located with existing user facilities (synchrotron radiation light sources, neutron scattering facilities, other specialized facilities) to provide characterization and analysis capabilities*
  - *Operated as user facilities; available to all researchers; access determined by peer review of proposals*
  - *Provide specialized equipment and support staff not readily available to the research community*
  - *Conceived with broad input from university and industry user communities to define equipment scope*
- NSRCs have been extensively reviewed by external peers and by the Basic Energy Sciences Advisory Committee

NSRC Timeline

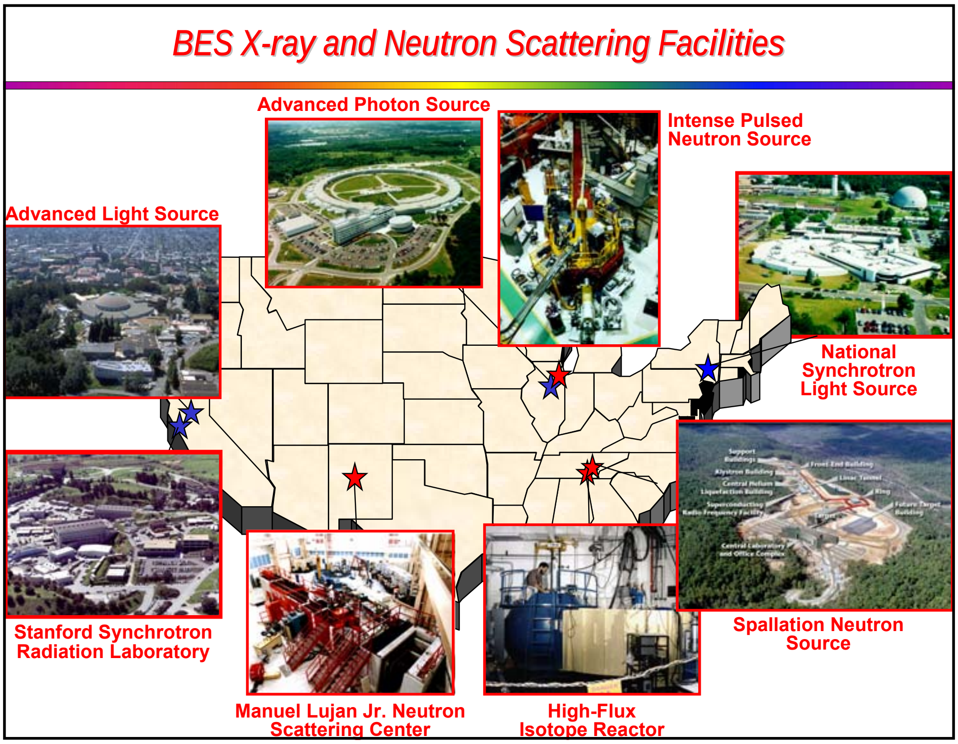
Date	Activity	FY 2000	FY 2001	FY 2002
1999-present	BESAC reviews NSRC concept and develops philosophy for their establishment			
December 2000	Proposals for NSRCs received	ANL, BNL, LBNL ORNL, SNL/LANL write and submit proposals		
April 2001	Mail peer review and panel review of proposals from ANL, BNL, LBNL, ORNL, and SNL/LANL to establish CD0 (Justification of Mission Need)		LBNL, ORNL, SNL/LANL receive CD0 approval (6/13/01)	
December 2001	Lehman review of Conceptual Design Reports (CDR) for LBNL, ORNL, and SNL/LANL using both a cost, schedule, scope, & construction management review team and a scientific review team. Scientific review team considers comments from the April 2001 review and from BESAC.			ORNL CDR approved. PED and construction funding requested for FY 03. CD1 signed (2/22/02), allowing use of PED funds. LBNL and SNL/LANL requested to do additional work before CDR is approved. Based on review, CD1 expected in May 2002, allowing use of PED funds during last quarter of FY 02. PED funding, but no construction funding, requested for FY 03.
February 2002	Mail peer review of resubmitted proposals from ANL and BNL to establish CD0			
April 2002			Lehman re-review of CDRs for LBNL and SNL/LANL using cost, schedule, scope, & construction management review team only	

NSRCs (★) and the BES User Facilities



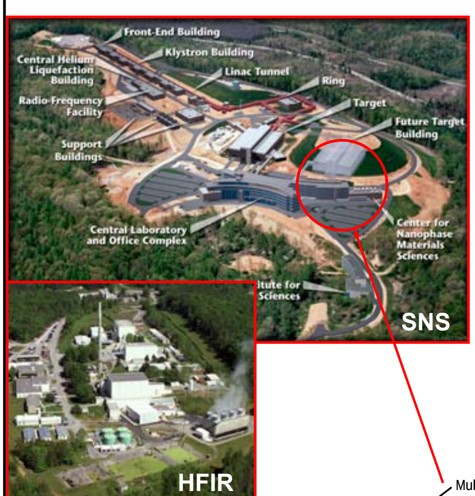
Under construction
In design/engineering
In design/engineering

- *4 Synchrotron Radiation Light Sources*
- *Linac Coherent Light Source (CD0 approved)*
- *4 High-Flux Neutron Sources (SNS under construction)*
- *4 Electron Beam Microcharacterization Centers*
- *5 Special Purpose Centers*
- *3 Nanoscale Science Research Centers (CD0s approved)*



The Center for Nanophase Materials Sciences

Oak Ridge National Laboratory

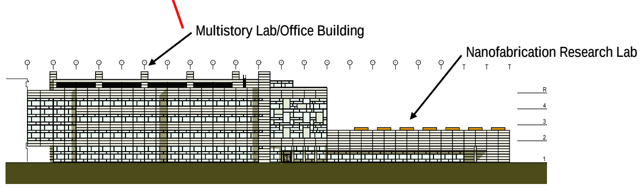


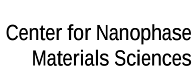
Unique tools and capabilities:

- World's absolute best neutron scattering capabilities are provided by the Spallation Neutron Source and the newly upgraded High-Flux Isotope Reactor

Scientific focus areas:

- Nanoscale materials related to polymers, macromolecular systems, exotic crystals, complex oxides, and other nanostructured materials
- Scientific theory/modeling/simulation, building on the outstanding ORNL materials sciences program





The Molecular Foundry

Lawrence Berkeley National Laboratory

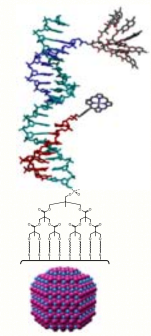
Unique tools and capabilities:

- Advanced Light Source
- National Center for Electron Microscopy
- National Energy Research Scientific Computing Center
- Nationally unique facilities, such as the e-beam nanowriter – nanofabrication facility
- Outstanding faculty and students in multidisciplinary research, including materials science • physics • chemistry • biochemistry • biomolecular materials • engineering

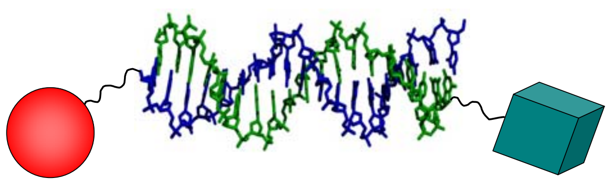
Scientific focus areas:

- Combination of “soft” and “hard” materials/building units
- Multicomponent functional assemblies

21st Century Challenge

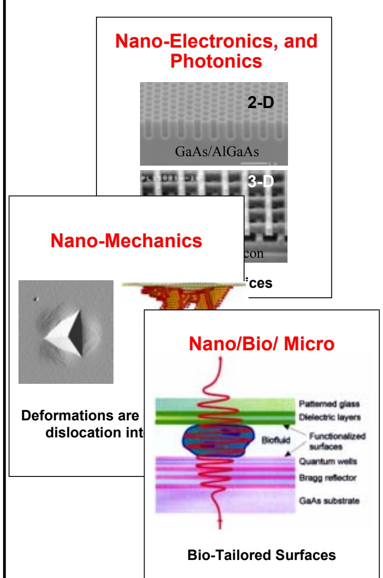


Combine nanoscale building blocks to make functional devices, e.g., a photosynthetic reaction center with integral semiconductor storage



The Center for Integrated Nanotechnologies

Sandia National Laboratories (Albuquerque) and Los Alamos National Laboratory



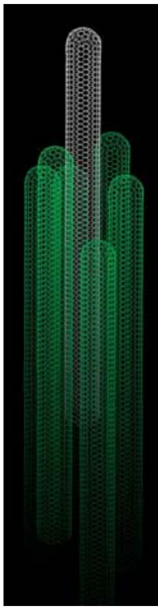
Unique tools and capabilities:

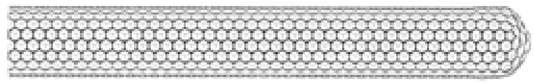
- Compound Semiconductor Laboratory (SNL)
- Microelectronics Development Laboratory (SNL)
- Nano lithography, imaging, and characterization; MEMS (SNL)
- Los Alamos Neutron Science Center (LANL)
- National High Magnetic Field Lab (LANL)
- Computing/theory (LANL)

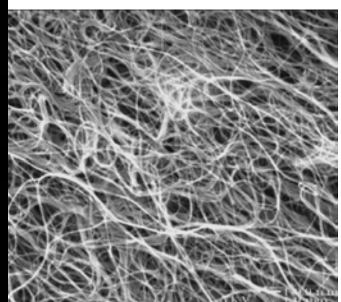
Scientific focus areas:

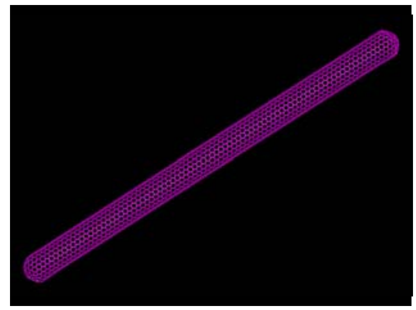
- Nanophotonics and nanoelectronics
  - Electronic, magnetic, and optical phenomena at nanoscale
- Nanomechanics
  - Mechanisms and limits of mechanical deformation
  - Unique mechanical properties occurring at the nanoscale
- Nano-micro interfaces
  - Bridging functional nanoassemblies to micro (and larger) world

Molecular Perfection: The Fullerene Nanotube





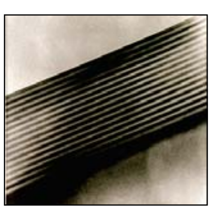




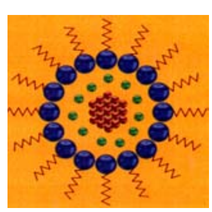
- The strongest fiber that will <u>ever</u> be made
- Electrical conductivity of copper or silicon
- Thermal conductivity of diamond
- The chemistry of carbon
- The size and perfection of DNA
- Can we harness this material?

Materials with Enhanced Functionality via Nanostructuring

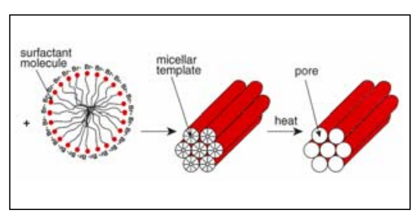
Layered-Structures



Nanocrystals



Nanocomposites



Layered-Structures:
- **Electronics/photonics**
- **Novel Magnets**
- **Tailored hardness**

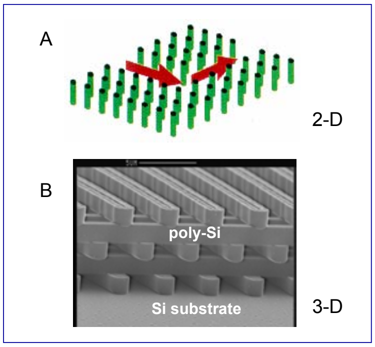
Nanocrystals:
- **Catalysts**
- **Tailorable light emission**
- **Supercapacitors**

Nanocomposites:
- **Separation membranes**
- **Adaptive/responsive behavior**
- **Pollutant/impurity gettering**

Nanoscience enables scientifically tailored materials

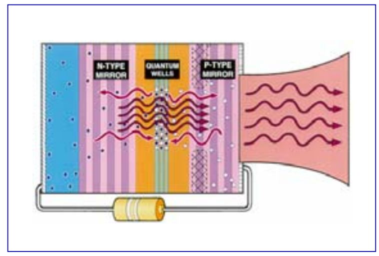
Materials with New Optical Properties via Nanostructuring

Photonic Lattices



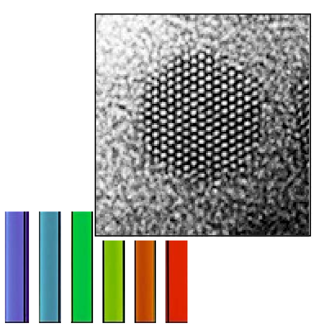
- **Optical signals guided through narrow channels and around sharp corners**
- **Near 100% transmission**
- **Key technology for telecommunications and optical computing**

Vertical Cavity Surface Emitting Lasers (VCSELs)

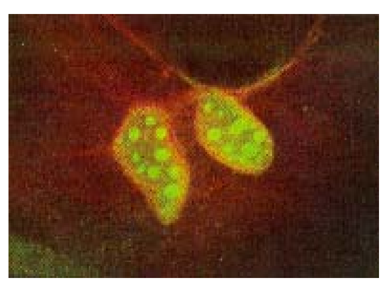


- **The VCSEL is to photonics what the transistor was to electronics. A key 21st century technology**
- **Most efficient, low-power light source (57% in ‘97)**
- **Applications in stockpile stewardship, optical communications, scanners, laser printing, computing...**

The Promise of Addressing Old Problems in New Ways



- Nanocrystals of CdSe fluoresce with different colors depending only on their size
- Different sized crystals can be selectively bound to different parts of a cell or to any desired structure to “light up” the parts

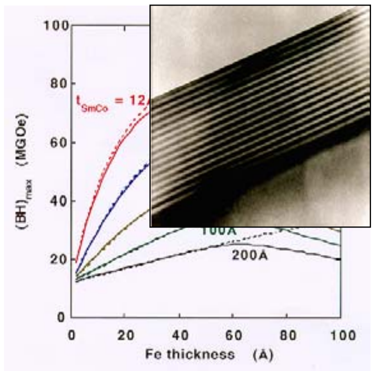


Semiconductor nanocrystals linked to bio-molecules light-up a cell’s actin filaments (red) and nucleus (green)

- Biological labeling
- Molecular processes in cells

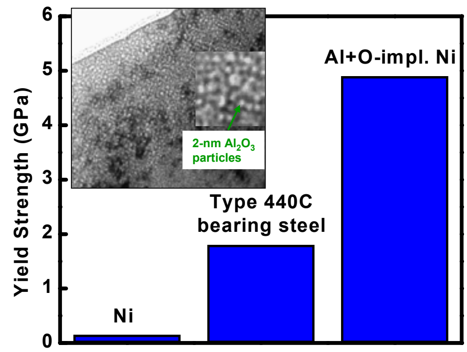
Materials for Improved Energy Efficiency and Performance

Exchange-Spring Magnets
SmCo/Fe



- Tailorable magnetic properties
- Lighter, stronger magnets
- More efficient motors

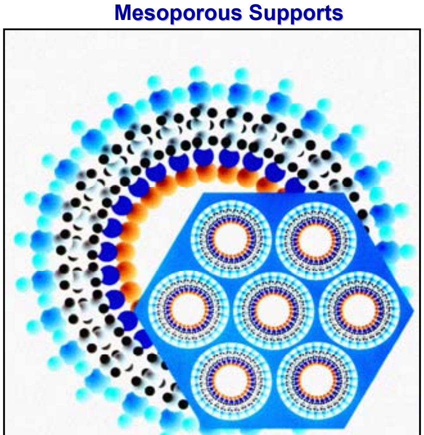
Ion-Implantation Metallurgy
Al+O Implanted Ni



- Superior strength
- Hard thin layers
- Greatly reduced friction & wear

3-D Self-Assembled Materials via Nanostructuring

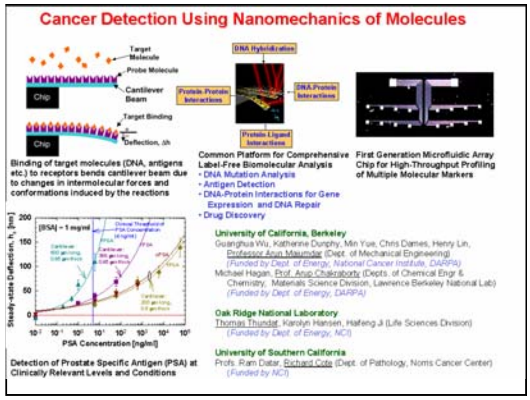
Self-Assembled Monolayers on Mesoporous Supports



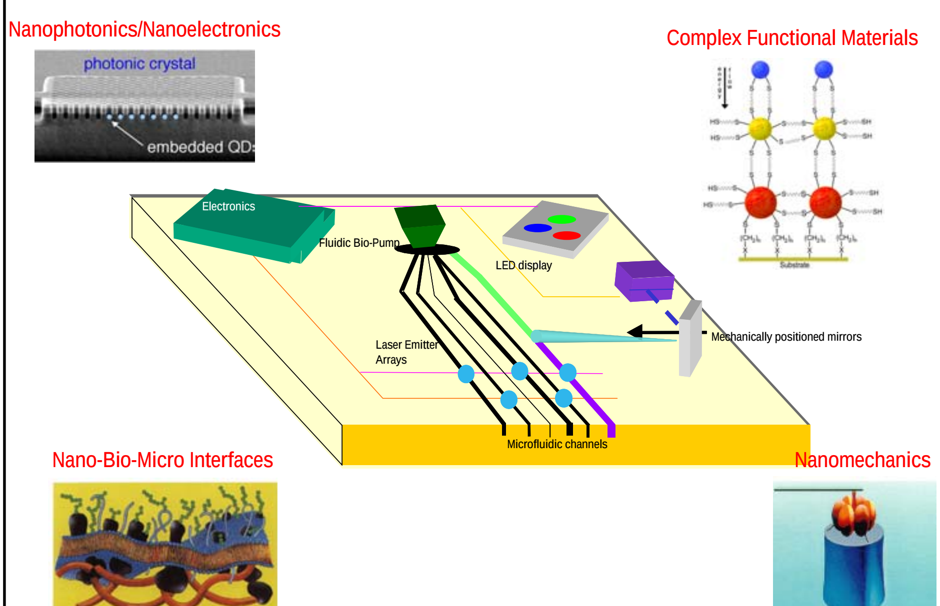
55 nm pore diameter, 900 m^2/gm surface area

- Chemically selective surfactant molecules self-assemble within the interstices of a mesoporous silica matrix derived through solution processing routes.
- Resulting material shows high adsorption capacity for mercury and other heavy metals.
- Numerous environmental and commercial applications.

Cancer Detecting Microchip



Ultimate "Lab on a Chip"



DOE Missions and Nanoscience/Nanotechnology Activities

- Science
  - Fundamental understanding of materials at the nanoscale, ultimately to create materials with novel properties and functions in support of other DOE missions.
- National security
  - NNSA has a strong interest in nanoscale S&T, which led DP and BES to establish the "Nanoscience Network" to jointly fund research at NNSA and SC laboratories. Three topics were selected for support based on joint peer review for scientific quality and relevance: nanoscale tribology and micromechanics; tailored nanostructures; and nanostructural photonics.
  - One of three BES Nanoscale Science Research Centers is the Center for Integrated Nanotechnologies, which is jointly administered by LANL and SNL.
  - BES funds nanoscale science research programs at LANL and SNL in nanoscale electronic materials.

DOE Missions and Nanoscience/Nanotechnology Activities

- Homeland defense
  - BES Workshop on Basic Research Needs to Counter Terrorism (2/28-3/1/02) focused on chemical, biological, nuclear, and radiological threats identified research needs.
  - A recurring theme was better detection.
  - Research needed to improve sensors for detection is at the nanoscale, including "single" molecule detection of explosives and chemical agents, specific virus or other biological agent detection, laboratories on a chip, and more portable and sensitive radiological detectors.
  - Other nanoscale areas of research included catalysts for decontamination, membranes for separations, and nanostructured materials as absorbers and reactive filters.
- Cleanup
  - Molecular sieves and filters for improved separations
  - Nanostructured materials for selective sequestration of specific contaminants

DOE Missions and Nanoscience/Nanotechnology Activities

- Energy security
  - Fossil energy
    - *Materials that perform well under the extreme conditions of temperature and pressure in energy production*
    - *Nanostructured catalysts for cheaper, cleaner, more environmentally friendly petroleum refining and product manufacturing*
  - Energy efficiency
    - *Strong, tough, ductile, lightweight, and low-failure-rate materials for improved fuel efficiency in ground and air transportation*
    - *Low-loss, high-performance magnets for more efficient motors*
    - *Self-assembling nanostructures for near-net-shape materials forming*
    - *Surface tailoring for reduced friction and improved wear*
    - *Hardened alloys and ceramics for cutting tools*
    - *Nanofluids with increased thermal efficiency for improved heat exchangers*
    - *Layered structures for highly efficient, low-power light sources and photovoltaic cells*
    - *Smart materials such as paints that change color with temperature and windows that respond to thermal inputs*
    - *Nanostructured catalysts for fuel cells and batteries*
  - Renewable energy
    - *Light harvesting and energy storage systems*
    - *Nanostructured materials for hydrogen storage*
  - Nuclear energy
    - *Radiation tolerant materials*
    - *Nanostructures that selectively bind and concentrate radionucleotides, thereby lowering waste disposal costs*

BES NNI Research Areas

Experimental Condensed Matter Physics
- **Structure and cooperative interactions of nanostructured materials**
- **Optical, electronic and magnetic properties of nanostructures, including quantum dots, nanoscale particulate assemblies and lithographically-produced nanoarrays**

Theoretical Condensed Matter Physics
- **Optical properties and confinement effects of quantum dots and arrays of quantum dots**
- **Fundamentals of charge, spin, and thermal transport in nanostructures (with leads), including nanowires, quantum dots and quantum dot arrays**

Structure and Composition of Materials
- **Characterization and modeling including high-resolution electron, neutron and photon based techniques; nanoscale structures and their evolution - hetero-interfaces, grain boundaries, precipitates, dopants and magic- and nano-clusters; development of experimental characterization tools to understand, predict, and control nanoscale phenomena**

Physical Behavior of Materials
- **Response of nanostructured materials to external stimuli such as temperature, electromagnetic fields, concentration gradients, and the proximity of surfaces or interfaces; electronic effects at interfaces, magnetism of nanoscale particles, local chemical and transport processes, and phase transformations**

Mechanical Behavior of Materials
- **Mechanical behavior of nanostructured composite materials; radiation induced defect cascades and amorphization; theoretical and computational models linking nanoscale structure to macro-scale behavior**

Synthesis and Processing
- **Synthesis mechanisms that control nanostructure and behavior of nanostructured materials; self-assembly of alloys, ceramics and composites; process science of nanostructured materials for enhanced behavior including thin film architectures, nanostructured toughening of ceramics, and dopant profile manipulation**

Materials Chemistry
- **Organic and polymeric nanoscale systems: synthesis, modeling, characterization and function**
- **Functionalized nanostructures and nanotubes, polymeric and organic spintronics, protein nanotube-based electronic materials and other biomolecular materials, organic-inorganic arrays and nanocomposites, organic neutral radical conductors**

Catalysis and Chemical Transformations
- **Reactivity of nanoscale metal and metal oxide particles and development of tools to characterize and manipulate such properties**
- **Chemical reactivity with nanoscale organic-inorganic hybrids**

Chemical Separations and Analysis
- **Electric field enhancement at nanoscale surfaces and probes for surface-enhanced Raman spectroscopy and near-field microscopy; fundamental physics and chemistry in laser-material interactions to support chemical analysis; nanoscale self-assembly and templating for ultimate application in ion recognition and metal sequestration**

Photochemistry
- **Fundamentals of electron transfer at interfaces between nanoscale materials and molecular connectors**

Materials Engineering
- **System performance across different length scale in the areas of energy conversion and transport (thermal, mechanical, electrical, optical, and chemical); sensing; information processing and storage; diagnostics and instrumentation**

Chemical Engineering
- **Effect of nanostructure on phase behavior under extreme conditions to electrochemical behavior and self assembly**
- **Synthetic pathways to form nanostructured materials from functionalized molecular building blocks**

2.3 CHEMICAL SENSORS BASED ON CARBON NANOTUBES

John Cummings
Nanomix, Inc.

(Presentation not available)

Nanomix, Inc. is a small nanotechnology firm in Emeryville, California. John Cummings, a Nanomix researcher, presented a review of the company's capabilities and work in nano-materials, specifically the design and synthesis of nanotube-based devices. The company core competencies are in three primary areas: the computational design of novel materials, the development and refinement of synthesis methods for nanomaterials, and working with product development to demonstrate applications of the novel materials.

The company is targeting two major areas for commercial applications, innovative nano-scale chemical sensors and hydrogen storage devices. The sensors would have applications in medical monitoring and diagnostics, environmental monitoring, and industrial and energy process controls. For a hydrogen economy to be a reality, safe, low-cost hydrogen storage technology is needed, and nanotube-based devices are an innovative option.

Nanomix's work with nanotubes and related structures capitalizes on both their inherent strength and their sensitivity to environmental factors. Functionalizing these structures can provide sensing capabilities, and structural manipulation such as multi-wall nanotubes can provide valuable mechanical properties. Through a combination of computational screening of candidate solutions and advanced synthesis methods, the company expects to produce both near-term and longer-term results.

2.4 Recent Developments in Sensors and Micro Analytical Systems

Ron Manginell
Principal Member of the Technical Staff
MicroAnalytical Systems Department
Sandia National Laboratories

Recent Developments in Sensors and Micro Analytical Systems

Ron Manginell
Principal Member of the Technical Staff

Sandia National Labs
MicroAnalytical Systems Dept.

Sandia National Laboratories

Outline

- National Security Threats
- NS and Industrial/Commercial Opportunities
- Microsensor Strategy
- Integrated Sensors
- Microanalytical Systems
- Microchemlab
- Conclusions

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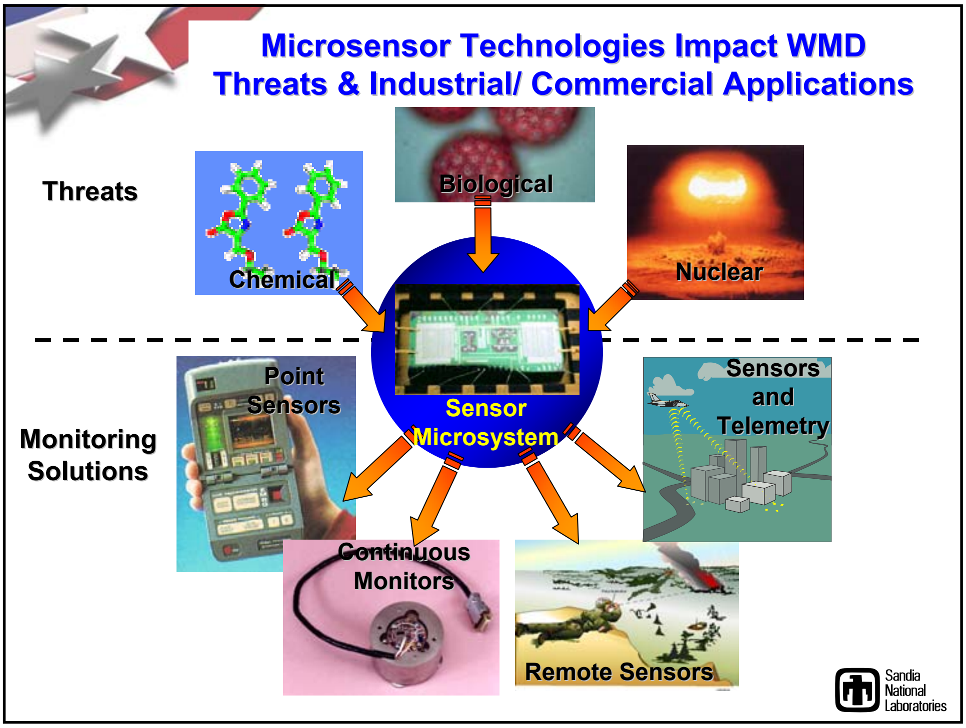
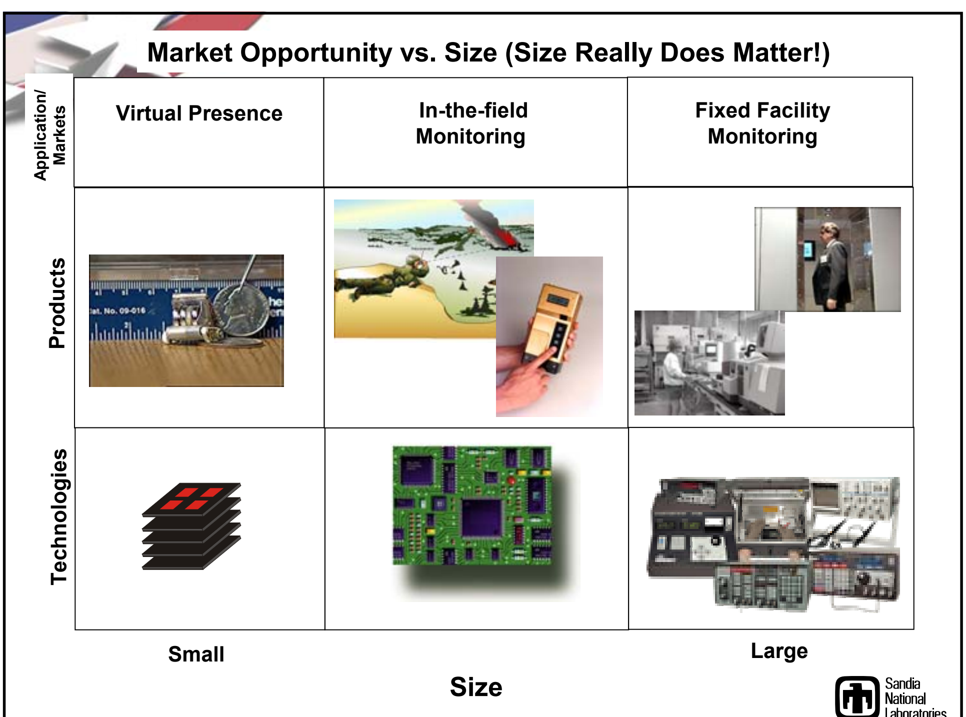
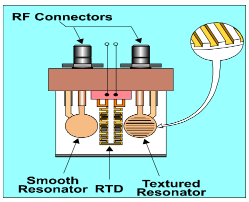

Microsensor Technologies Impact WMD
Threats & Industrial/ Commercial Applications
Threats
Chemical
Biological
Nuclear
Sensor
Microsystem
Monitoring
Solutions
Point
Sensors
Sensors
and
Telemetry
Continuous
Monitors
Remote Sensors
Sandia
National
Laboratories

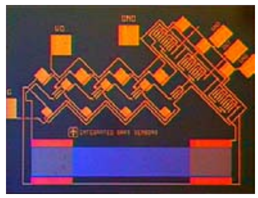

Market Opportunity vs. Size (Size Really Does Matter!)
Application/
Markets
Virtual Presence
In-the-field
Monitoring
Fixed Facility
Monitoring
Products
Technologies
Small
Large
Size
Sandia
National
Laboratories

Microsensor Strategy

Apply state of the art microfabrication techniques to realize new microsensor systems.

Discrete Sensors → **Integrated Sensors** → **Micro Analytical Systems**





- Quartz fluid monitor for CBM
- SAW gas sensor
- Fiber-optic gas sensor
- Fringe-field sensor

- Chemiresistor
- Hydrogen sensor
- Radiation dose monitor
- Combustible gas sensor
- FPW sensor
- Integrated SAW sensor
- MASA

- Ion mobility spectrometer
- Polychromator
- Microchemlab

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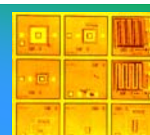
Integrated Sensors

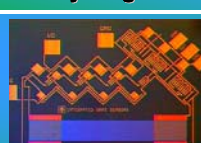
FET-Based

Hydrogen Sensor

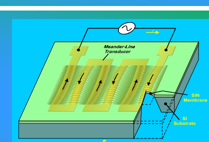


RadFET

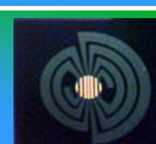
Acoustic-Based



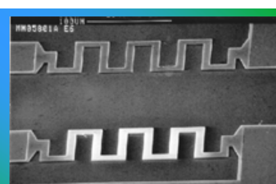
SAW on GaAs



FPW



Transceiver



Catalytic Gas Sensor

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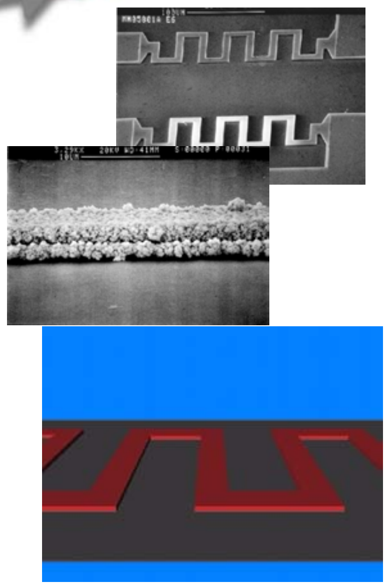
Micromachined Catalytic Gas Sensor



- Suspended poly-Si filament with catalytic Pt coating is heated by current flow
- Combustible gases react with O_2 on filament, releasing heat
- Gas concentration determined from power required to maintain temperature
- CMOS-Integrated electronics

Applications:

- Natural gas BTU monitor
- Catalytic converter monitor

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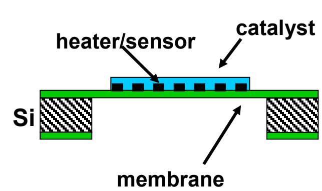
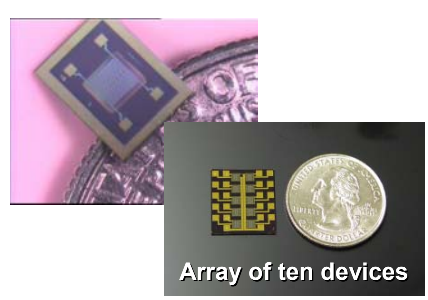
Microhotplate LHV for Real-Time Fuel Content Measurement

Microhotplate LHV Concept:

- Catalyst placed on its surface
- Heat generated by *catalytic* combustion is compared with a reference element – direct measurement of energy content
- Constant temperature control circuit – measure power
- Arrays for speciation
- Real-time for efficiency and cost improvements
- NG for now; SynGas in RAM





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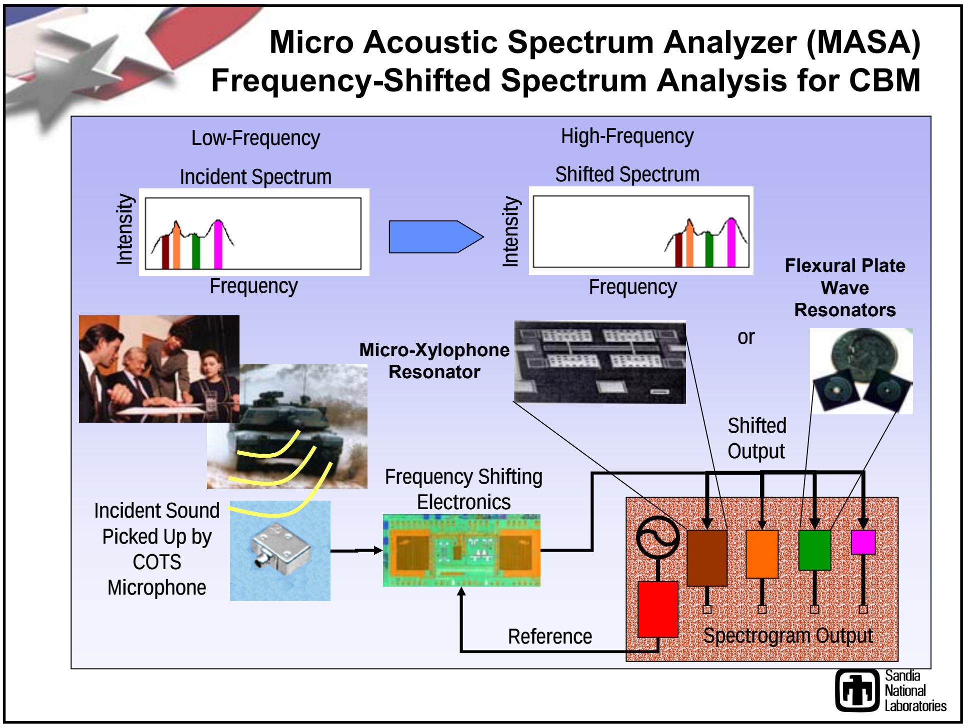
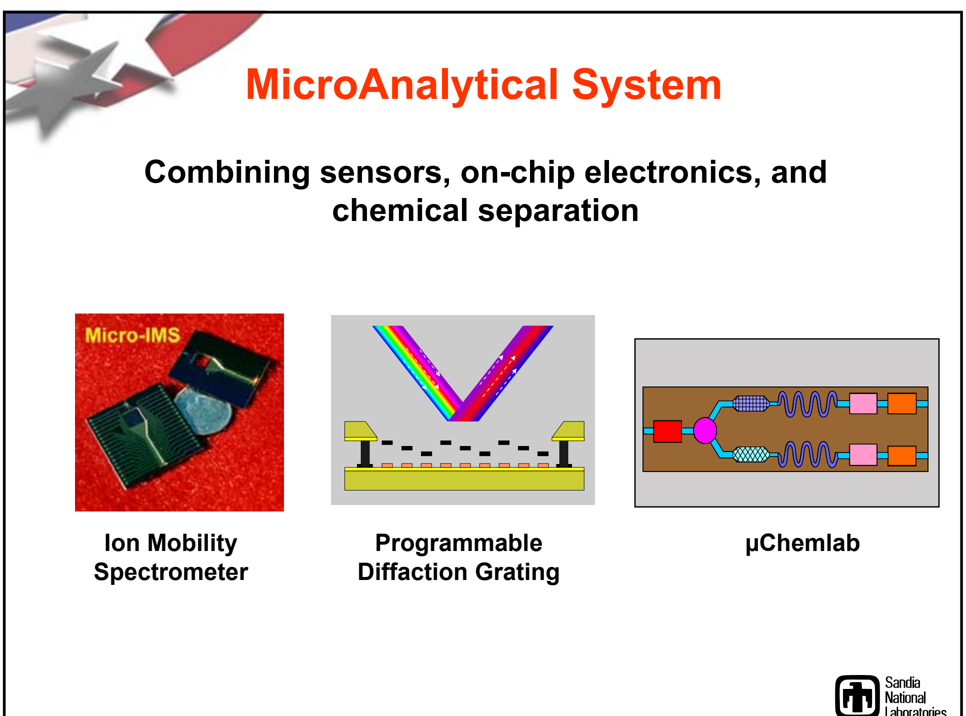
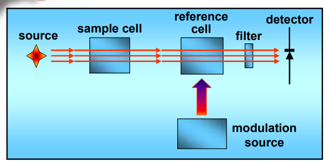
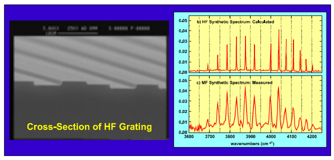
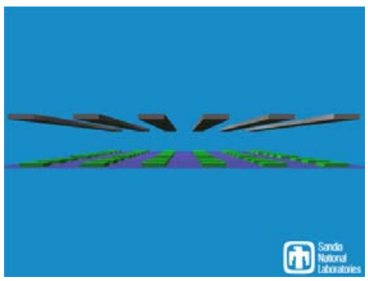

Micro Acoustic Spectrum Analyzer (MASA)
Frequency-Shifted Spectrum Analysis for CBM
Low-Frequency
Incident Spectrum
Intensity
Frequency
High-Frequency
Shifted Spectrum
Intensity
Frequency
Flexural Plate
Wave
Resonators
or
Micro-Xylophone
Resonator
Shifted
Output
Frequency Shifting
Electronics
Incident Sound
Picked Up by
COTS
Microphone
Reference
Spectrogram Output
Sandia
National
Laboratories


MicroAnalytical System
Combining sensors, on-chip electronics, and
chemical separation
Micro-IMS
Ion Mobility
Spectrometer
Programmable
Diffraction Grating
µChemlab
Sandia
National
Laboratories

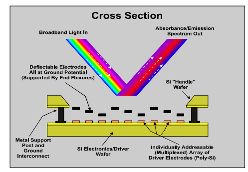
Micromachined Diffraction Grating







- Optical correlation spectrometer identifies spectral components
- Reference spectrum generated by an aperiodic diffraction grating
- Generate arbitrary reference spectra using electrically adjustable diffractors



Applications:

- Chemical plume analysis, effluent monitoring (DARPA)

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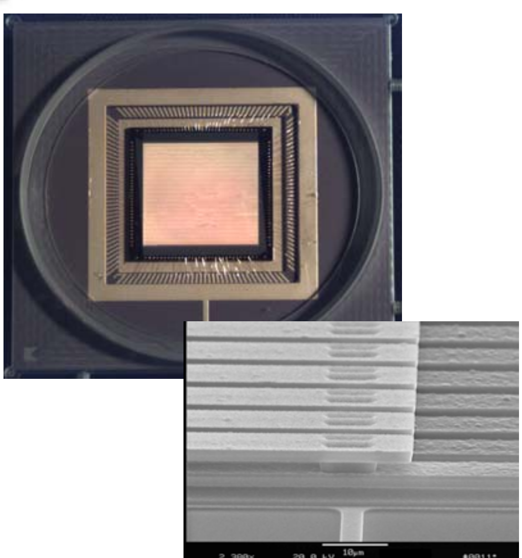
1024-Element Polychromator Grating



- 1024Grating Elements
- Element Dimensions 10 μm x 1cm
- Vertical Travel 2 μm
- 3-5 μm Spectral Range
- Device Dimensions 1cm x 1cm
- 128 Independent Actuating Voltages

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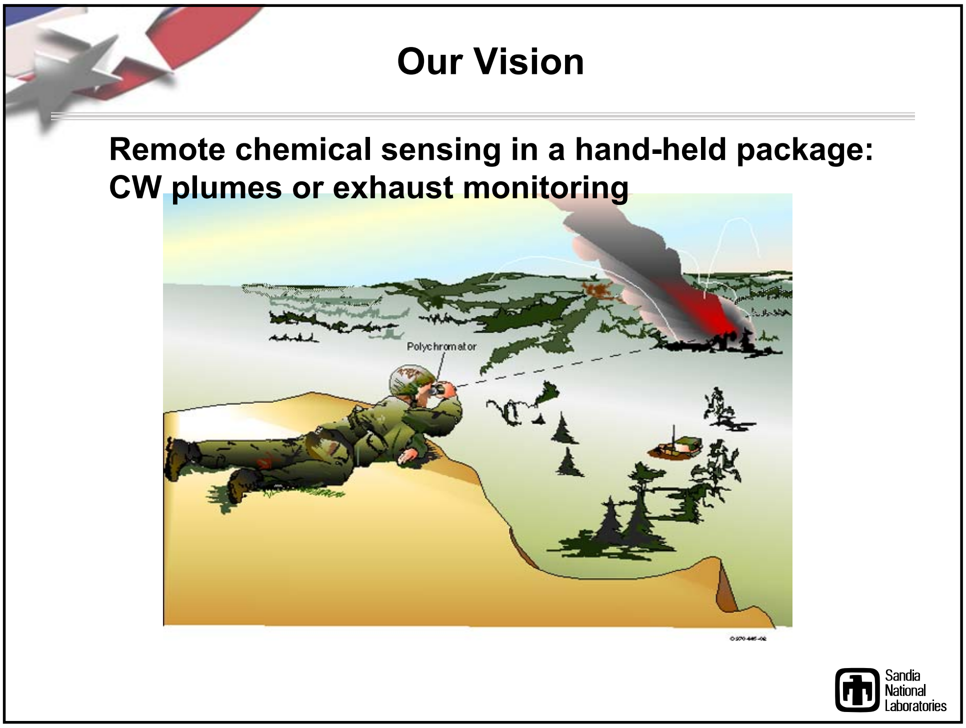
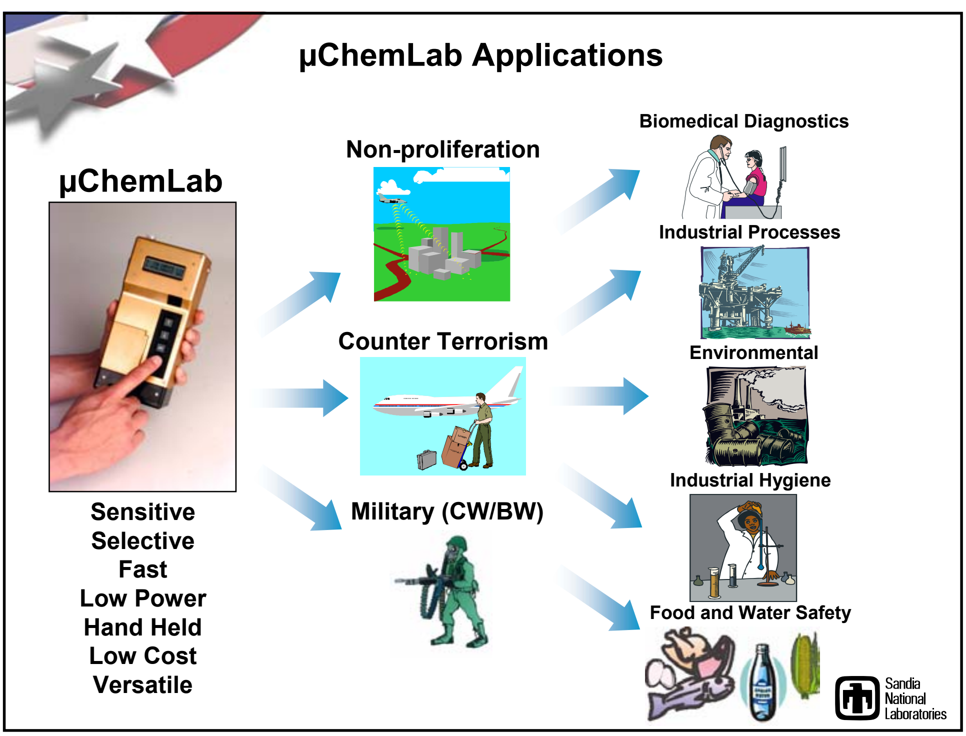
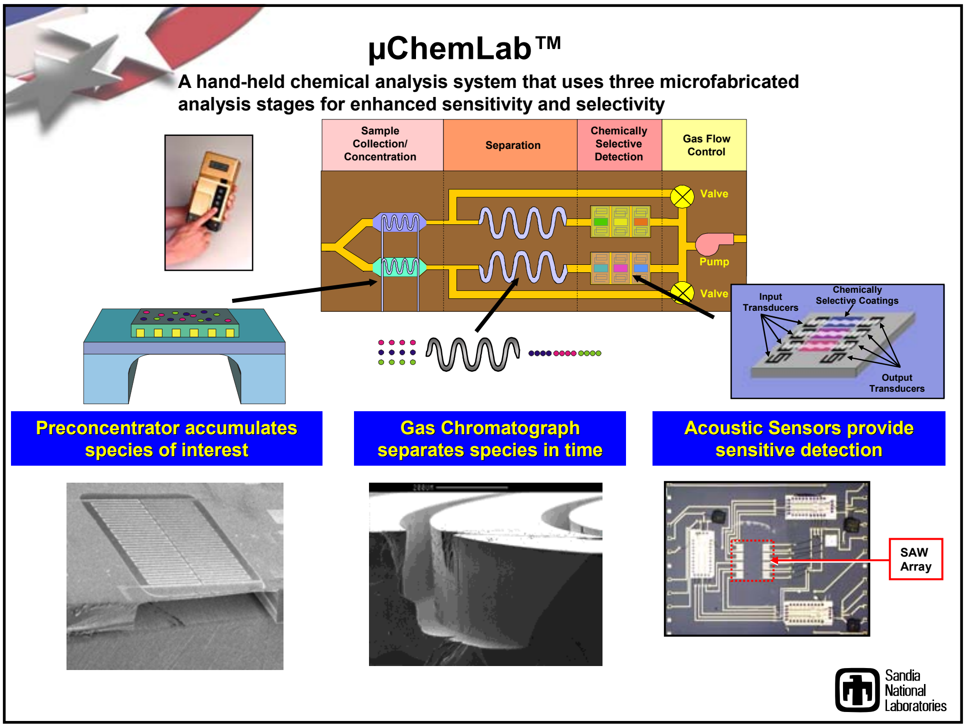
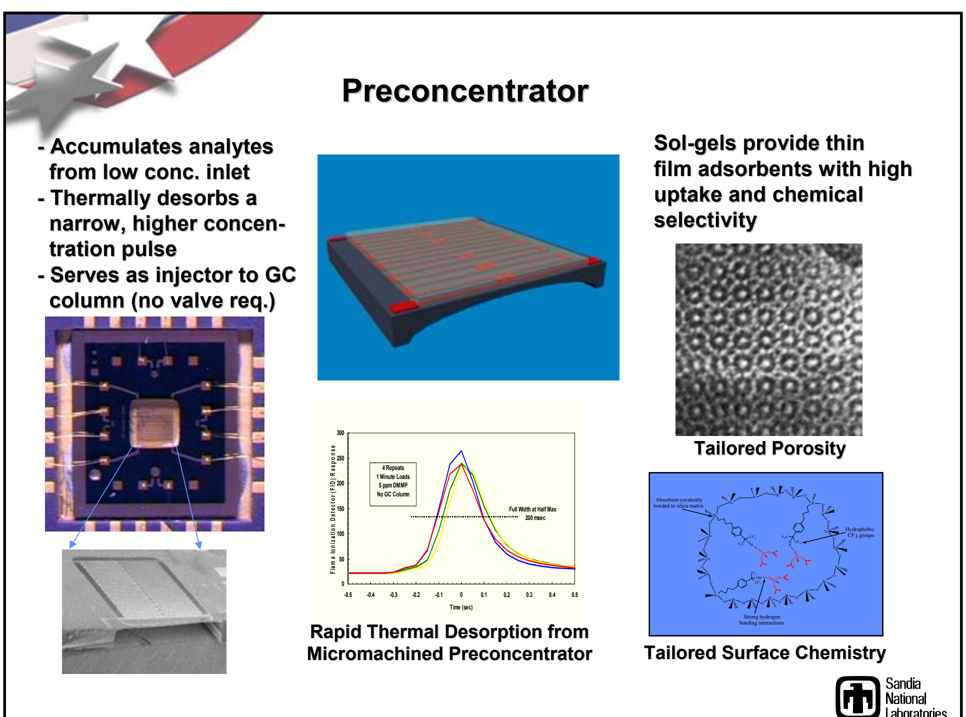
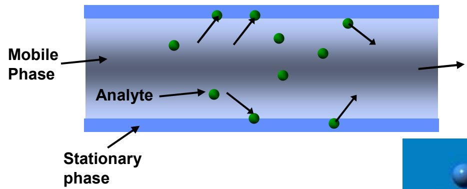

Our Vision
Remote chemical sensing in a hand-held package:
CW plumes or exhaust monitoring
Polychromator
Sandia National Laboratories


µChemLab Applications
µChemLab
Sensitive
Selective
Fast
Low Power
Hand Held
Low Cost
Versatile
Non-proliferation
Counter Terrorism
Military (CW/BW)
Biomedical Diagnostics
Industrial Processes
Environmental
Industrial Hygiene
Food and Water Safety
Sandia National Laboratories


µChemLab™
A hand-held chemical analysis system that uses three microfabricated analysis stages for enhanced sensitivity and selectivity
Sample Collection/ Concentration
Separation
Chemically Selective Detection
Gas Flow Control
Valve
Pump
Valve
Input Transducers
Chemically Selective Coatings
Output Transducers
Preconcentrator accumulates species of interest
Gas Chromatograph separates species in time
Acoustic Sensors provide sensitive detection
SAW Array
Sandia National Laboratories


Preconcentrator
- Accumulates analytes from low conc. inlet
- Thermally desorbs a narrow, higher concentration pulse
- Serves as injector to GC column (no valve req.)
Sol-gels provide thin film adsorbents with high uptake and chemical selectivity
Tailored Porosity
Full Width at Half Max 200 msec
Time (sec)
Rapid Thermal Desorption from Micromachined Preconcentrator
Tailored Surface Chemistry
Sandia National Laboratories

Chemical Separation Using the Gas Chromatographic (GC) Column

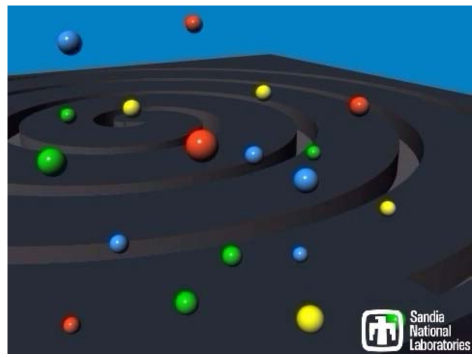


-A mixture of analytes is injected into the column

-A carrier gas (air) carries the mixture thru the column

-Analytes are repeatedly absorbed/desorbed by a coating (stationary phase)

-Different coating/analyte affinities cause separation



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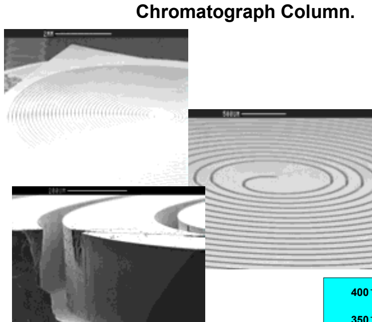
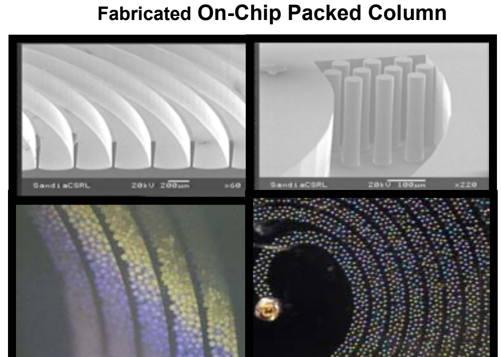
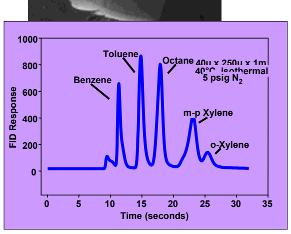
GC Column for Rapid Separations

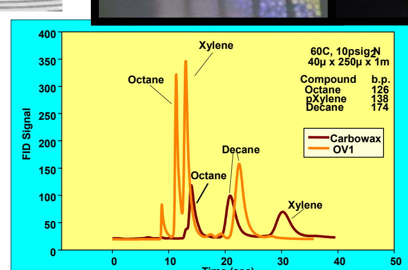
Bosch Deep Reactive Ion Etching Capability used to Fabricate World's Smallest Integrated Gas Chromatograph Column.



Fabricated On-Chip Packed Column







Selectivity Shown for Micromachined GC Column Using Two Different Coatings

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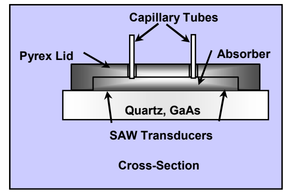
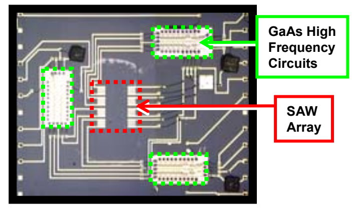
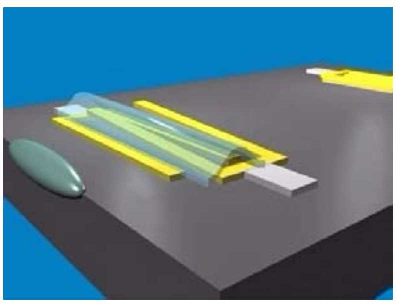
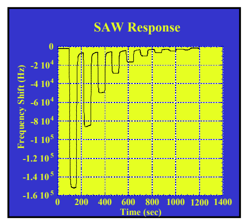
Surface Acoustic Wave (SAW) Detector



- Surface acoustic wave is excited/detected using interdigital transducers on a piezoelectric substrate
- Sensor coating momentarily absorbs analytes eluted from GC column, changing SAW velocity (phase shift).
- Pattern of responses from array augments discrimination of GC separation







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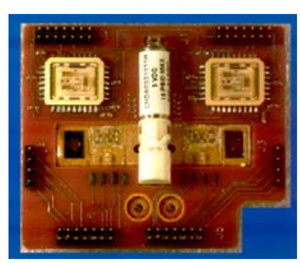
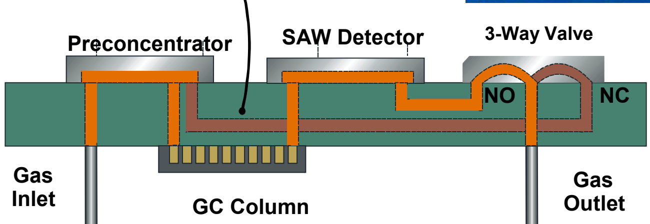
Gas analysis components are integrated on novel electrical/fluidic circuit board

Electrical and fluid connections are made simultaneously.





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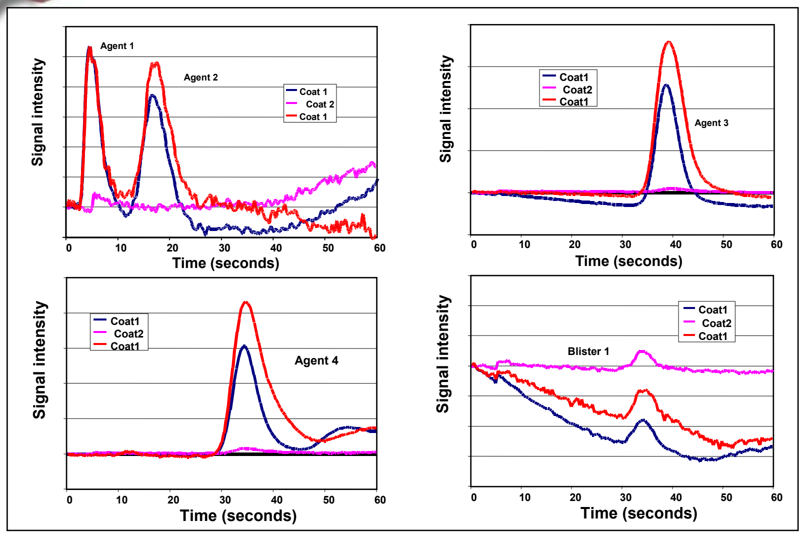
Live Agent Testing of µChemLab



Thanks to Jay Grate of PNNL for Coating 1 Material and to Kwok Ong and the Applied Chemistry Team at Edgewood Chemical and Biological Center for Live Agent Tests

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Field Testing of µChemLab

Detection of Chemical Warfare Simulants In Particulate Laden Environments

Thanks to Kiran Shah at DTRA

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The PROTECT Chem-Bio Demonstration Program

PROTECT: Program for Response Options and Technology Enhancements for Chem-Bio Terrorism

Program to improve infrastructure facility protection

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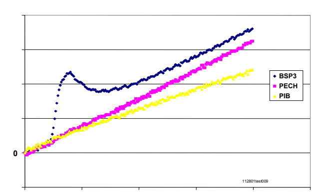
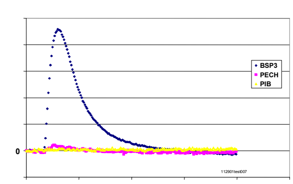
µChemLab PROTECT Prototype

- **Improved temperature control**
- **Durable pumps**
- **Gas chromatograph for false positive reduction**
- **Flexible method development**



PROTECT no Temp Control



PROTECT with Temp Control

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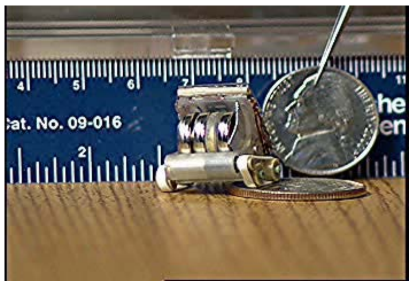
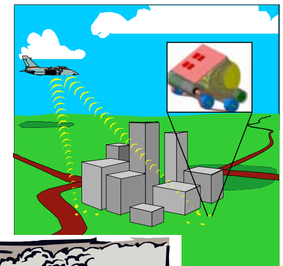
Micro Robot

Operating individually or in cooperative swarms, microrobots could:

- gather intelligence
- detect hazardous chemicals
- inspect critical facilities such as buildings and bridges.





Turns on a dime. Parks on a nickel.

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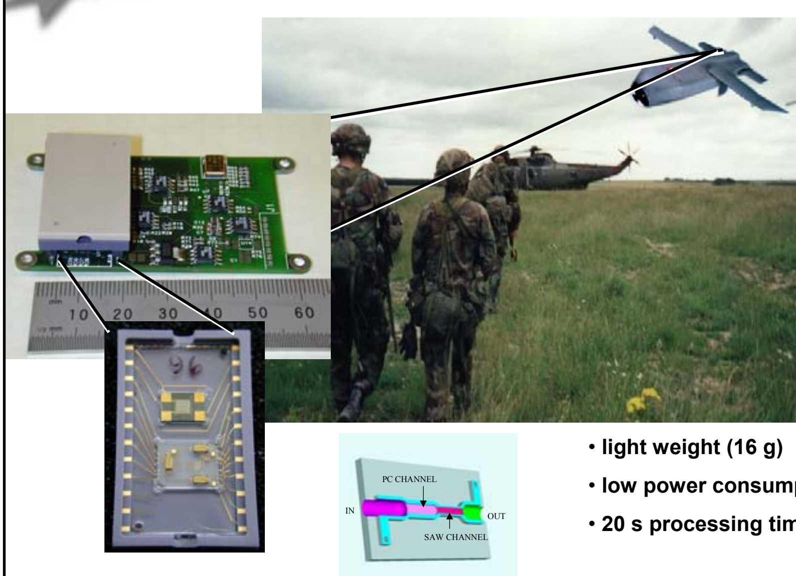
SnifferStar - Chemical Sensor for micro-UAVs



- light weight (16 g)
- low power consumption
- 20 s processing time

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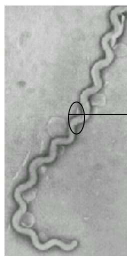
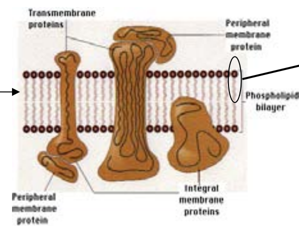
Biological Agent Detection Using µChemLab and µPyrolizer

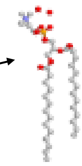
Fatty acids are know biomarkers:
can provide a signature pattern to differentiate bacteria



Bacterium



Cell membrane - lipid bilayer with proteins



A common membrane phospholipid, a diglyceride

A fatty acid

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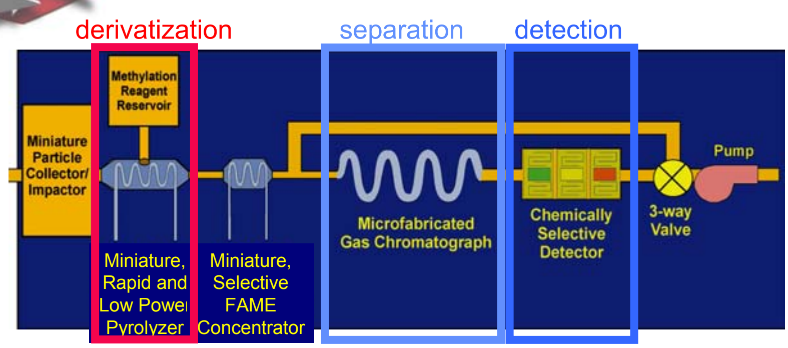
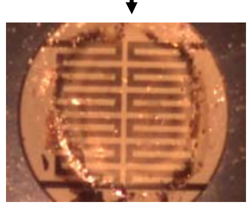
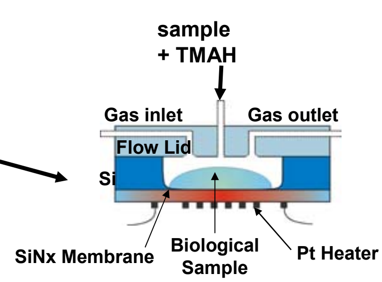
Schematic for FAME Detection







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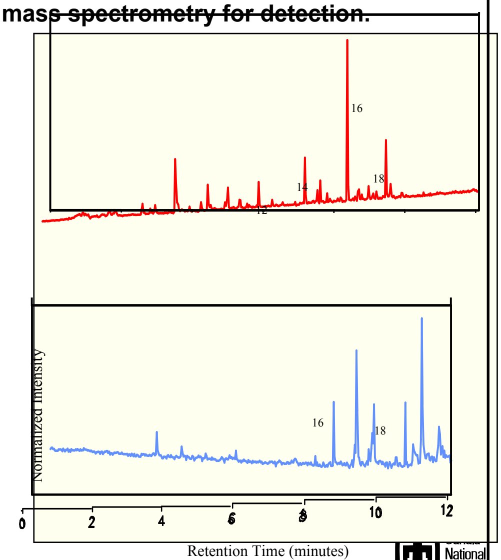
Initial FAME Testing

Using GC column and mass spectrometry for detection.

- ***Bacillus subtilis***
  - Endospore forming
  - Gram positive aerobic
  - Same genus as anthrax
  - FAs in literature: iC15, aiC15, C17, C16

- ***Pseudomonas Fluorescens***
  - Soil and water bacteria
  - Gram-negative aerobic
  - same genus as pseudomonas aeruginosa
  - FAs in literature: C16, C17, C18, C12



12,14,16,18- methyl esters of C14:0, C16:0, C18:0

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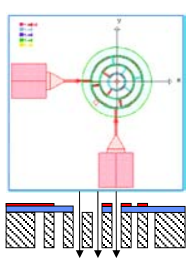
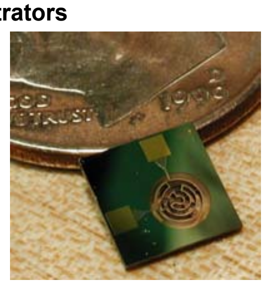
Future of μChemLab

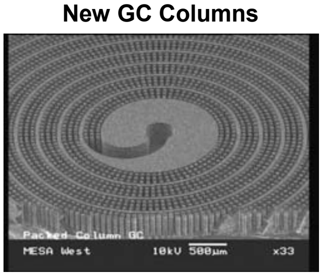
New Preconcentrators



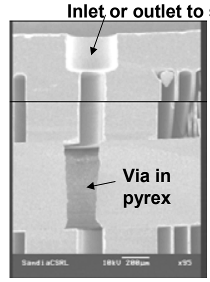


3-D preconcentrator has 10X higher surface area for collection

New GC Columns



Posts made during fabrication eliminate need to pack with beads



Composite View

Stacked columns provide greater column length for better separations

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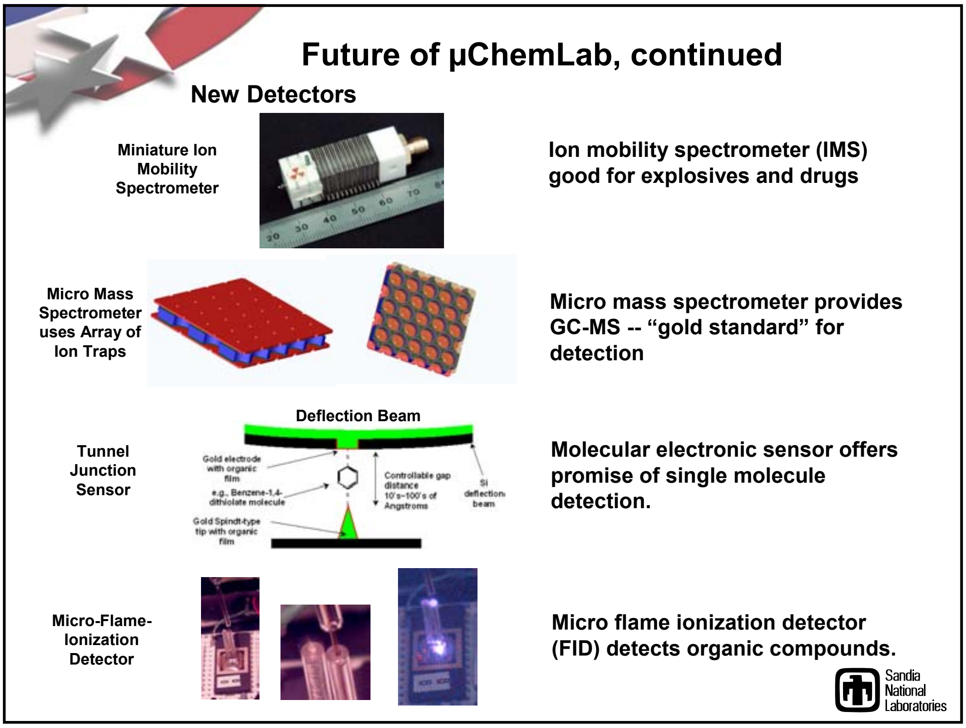
Future of µChemLab, continued
New Detectors
Miniature Ion Mobility Spectrometer
Ion mobility spectrometer (IMS) good for explosives and drugs
Micro Mass Spectrometer uses Array of Ion Traps
Micro mass spectrometer provides GC-MS -- "gold standard" for detection
Deflection Beam
Tunnel Junction Sensor
Gold electrode with organic film
e.g. Benzene-1,4-dithiolate molecule
Gold Spindt-type tip with organic film
Controllable gap distance 10's-100's of Angstroms
Si deflection beam
Molecular electronic sensor offers promise of single molecule detection.
Micro-Flame-Ionization Detector
Micro flame ionization detector (FID) detects organic compounds.
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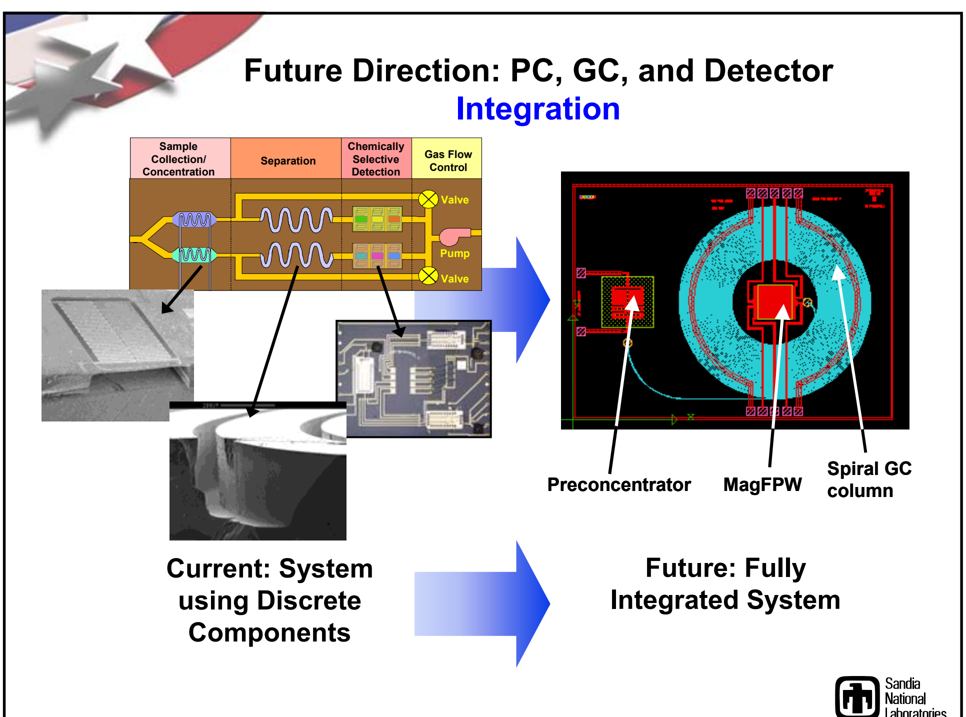
Future Direction: PC, GC, and Detector Integration
Sample Collection/ Concentration
Separation
Chemically Selective Detection
Gas Flow Control
Valve
Pump
Valve
Preconcentrator
MagFPW
Spiral GC column
Current: System using Discrete Components
Future: Fully Integrated System
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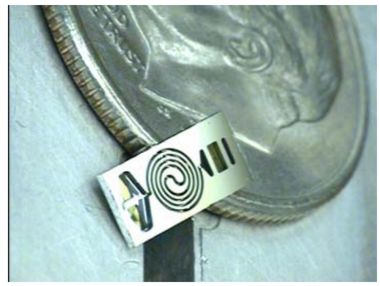
Monolithically-integrated µChemLab fabricated in the MDL and CSRL

Surface micromachining (CMOS fab) front-side processing

Bosch etching



- •Precise control of FPW boundaries
- •GC coating ports, front side
- •Dual FPW
- •Front or back side gas contact

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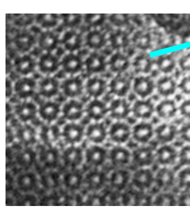
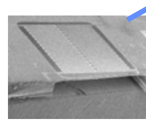
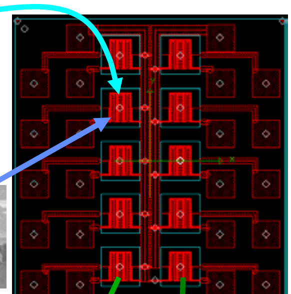
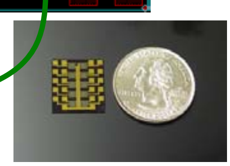
µChemlab™ Calibration Source Based on Array of Preconcentrator Elements: On Demand Calibration

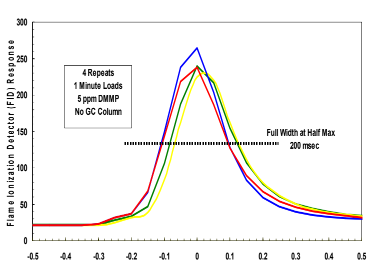
"Spike" sol-gel or polymer film solutions with precise concentration of calibrant molecules, *before* patterned deposition of films on an array of microhotplates











Controlled heating of individually addressable elements provides reproducible vapor aliquots for sensor system calibration

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Acknowledgements

to the μChemLab team:

- Doug Adkins
- Larry Anderson
- Carol Ashby
- Matthew Blain
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- Richard Kottenstette
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- Ronald Manginell
- Jesus Martinez
- Curtis Mowry
- Alex Robinson
- Steve Rohde
- James Sanchez
- Steve Showalter
- Michael Siegal
- Joe Simonson
- Sara Sokolowski
- Lisa Theisen
- Dan Trudell
- Fernando Uribe
- Dave Wheeler
- W. Graham Yelton
- Sherry Zmuda

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Conclusions

- **There are many *applications* for μChemLab**
  - **First responder units**
  - **μUAVs**
  - **Dosimeter badges**
  - **Intelligence collection**
- **The μChemLab program is a *model* for microsystem development**
- **Continuing *innovations* will increase the power and versatility of μChemLab**
  - **New preconcentrators**
  - **New GC columns**
  - **New detectors**
  - **Higher levels of integration**
  - **Internal calibration**
  - **Modifications for BW detection and water surety**

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Section **3.0**

PROGRAM PORTFOLIO REVIEW

Following the plenary session, the meeting was broken into three parallel sessions. The sessions began with review of twelve representative projects supported by the Advanced Research Program. These projects are a part of NETL's program on sensor development, and were selected because they were directly related to the subject areas to be discussed in the workshop.

The review criteria has two parts. The first part is from the program-portfolio perspective. It includes relevance to the DOE programs for advanced power systems, the effectiveness in attacking the technical barriers, and potential impact. The second part is related to the individual projects, including their objectives, performance, and possible outcome. Each session has a peer review panel consisting of five experts from industry, national labs, and other research organizations. Input in the form of review sheets were also collected from general audience. Aggregate or programmatic suggestions to the NETL program were also solicited.

From the program-portfolio perspective, the reviewers generally thought most of these projects were relevant to the DOE needs for developing advanced sensors for power systems. The reviewers endorsed the idea of using sensors to improve control of power systems, and paid close attention to the response times of many proposed sensors. There were two projects that addressed using multiple sensing to measure gas components to help control the combustion process. These projects were directly responding to the findings of the previous workshop indicating that control of air: fuel ratio is critical for improving combustion performance, and that moving sensors closer to the combustion zone is desirable.

On the barriers sides, the reviewers raised most concerns about practical issues, such as particulate contamination, the interface with electronics, and packaging. These areas need to be improved. For example, although SiC materials can operate at elevated temperatures, reviewers had concerns about whether the wiring and packaging will function well at such high temperatures. The H2O effect on SiC at high temperature is another practical issue.

The reviewers suggested NETL pay special attention to the "real-world" application issues such as particulate contamination, system-interface issues such as extraction and sampling systems and optical windows, and packaging that will allow advanced sensors to survive in harsh environments over useful time-frames.

Some suggested that NETL establish a test protocol that will encompass these concerns, and thus aid developers in targeting and achieving critical fossil-energy system goals. Reviewers also suggested that NETL support other emerging and competing technologies, including nanotechnology, silicon-on-insulator, wave-based, and optical measurement technologies.

The following sections present the abstracts for the 12 projects.

3.1 DEVELOPMENT OF GAS SENSORS

- **Development of Silicon Carbide Devices for Harsh Environments**

Ruby N. Ghosh
Center for Sensor Materials
Michigan State University
East Lansing, MI 48824

Silicon carbide based devices have enormous potential as chemical sensors for control and emissions applications in energy plants. Unlike silicon, silicon carbide (SiC) Is a wide bandgap semiconductor, which enables electronic device operation at temperatures in excess of 900°C. In addition SiC is chemically stable in reactive ambients. We are investigating SiC metal-oxide-semiconductor (MOS) capacitors with catalytically active refractory metal gates as gas sensors in these harsh, high temperature environments. The response of catalytic gate SiC sensors, operating at elevated temperature, to hydrogen containing species is poorly understood. From *in situ* electronic measurements of the SiC sensors in a controlled gaseous environment we have discovered that there are two independent phenomena that lead to hydrogen transduction following dehydrogenation at the heated catalytic gate. First is the chemically induced shift in the metal/ semiconductor work function difference, which is the "classic" phenomena observed in room temperature silicon based devices. Secondly, at temperatures above 500°C, there is the passivation/creation of charged states at the oxide/semiconductor interface upon switching between reducing and oxidizing environments. MOS capacitance sensors typically operate in constant capacitance mode. These results affect sensor sensitivity since the slope of the capacitance-voltage curve changes dramatically with gas exposure at high temperature. In addition, we discuss how the choice of capacitance set point determines the time response and reliability of SiC MOS capacitors operating as hydrogen

- **Combustion Flue Gas Monitor Based on Semiconducting Metal Oxide Sensors Technology**

Brent Marquis
Director of Research Engineering
Sensor Research & Development Corporation
Orono, ME 04473

Sensor Research and Development Corporation (SRD) has been developing a sensor system for the detection and measurement of flue gas constituents generated in coal-fired power plants through a DOE contract. This sensor system is based on semiconducting metal oxide (SMO) film technology. SMO films can be operated as "chemiresistive" type sensors by measuring each film's electrical resistance while gases chemically react with its surface. The sensor's response "signal" results from the donation or withdrawal of electrons to or from the SMO film caused by these chemical reactions (oxidation/reduction, "redox" reactions). The magnitude and signature of the "signal" are proportional to the change in film resistance and indicative of the gas types and concentrations present.

Unlike the current measurement systems being used to analyze flue gas emissions, SMO sensors are small, inexpensive, mechanically and thermally robust, and capable of *in situ* real-time monitoring even in harsh uncontrolled environments, such as flue gas streams. SMO sensors are proven reliable, highly sensitive (<parts per million (ppm)), and quantitative. However, SMO sensor technology requires further research and development efforts to selectively detect and measure flue gases including nitric oxide (NO), nitrogen dioxide (NO_2), ammonia (NH_3), hydrogen sulfide (H_2S), sulfur dioxide (SO_2), carbon monoxide (CO), carbon dioxide (CO_2), etc.

SRD has been investigating several strategies to improve the selectivity and reliability of the SMO sensors including a variety of chemical (e.g., acid/base oxides, catalysts, pretreatment, operating temperature) and physical (e.g., grain size and geometry) configurations, processing the gas stream before it is allowed to contact the sensor surface (e.g., permeable membranes and in-line prefilters), and characterization of response kinetics of gases reacting with the sensor surface (e.g., response signatures, rates of response and recovery, direction of response, statistical techniques).

SRD presents the results from testing many metal oxide materials to NO, NO_2, NH_3, SO_2, and H_2S, as well as other flue gas interferents including CO, CO_2, methane (CH_4), and C_2H_4 (ethylene) ranging from 1-200 ppm while operating the sensors at temperatures between 100-500^oC. The sensor to sensor reproducibility, response repeatability, response kinetics, baseline and response stability, and long-term performance are discussed, followed by the next steps necessary in the development of an SMO-based flue gas monitor.

- **Advanced Solid-State Sensor Technology for Vision 21 Systems**

[1]C.D. Stinespring and [2]K. Meehan
[1]C. Peng and [3]A. Woodworth

[1]Department of Chemical Engineering
West Virginia University
Morgantown, WV 26506-6102

[2]Bradley Department of Electrical and Computer Engineering
Virginia Institute of Technology
Blacksburg, VA 24062

[3]Department of Physics
West Virginia University
Morgantown, WV 26506

The goal of this research is the development of a two-dimensional gas species and temperature sensor array based on silicon carbide technology. To accomplish this goal, the research addresses several key issues relating to device design and fabrication that currently limit existing silicon carbide sensors. Successful completion of this work will allow the integration of robust gas and temperature sensors to provide real-time on-line monitoring and control of Vision 21 systems. During the first year, work has focused on two major areas. The first involves an investigation of the deposition of SiC epilayers and thermal stabilization metal-SiC interfaces. Both of these are critical steps in the sensor fabrication process. The second research area involves sensor design and fabrication.

The deposition of 3C-SiC epilayers on Si (100) substrates using gas source molecular beam epitaxy (GSMBE) has been demonstrated. Si rather than SiC was chosen as the substrate for these initial studies to avoid substrate preparation issues in the early stages of the work. These substrate issues for SiC are being addressed in separately funded research at WVU. Subsequently, studies investigating the deposition and thermal stability of the Pd/SiC and Pd/SiO_2/SiC have been preformed for 6H-SiC (0001) substrates. These studies are continuing and structures are now being prepared for electrical characterization.

Based upon previous research, both published and carried out at WVU, a Schottky diode structure has been adopted for the gas sensor and a p-n diode for the temperature sensor. Modeling analyses have been performed to determine the optimal doping concentrations to minimize leakage currents and maximize the change in voltage at a constant current of a Schottky diode over a temperature range from room temperature to 573 K. Higher temperature operation is possible. However, the temperature range was constrained initially to allow the use of contact metallizations that have already been developed at WVU. Fabrication of prototype devices will be initiated shortly.

- **Fiber Optical Micro-Detectors for Oxygen Sensing**

Gregory L. Baker and Ruby N. Ghosh
Department of Chemistry and Center for Sensor Materials
Michigan State University
East Lansing, MI 48824

Fiber optic oxygen probes are well-suited for development as micro-sensors for oxygen levels in power plant exhaust ambients, but existing sensors either lack the thermal stability needed to sample power plant exhausts or respond too slowly to be useful for real-time control of combustion. We recently designed and tested at room temperature a fiber sensor based on the quenching of luminescence from Mo_6Cl_{12} clusters embedded in a highly permeable polymer. The sensor is capable of detecting oxygen in the 0.1% to 20% range with an intrinsic response time estimated to be 1 second. Unlike the active agents used in most oxygen sensors, the MO_6Cl_{12} clusters are stable at high temperatures and can be the basis of a high temperature oxygen sensor. We plan to extend our previous results to 600°C by replacing its organic components with inorganic materials that have superior thermal stability. In particular, we will replace the polymer used in the room temperature version of the sensor with porous sol-gel matrix. Because of the inertness of the clusters, there should be no chemical interferences with the matrix, and no effect of the matrix on the optical properties of the cluster. High temperature stability issue will be first addressed by characterizing the stability and optical properties of thin sol-gel films deposited on planar fused silica substrates, and then moving from planar substrates to fibers. Long term stability tests will be used to examine possible sensor fatigue and fouling.

3.2 EMISSIONS MEASUREMENT

- **A Cavity Ring-Down Mercury Continuous Emission Monitor**

Christopher Carter
Sensor Research & Development Corporation
65
Orono, ME 04473

The U.S. Environmental Protection Agency (EPA) announced in December of 2000 that it would regulate mercury (Hg) emissions form coal-fired power plants under Title III of the Clean Air Act Amendments of 1990. The EPA plans to finalize these regulations by December 2004 and require compliance by December 2007. Assuring compliance with these EPA regulations will require a real-time, accurate, continuous emission monitor (CEM).

Sensor Research & Development Corporation was awarded a Department of Energy contract for the development of a novel mercury CEM based on the technique of Cavity Ring-Down Spectroscopy (CRD). CRD is a measurement of the rate of absorption of a sample within a closed optical cavity, rather than the standard measurement of the absorbed signal strength over a given sample path length. It maintains much of the simplicity and advantages of atomic absorption spectroscopy, but with the potential of up to 10^5 increase in sensitivity. This high sensitivity is a result of the extremely long effective path lengths possible (tens of kilometers) with CRD.

Typical concentrations of mercury in flue gas emissions are on the order of 1 ppbv. This low concentration present with the much higher concentration of other interfering flue gases presents a very challenging environment for monitoring. In fact the majority of available Hg-CEMs rely on extensive sample pretreatment to be able to analyze the Hg content. Often the mercury content is so low that sampling must be done over a period of time to accumulate enough mercury to detect.

CRD has been shown to work within hostile environments and multi-component gas streams. The inherent sensitivity and self-calibrating ability make CRD an idea detection method for true continuous monitoring of mercury in flue gas emissions.

We present results of mercury detection using CRD. Preliminary results of interferent gases are shown as well. Additionally, the future directions and plans for the project are presented.

- **Development and Applications of Gas-Sensing Technologies to Enable Boiler Balancing**

Pabir K. Dutta
Center for Industrial Sensors and Measurements (CISM)
The Ohio State University
Columbus, OH 43210

The Center for Industrial Sensors and Measurements (CISM) at The Ohio State University and GE Reuter-Stokes (GERS), a part of GE Power Systems, will team up to develop a ceramic-based microsensor array to monitor total NO_x (0-1000 ppm), CO (0-1000 ppm) and O_2 (1-15%) within the hot zones of the burner (480-815^{o}C) to provide feedback for burner balancing and optimization. The local state of the combustion will be determined by measuring O_2, CO and NO_x. These gases provide a measure of the completeness of combustion as well as the main controllable pollutant (NO_x) in the combustion. The sensor design approach is centered on the appropriate choice of the sensing principle, development of novel materials and intelligent use of catalysts. For O_2 sensing, potentiometric measurements across a yttria-stabilized-zironia (YSZ) electrolyte with Ni/NiO internal reference electrode will be developed. A potentiometric design will also be the basis for a total NO_x sensor, where a catalyst filter will minimize interference of CO and convert NO/NO_2 to a total equilibrium NO_x value. CO sensing will be done with resistive titania sensors, modified by catalysts and/or pn composites to produce selectivity and sensitivity. Cross-sensitivities between sensors will be addressed by development of powerful pattern recognition schemes based on nonlinear regression methods. Individual heating systems for sensors will be designed. Optimally designed sensor arrays will be tested in coal-fired power plants and improvements over current technology will be demonstrated.

- **Development of On-Line Instrumentation and Techniques to Detect and Measure Particulates**

Sheng Wu, Wong Chu Tang, William A. Goddard
California Institute of Technology
Pasadena, CA 91125

A method for non-intrusive particulate matter (PM) monitoring is proposed here. Traditional PM analysis are usually invasive and time consuming, i.e., they require PM collection process which distort the real time, *in situ* PM distribution significantly.

With the rapid development of low cost, ultra compact solid state lasers in recent years, we plan to use lasers with multi colors and peak intensities to probe the PM in hazardous environment, and monitor the scattering at limited fixed angular positions. We use super computers to simulate the electro-magnetic field scattering, using Mie theory for elastic scattering, and Raman and surface harmonic generation for inelastic scattering. Theoretical results will be compared to experimental data. A knowledge base will be constructed to characterize PM in real time. This setup promises easier, instantaneous data for the PM size distribution and rough chemical composition. This study will provide new insight into the elastic Mie scattering with multicolor lasers. It will also yield new theoretical and experimental results about inelastic scattering processes of single PM particles, such as Raman and surface harmonic optical generation.

- **Multifunctional (NO_x/O_2/CO) Solid State Sensor for Coal Combustion Control**

Eric D. Wachsman
Department of Materials Science and Engineering
University of Florida
Gainesville, FL 32611-6400

We have developed solid-state sensor technology that can provide an inexpensive, rugged, solid-state device capable of measuring the concentration of multiple species (such as NO and CO) in combustion exhaust. These small (<1 cm^2) simple potentiometric (voltage output) sensors are sensitive to each of these gasses and can be readily combined on a single chip to provide a multifunctional (NO_x, CO, O_2) sensor. This technology is the basis for a low cost, simplified way to meet emissions monitoring regulations. In addition, this type of sensor can be used to improve combustion control, resulting in both improved fuel utilization and reduced emissions.

Our sensor technology is similar to that used in conventional automotive O_2 sensors and thus can be used directly in high temperature exhaust. However, both the sensing and reference electrode are in the same gas stream, significantly reducing fabrication costs. The major technical challenge to developing and commercializing low-cost, solid-state, electrochemical sensors for emissions monitoring is attaining the necessary gas selectivity. Specifically, the sensors must exhibit a highly selective response to ppm levels of NO_x and CO in the presence of percent levels of O_2.

We have developed an innovative scientific approach "Differential Electrode Equilibria" that provides the necessary sensor selectivity. We have demonstrated that this approach provides the selectivity to measure, for example, ppm levels of NO with high sensitivity in lean-burn (13-17% O_2) exhaust gas. Moreover, due to the selectivity of our sensor the O_2 concentration can vary over a wide range with negligible effect on our sensors response to NO concentration. In addition, our sensor provides rapid (~1 s) reversible response to fluctuations in gas concentration.

Since we have already demonstrated this approach works for NO the goals of our proposed research are to: advance the fundamental understanding of this approach by applying it to the development of selective NO_2, CO and O_2 electrode elements; fabricate and test a multifunctional (NO_x, CO, O_2) sensor; and develop a miniature low-cost multifunctional (NO_x, CO, O_2) sensor prototype for evaluation by commercial/industrial companies. To further this latter goal we have teamed with GE Power Systems to field test our sensors in their boiler balancing system. In achieving these goals we will both advance the science of solid-state electrochemical sensors as well as bring closer to commercialization a device that will result in both improved fuel utilization and reduced emissions from coal combustion.

3.3 COMBUSTION MEASUREMENT AND CONTROL

- **High-Temperature Solids Velocity Probe**

Esmail R. Monazam
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An innovative laser probe system can now accurately measure the instantaneous velocity and direction of particles moving through a specific region of 1100°C Circulating Fluidized Bed (CFB). The probe consists of a laser beam projector and a maneuverable conduit that is inserted through the wall of a pneumatic transport pipe to illuminate a precise sample volume in the material flow. The probe projects a pattern of four laser beams into a tiny region just ahead of the probe conduit causing a reflection to be generated as a particle passes through each beam. Reflected laser energy is collected by a lens focused on a narrow region of the laser beams and coupled into a fiber line. An Avalanche Photo Diode (APD) then converts the reflected energy into an electronic waveform. A program written in LabVIEW G utilizing signal processing techniques computes the particle's physical attributes from this resultant waveform. This probe accurately measures velocity, direction and size of individual moving particles, something not performed by previous designs, then displays and records these results in an Excel format for historical analysis.

- **Carbon Monitor for Coal and Fly Ash**

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The Microwave Excited Photoacoustic Effect (MEPA) is being used at Iowa State University to develop an instrument to determine the percent carbon in fly ash. Three test instruments are being evaluated. The first test instrument is a single microwave frequency system previously constructed to measure photo-acoustic signals in an off-line configuration. A second instrument is being constructed based in part on lessons learned with the first instrument, but which also expands the capabilities of the first instrument. Improvements include a control loop to allow more constant microwave power output and an ability to operate over a range of microwave frequencies. The third instrument will be designed based on the experiences of the first two instruments and will operate in an on-line carbon-in-ash monitoring system for coal-fired power plants.

Various parameters affect the magnitude of the photoacoustic effect. The parameters that are known are being observed and controlled to minimize the statistical variance of the detected signal. Some of these parameters include test cell filling volume, compaction of fly ash within the test cell, and carrier modulation frequencies. These parameters are currently being tested in the single frequency off-line test cell. Data are presented showing the feasibility of the instrument.

In addition, tests will soon be started to measure the MEPA under predominately electric fields only and under predominately magnetic fields only. These later tests are being conducted to see if some discrimination can be made between the measured signals and magnetic versus non-magnetic material in the fly ash.

- **Sensor Development for Next-Generation Turbines**

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The guiding principles of advanced power generation into the next century are defined in the Department of Energy's **Vision 21** program. Advanced power systems for the 21st century will need to operate at near zero emissions with greater efficiencies on coal, and other fuels, and at an economic cost that is lower than for the present state-of-the-art systems. To meet the target NO_x levels of Vision 21, even natural gas fired turbines must operate with a finely controlled fuel/air ratio, near the lean extinction limit. In practice, changes in flow splits caused by manufacturing tolerances or engine wear can compromise emissions performance. Furthermore, unexpected changes in fuel composition, or momentary changes in fuel delivery can lead to problems with flame anchoring. These type of problems are amplified for Vision 21 systems that will likely be a "hybrid" design that combines two or more power technologies into an integrated power generation system (e.g., Fuel Cell-Turbine Hybrid). Regardless of the application, low emissions combustion technologies capable of meeting the Vision 21 goals require narrower operating limits and tighter controls. Furthermore, the development of combustion *in situ* monitoring capability, that can facilitate these performance goals, is identified as a critical need for current advanced turbine systems and future fuel-flexible turbine (e.g., syngas) technology.

Researchers at the National Energy Technology Laboratory (NETL) and Woodward Industrial Controls are developing a durable, low-cost, *in situ* monitoring techniques for control and diagnostics of natural gas combustion systems. This technique is based on the flow of electrical current through a hydrocarbon flame resulting from an applied electric field across the flame and the flame ionization reactions. The novel technique developed at NETL uses a sensor configuration that integrates two electrically isolated electrodes onto the premixing fuel injector center-body, near the tip and the combustion flame anchor. An equal voltage is applied to the two electrodes to create an electric field across the flame, and the current flowing to the remaining combustor surfaces is measured. Prototype sensor tests in NETL combustion rigs have demonstrated the potential of this two-electrode configuration to facilitate *in situ* monitoring for both diagnostics (e.g., *incipient* flashback and auto-ignition detection) and control of the local combustion process.

NETL recently signed licensing agreements for the Combustion Control and Diagnostics Sensor (CCADS) patents with Woodward Industrial Controls, an independent manufacturer of controls and fuel systems for gas turbines. Researchers at NETL are working with Woodward through a Cooperative Research and Development Agreement to address R&D issues associated with commercializing the CCADS technique.

- **Computational Fluid Dynamics Investigation of Furnace Operational Conditions to Burner Flow Controls**

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In the age of deregulation and concerns over boiler emissions, the electric utility industry has been moving toward installation of improved methods of burner flow measurement and control to optimize combustion. As utilities consider strategies for measuring and controlling air and coal flows, a critical question that must be answered is what level of control is required to achieve "optimal" combustion. The sensitivity of parameters, such as NO_x and CO emissions, and LOI, to burner flows is likely dependent on furnace geometry, the specific burner location, load, as well as firing configuration. The investigation of these sensitivities through bench or pilot scale testing can be extremely time-consuming and expensive, and the amount of information acquired through such testing is often limited. Testing these sensitivities in full scale boilers is difficult due to the dynamic nature of boiler operation, which precludes the well-controlled testing warranted in this type of investigation.

This abstract provides an overview of the objectives and plans of a new DOE funded project that will focus on quantifying the impacts of variations in burner air and coal flows on furnace operational conditions. The approach is to use computational fluid dynamics (CFD) based models of existing coal fired boilers, parametrically varying burner air and coal flows to predict the impacts on furnace behavior such as NO_x and CO emissions, furnace exit gas temperature, unburned carbon in the fly ash, and particulate deposition. CFD modeling provides a strategy for investigation of these sensitivities under well controlled conditions. We will utilize REI's three dimensional, multiphase, turbulent reacting flow code *GLACIER* to perform the analyses. Plans are to evaluate two tangentially-fired, two wall-fired, and one cyclone-fired furnace. The particular boilers to be evaluated in this program will be selected from approximately 100 utility boilers that have been previously simulated by REI. The results from these evaluations will provide information necessary to make recommendations on: 1) whether independent controls should be placed on all burners, or whether multiburner controls are adequate, and 2) what variations around set points are tolerable. REI will work closely with personnel from the EPRI Instrumentation and Controls (I&C) Center to construct the matrix of parametric variations to consider for each furnace to maximize the value of the recommendations to DOE NETL as well as industry.

Section **4.0**

BREAKOUT-GROUP SESSIONS

4.1 DEVELOPMENT OF ADVANCED GAS SENSORS/SYSTEMS

Participants
Gas Sensors/Systems

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*** Report Out Presenter**

FACILITATOR: KEVIN MOORE, ENERGETICS, INCORPORATED

Introduction

To facilitate understanding of the demanding conditions faced by fossil-energy sensor systems, clear definitions of specific needs and materials prioritization from the user community are essential. This is particularly true for potential researchers from outside the fossil-energy R&D world. Accordingly, the participant from Southern Companies offered a detailed measurement list that was accepted into the record by the group and is attached as an example of specific user requirements. An activity that would enhance future user-researcher interactions in this area would be industry surveys to enumerate needs and priorities from as broad a user community is possible.

Numerous other crosscutting issues were examined by the group. Foremost was the idea of exploring the use of cheap, redundant sensors that could be "consumed" as an alternative approach to focusing on long-term sensor survivability and RAM (reliability, availability, and maintainability) issues. Another alternative is a sensor that "loops," but this is considered a far less likely option.

There was a strong consensus that establishing a test bed for standardization with the potential to meet EPA and other regulatory requirements is an essential element of the sensor R&D process.

Application at existing sites, e.g., stack continuous emissions monitoring, is important as well. High-temperature, high-pressure prototype sensor development, experimentation, and verification are expensive, and test series to verify performance will require government support to enable consistently reliable results. Nevertheless, the economic benefits to power generators from just modestly increased efficiency could be tremendous and should be modeled, optimized, demonstrated, and publicly reported.

Barriers and Issues

Barriers feedback from the group was readily categorized under crosscutting and systems topics. The crosscutting topic has five subgroups: systems integration, economics, design architecture, testing standardization, and materials. Design architecture issues dominated, with the idea of redundant, replaceable "throwaway" sensors being an alternative to highly robust "survivable" sensors. For systems integration, packaging was a big issue. Materials barriers focused on stability issues for sensors and substrates at high temperatures and high pressure and with significant cycling requirements. Test standardization is necessary to facilitate the development and application of sensors, with specific protocols being necessary for valid testing. Systems-specific barriers were identified for systems including gasification, turbines, combustion, and fuel cells. For all barriers, the predominance of market pull over technology push is seen as a current market characteristic, and limits the adoption of new technology into practice. However, adapting technologies from other areas such as automotive applications holds promise.

Opportunities

The R&D opportunities used the same topic headers as barriers, and there was one additional topic for fuel cells. Participants prioritized opportunity needs using four votes. The voting resulted in four top priority opportunities (with number of votes and category in parenthesis) as follows:

- Materials development coupled with mechanism and modeling (13 - materials),
- Shared test bed for realistic evaluation (11 - testing standardization),
- Repository database for sensor performance and operating experience (8 - design architecture), and
- High-temperature packaging development effort for sensors and electronics (8 - systems integration).

Action Plans

The group produced lists of applications, products and critical steps for each of the four top vote getters along with needs for integration, resources, and teaming actions. In general, it is believed that an effective approach would entail DOE leading collaborations with either industry or university consortia. For the top vote getter, materials development, there was a strong emphasis on specifying and prioritizing conditions for different applications as noted above. Standard reference data (SRD) properties books and models for long-term predictability, especially for temperature cycling, would be necessary. Polling end users beforehand would facilitate a portion of the data gathering activity. Universities and labs would have the resources to compile fundamental material properties for public domain integration. Leveraging with the advanced research materials program would be beneficial. Having a shared sensor test bed for realistic evaluation was the second top vote getter. It would need multiple applications for gasification, combustion, and fuel cells. One product should be the development of new reference methods like the automotive FTIR (Fourier Transfer Infrared) spectroscopy, and standardized protocols and open access for alpha testing would be critical. It would need to be a DOE facility with a governance board for integration and industry participation.

Similar actions were developed for the other two top vote getters. A repository database must provide clear definitions of performance targets and applications, ideally based on well defined and validated user needs. High-temperature packaging development must link to materials development above and address interfaces, thermo-mechanics, and noise implications. Specific suggestions offered including batch processing approaches to lower cost and mechanisms to accurately position sensors. A few key actions were developed for two other opportunities. Silicone carbide substrates device processing for long-term stability and increased sensitivity needs cheaper high quality substrate and new epitaxy techniques. The Departments of Defense, Energy and Commerce should work in concert to develop a pool of users for diode lasers, albeit it failed before.

POWER SYSTEMS DEVELOPMENT FACILITY (PSDF) WILSONVILLE, AL
DESIRED IN-SITU GAS ANALYSIS MEASUREMENTS:

Transport reactor outlet fast response for O_2 breakthrough detection (<10 seconds):

Carbon Monoxide (CO)	0-25%	Normal 10-20%
Oxygen (O_2)	0-5%	Normal 0%

Maximum pressure = 350 psig, Operating Pressure = 100-300 psig.
Maximum temperature = 2,000° F, Operating Temperature = 1,200 – 1,950° F
Particles = 15,000 ppmw Fly Ash (High Carbon = 25-30%)

Particulate Control Device (PCD) Outlet:

Oxygen (O_2)	0-5%	Normal 0%
Carbon Monoxide (CO)	0-25%	Normal 10-20%
Carbon Dioxide (CO_2)	0-25%	Normal 8-15%
Hydrogen (H_2)	0-20%	Normal 6-10%
Moisture (H_2O)	0-40%	Normal 5-35%
Ammonia (NH_3)	0-5000 ppm	Normal 1000-4000 ppm
Hydrogen Sulfide (H_2S)	0-2000 ppm	Normal 300-600 ppm
Benzene	0-500 ppm	Normal 50-200 ppm
Naphthalene	0-500 ppm	Normal 50-200 ppm

Maximum pressure = 350 psig, Operating Pressure = 100-300 psig
Maximum temperature = 1200°F, Operating Temperature = 600-800°F
Particles = 0-15 ppmw Fly Ash (High Carbon = 25-30%)

Table 4-1-1 presents the detailed results for barriers and issues, Table 4-1-2 presents the R&D opportunities, and Table 4-1-3 presents action plants.

Gas Sensors/Systems

Table 4.1-1. What are the Barriers/Issues to Development of Advanced Gas Sensors/Systems?

Crosscutting					Systems	
Systems Integration	**Economics**	**Testing Standardized**	**Design Architecture**	**Materials**	**Turbine**	**Fuel Cell**

• Sampling, packaging
• Wireless
• Lead wires, signal processing
• Common sensor information interface definition
• Adaptability
  – Size
  – Feedback
• Connectivity, information protocol, and packaging
• High temperature/ harsh environment capable, cost effective packaging
• High temperature/harsh environment capable, integrated electronics
	• Limited market opportunity (no incentive: fuel cell, turbine, gasification)
	• Market pull not technology push
	• Determine breakeven (cost) point
	• Adapt technology from automotive
	  – How do we do it?
		• Common testing protocols
		• Build-in test
		• Do we have O^2 available in gas stream
		• Testing in real world conditions – test bed
		• Temperature range (post combustion)
		• Relevant gases
		  – Levels
		• Sample rate
			• Combustion systems Issue:
			  – Range of sensor required for development is wider than range of controls end-use application
			• Optical access to systems for laser, e.g., windows
			• Multi-sensor platform and algorithm for post-processing data to remove "noise" temperature, pressure, etc. variations
			• Barrier traditional thinking
			  – Throw away sensors
			• Replaceable sensors
			• Materials development vs. optical methods or gas treatment
			• Why micro?
			• Why RAM? (reliability, availability, maintainability)
			• Diode laser technology-tuning range, power
			• Repository database for sensor performance "operating experience"
			• Extreme redundancy
				• High temperature high pressure material considerations
				  – Metals
				  – Semicoi
				• Stable material for high temperature (>900°C) applications
				• Price of substrate (SiC) material
				• New catalyst materials for sensors for higher selectivity
				• Poisons and interferants in fuels and exhaust
				• Thin film metal agglomeration in sensors (HT)
				• Temperature swings, cycles
				• SIL – long term stability of sensor/substrate material
				• Different chemical reactions between gas species and sensor depending on temperature
				• Fundamental nanotechnology research and materials modeling to develop new sensor materials
					• Temperature of operation NO_x
					• Materials – inlet 2600°F
						• In situ sensors for high temperature (>600°C-1000°C) and chemically harsh – both reducing and oxidizing-fuel cell environments and maybe 40,000 hour life time
						• Fuel cell/cost cutting
						• SOFC – cost/RAM
						• Materials/fabrication

					Combustion	**Gasification**

					• Selective sensors
					• Arrays and modeling
					• High temperature materials
					• Membrane and sampling
						• Ultimate 500 PSIG/ 2000°F reducing
						• Harsh environment has:
						  – Particulates
						  – Deposits
						  – Etc.
						• In situ NH_3 and H_2S measurements for gasifier
						• Corrosive environments
						  – Limits lifetime/ performance

Gas Sensors/Systems

Table 4.1-2. What are the Opportunities for Development of Advanced Gas Sensors/Systems?

✪ = Vote for Priority Topic

Systems Integration	Economics	Design Architecture	Testing Standardization	Materials	Fuel Cell
• Identify existing exchange protocol and selection one or two ✪ • High temperature packaging development effort ✪✪✪✪✪✪✪✪ – High temperature harsh environment integrated package sensors and electronics • Ruggedization, integration of optical sensor systems plus miniaturization • Adapt from industry-packaging, communication standards ✪✪ • Remote detection/sensing, e.g., automotive transmission ✪✪✪✪✪ • Process control feedback ✪	• Shared sensor manufacturing facility (vs. testing) ✪✪ • Pool of users for diode lasers ✪✪✪✪✪	• Repository data base for sensor performance and operating experience ✪✪✪✪✪✪✪✪✪ • Optical spectroscopy ✪✪✪✪✪ • New diode laser tunable systems – Electro-optical crystal tuning, MEMS tuning, new cavity designs • Extreme redundancy ultra low cost sensors ✪✪✪ • New approaches to particulate sensors • High temperature MEMS ✪✪✪ • New approaches to enhancing species selectivity ✪✪✪	• Gasifier test bed PSDF Wilsonville, AL • Shared sensor test bed for realistic evaluation ✪✪✪✪✪✪✪✪✪✪✪	• Ceramic sensors with enhanced sensitivity through nanoscale synthesis, e.g., post combustion ✪✪ • SiC substrate and device proceeding for long term stability and enhanced sensitivity ✪✪✪✪✪ • Materials development coupled with mechanism and modeling ✪✪✪✪✪✪✪✪✪✪✪✪✪ – Thermomechanical reliability, lifetime prediction, modeling/simulation – High temperature and pressure materials characteristics • Pros and cons of 3 platforms – Metal oxide – SiC – Nanostructure materials • High temperature solid electrolyte based electrochemical sensors from auto industry ✪✪✪ • Carbon nanotubes (nanoelectronic) – Reducing environment – Marriage with SiC – Marriage with MiO • Corrosion restart thermocouple housing for gasifers ✪ • Understanding long-term interface changes degradation issues and effect on sensor performance ✪✪✪	• Electrode catalyst materials for H_2S, H_xS, S_xO_y, S_x, solid oxide electrochemical sensors

Gas Sensors/Systems

TABLE 4.1-3. ACTION PLANS

TOPIC	APPLICATIONS: WHAT/WHERE (THINK CROSSCUTTING MULTIPLE APPLICATIONS)	R&D PRODUCTS AND CHARACTERISTICS	CRITICAL STEPS	INTEGRATION LOGIC, ALGORITHMS, ACTUATORS, NETWORKS (THINK SYSTEMS)	RESOURCES: PEOPLE, LABS, TOOLS, INFORMATION	TEAMING: LEAD AND COLLABORATION
Materials Development Coupled with Mechanism and Model **(13 votes)**	• Vision 21 • Specify and prioritize conditions in different sensing applications (precombustion, fuel cells, combustion, post combustion)	• Temperature cycling what causes failure? • Database material properties • SRD Standard Reference Data "properties" books • Models for long term predictability	• DOE poll end users first • Get experimental data • Validate the models • Materials prioritization method based on end user	• Feedback to architecture • Modeling integration for Vision 21 systems • Public domain availability, e.g., website	• Fundamental material properties people, universities and labs	• University, Labs, Industry, DOE lead • Materials workshop fundamental properties • End user developer consortia • $1 million/yr leverage with AR materials • $5 million per year
Shared Sensor Test Bed (11 votes)	• Multiple test beds – Combustion – Fuel cell – Gasification • Combustion, fuel stream, exhaust	• Feedback to DOE for current applications • Experience regarding sensor instrumenta-tion and feedback controls • Development of new reference methods like Automotive Fourier Transfer Infrared (FTIR)	• Standardized protocols • Open access for alpha testing • Provide standard instrumentation – e.g., optical access port where possible	• Confidential results • Teaming with controls and instrumentation • Governance board	• DOE funded facility • Investigate SAE 131 standards • NIST validate reference standard • Facility calibration history, response surface	• DOE/industry leads • Access for SBIR and academia
Repository Data Base for Sensor Performance (8 votes)	•	• Clear definition of performance targets for pertinent applications – e.g., zero emissions in V21 • Clear definitions of applications now and future • Number of sensors required	• Poll industry end users	• EPA "battle" validation • Incorporate – Failure mode applications – Redundancy – Reliability	• Use sensors for existing applications, e.g., stack continuous emissions monitoring (CEM)	• DOE/university consortia lead

Gas Sensors/Systems

TABLE 4.1-3. ACTION PLANS *(CONTINUED)*

TOPIC	APPLICATIONS: WHAT/WHERE (THINK CROSSCUTTING MULTIPLE APPLICATIONS)	R&D PRODUCTS AND CHARACTERISTICS	CRITICAL STEPS	INTEGRATION LOGIC, ALGORITHMS, ACTUATORS, NETWORKS (THINK SYSTEMS)	RESOURCES: PEOPLE, LABS, TOOLS, INFORMATION	TEAMING: LEAD AND COLLABORATION
High Temperature Packaging Development Effort **(8 votes)**		• How interface, DC in, information out • Thermomechanics	• Link to material properties data base • Determine means to fix – solder position sensor • Technology to lower cost, e.g., batch processing • Long term stability of package • Determine maximum temperature for sensor location	• Current systems approach • Look at noise applications, e.g., thermocouple • Black body radiation	• Evaluate data base based on refractory materials • Small group to start	• NASA/University consortia lead

SiC substrate and Device Processing for Long Term Stability and Enhanced Sensitivity **(5 votes)**	Key Points • Cheaper high quality substrate • New epitaxy (epi) techniques and processes • Funding for characterization and device processing • Mechanistic Studies • Development of device modeling under application conditions
Pool of Users for Diode Lasers **(5 votes)**	Key Points • It failed before • DOD/DOE/DOC work in concert to develop viable pool

4.2 Emissions Measurement

Introduction

The assurance of compliance with regulatory requirements was the focus of the group. Given that regulations change frequently and industry must continually conform to stricter limits and targets, the group adjusted its focus to the process control of systems rather than specific downstream emissions criteria. Improvements in the process-control capabilities were seen to offer the potential to meet a wider range of requirements, providing a higher-value approach than simply focusing on specific end-of-the-pipe criteria.

Participants
Emissions Measurement

Name	Organization
Steve Allison	Oak Ridge National Laboratory
Greg Baker	Michigan State University
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Christopher Carter	Sensor R&D Corporation
Tim Collings	GE Power Systems
Bob DeSaro	Energy Research Co.
Prabir Dutta	The Ohio State University
Bill Farthing	Southern Research Institute
Fred Glaser	U.S. DOE-FE/HQ
Carl Palmer*	GE Reuter–Stokes
A.C. (Paul) Raptis	Argonne National Laboratory
Mike M. Ross	ALSTOM Power (Tech Center, UK)
Eugene E. Smeltzer	Siemens Westinghouse Power Corp.
Nenad Sarunac	Energy Research Center, Lehigh University
Yongchun Tang	California Institute of Technology
Eric Wachsman	University of Florida
Steve Woodruff	U.S. DOE/NETL

*** Report Out Presenter**

Facilitator: Lori Hollidge, Energetics, Incorporated

While process control became the overriding theme of the session, other crosscutting issues were also prevalent. Of these, elucidating industry's needs was a prominent topic. Given the uncertainty of regulatory processes and requirements, industry needs are an evolving target, with the specific measurements (chemical species, frequency, accuracy, reliability) being subject to change. Whatever the specific needs, however, attributes such as greater precision, broader-spectrum measurement capability, and non-intrusive sensing can be expected to prevail. Accordingly, the development of advanced sensor and control systems are most likely to provide the flexible, broad-range capabilities needed to meet changing requirements.

Other general discussion not expressed directly on the storyboards is worth noting. The group discussed the barriers to better sensors, including system environments, changing needs, packaging, and lack of knowledge. The environment in general is adverse, including high temperatures, gases, and corrosiveness. Sensor packaging is a concern because it is often not adequate to protect sensors from damage due to fly ash and other harsh system conditions. In addition, industry would like non-invasive sensors that can be used to observe the hottest parts of the power plant system. To meet these requirements will entail a highly integrated approach among materials developers, sensor developers, and the designers and manufacturers of power systems.

For example, the lack of adequate coatings and sealants were seen as the primary reason for sub par sensing. Interfaces and bonding adjoining materials is a critical need area. For coatings, thermal cycling fluctuations cause micro-cracks in current coatings. Despite this inadequacy, it was also suggested that existing coating materials could be used for sensor materials themselves.

The group identified cost reduction and improved reliability as probable (and critical) trends in sensor development. Other trends presented included extreme temperature capabilities and miniaturization (e.g., laser and optical sensors will be integrated into smaller packages). The group was also hopeful that the emerging physics of interactions – at the nano-scale and between the nano- and micro-scales – will provide an entirely new realm of sensing possibilities.

Barriers and Issues

Barriers were categorized into five categories: Basic Technology, Optimization Control, Emissions/EPA/Reporting, Application Issues, and Other/Commercial. Basic Technology focused on reliability, timeliness, stability, and interferences between system components. The primary themes in Application Issues were operation in harsh environments and reliability in the field. Variation in gas constituents and environments was a big issue for the group. Finally, the participants felt that emissions measurement and process control are fragmented across many other technologies, which inhibits them from being developed as a core business.

Opportunities

The opportunities were grouped into four categories: Sensors for Controls, Laboratory and Field Testing, Fundamental Research, and Policy. Participants prioritized opportunity needs using five votes. The voting resulted in five priority opportunities (with number of votes and category in parentheses):

- In-situ representative measurement of oxygen, loss on ignition (unburned carbon), nitrogen oxides, and carbon monoxide (14 – Sensors for Controls);
- New concepts for sensing, including mechanisms of materials selectivity, wave technologies, acoustics, electromagnetics, and NMR (12 – Fundamental Research);
- Sensors materials technology (11 – Fundamental Research);
- Fund test facilities for sensors (10 – Laboratory and Field Testing); and
- Specific DOE program on sampling interface issues (7 – Fundamental Research).

Action Plans

The group developed a list of applications, products, critical steps, integration opportunities, resources, collaboration efforts, and cost needs for the top vote getters, as appropriate. The funding required to implement the action plans should be considered a ballpark figure. A common theme for collaboration was to include government, national labs, universities, and industry.

The opportunity with the most votes was in-situ representative measurement of O2, LOI (unburned carbon), NOx, and CO, including NOx reduction and improved combustion efficiency. Relevant to developing commercial products, critical steps would include identifying the current state-of-the-art technology, demonstration in simulated environment, and field testing. In addition, controls companies and power systems representatives should be consulted.

The group discussed that parallel projects for multiple sensors would be necessary, and estimated that it would take 5 years and $100M to achieve a fully commercial product.

The next highest vote getter, new concepts for sensing, feeds into product development. Critical steps would include studies on existing basic principles from other applications, as well as the basic science of wave technologies, acoustics, electromagnetics, and NMR. The group felt strongly that the Basic Energy Sciences program within DOE should be consulted, and that small business should be targeted. It was estimated that each project would take around 3 years to reach the technology proof-of-concept stage, with a total of $10M. The participants also thought it important to note that this is a high-risk area and it is likely that only one out of ten projects will be successful.

Sensors materials technology, which is necessary for product development, was the third highest vote getter. Fundamental studies on electrochemical sensors would need to be conducted, and material field tests would be important. Each project would take 2-3 years to complete within a DOE program of 4-8 years. Funding was estimated at $20M.

Fund test facilities for sensors, receiving the fourth highest votes, would require a pilot-scale facility and test ports at existing utilities. The group also noted that it is important that when someone in the field is ready to test, the people that have a system to test need to be ready, and vice versa.

Finally, a specific DOE program on sampling interface issues would require development of methods for heating, cooling, cleaning, and access. Work could be carried out at existing test sites, and any applicable regulating agency would be involved. The group estimated that each project would require 1-2 years to complete.

Table 4-2-1 presents the detailed results for barriers and issues, Table 4-2-2 presents the R&D opportunities, and Table 4-2-3 presents the action plans.

Emissions Measurement

Table 4.2-1. Barriers to Advanced Emissions Measurement

Basic Technology	Optimization Control	Emissions/EPA/ Reporting	Application Issues		Other/ Commercial
• Interferences between components • Selective, sensitive, stable gas sensors • Inferential sensors (soft sensors) • Lower cost, rugged, laser systems • Fast response, rugged, inexpensive, gas sensor array • Real time flame temperature sensor (gas turbines) • Accurate, reliable measurement of turbine air flow • The variability in gas constituents for coal derived systems – interferences • The stability of materials at high temperature in corrosive environments • Number of gases to monitor • Miniaturization of sensors • Low levels to monitor in harsh environment • Need state-of-the-art of sensing technologies for emissions • Response time requirements • Look at others technologies, i.e., acoustics, electromagnetics, spectrum, spectroscopic, etc. • Sensitivity, selectivity, calibration requirements • Need selectivity in sensors that rely on oxidation chemistry (i.e., electrochemical based sensors) • Need in situ, on-line NO_x sensor development for control or emissions	• Not enough plant control parameters to tweek even with good sensor information • Instruments need feedback potential to control process • Point measurements vs. average value (area average, path average, etc.) • Some think that sensors are only good if absolute accuracy is provable, However, relative accuracy has good use as well.	• What input does DOE/NETL have into EPA regulations? • Standards for different sensor technology • Regulatory uncertainties – targets continue to change • Why measure Hg at stack? Why not input? • Comparing different sensor technology	• Sensors exposure to harsh environment (ash, SO_3, etc.) • Accuracy and repeatability in field difficult to achieve • Environment is difficult but also varied depending upon application • Slagging and/or PM accumulation on sensors • Lab equipment too expensive and too difficult to use in the field • Make available standardized testing facilities, e.g., DOE lab • Access to “real” systems for measurement, evaluation, and testing • Representative sampling in the “real world” • Sensor deployment and access restrictions (existing facilities)	• Sensor packaging • Field calibration difficult • Interfacing sensors to process gas streams • Sample handling • Sample conditioning and delivery to a sensor element • Temperature controlled sensors (heating systems) • Need optical access for long-term applications in combustors • Test rigs not designed to test new sensors • Obtaining long term, quality testing time for sensors in realistic harsh environments	• Companies won’t invest until technologies are “proven” • Mindset: Typical power plants expect long life, but are used to sensors at lower temperature (e.g., 400^{o}C O_2 sensor); An expectation problem • Commercial SCR’s FGD’s etc. “Why bother” monitoring if I’m cleaning up at the tail end anyway • Acceptance: only want to measure what is regulated • Sensors for optimization need easy-to-prove $ savings • Lack of fundings from industrial partner • Sensing and instrumentation is fragmented across other core technologies – not seen as core business – Getting critical mass for development • Conservative test engineers • The market for these advanced systems is uncertain

Emissions Measurement

TABLE 4.2-2. OPPORTUNITIES TO OVERCOME THE BARRIERS

✪ = VOTE FOR PRIORITY TOPIC

TESTING – LABORATORY AND FIELD	POLICY	FUNDAMENTAL RESEARCH	SENSORS FOR CONTROLS
• Fund test facilities for sensors ✪✪✪✪✪✪✪✪✪✪ – Field tests need greater funding or reduced cost sharing burden – Greater collaboration and designing – Pilot-scale facility – Utility to provide open test ports at their facility – PM testing, optical testing, in situ gas • Databases of results • Selling measurement services	• Tax incentives to modernize power-plants • Make efficiency part of national energy strategy • EPA should set lower emissions standards and raise penalties ✪ • EPA representative should be here • Inducements to include utilities in process of testing ✪ • Eliminate grandfather clauses • DOE/industry publish definitive systems and targets for specs sensor systems ✪✪✪✪ • Instrument component manufacturers need to be incentivized to reduce cost and improve reliability for field use ✪✪	• Focus R&D on low cost throwaway sensors ✪ • Real-time Hg sensors (speciated) ✪✪✪✪ • Couple automotive and power plant sensor research – cross-fertilize • New concepts for sensing ✪✪✪✪✪✪✪✪✪✪✪✪ – Wave technologies, acoustics, electromagnetics, NMR, etc. • Specific DOE program on sampling interface issues ✪✪✪✪✪✪✪ • Optical access to systems • Sensors materials technology ✪✪✪✪✪✪✪✪✪✪✪ – Sensors in structure themselves – Use software to make measurements/predictions – Smart materials, i.e., smart sensors – Material compatibility or sensor design needs to be funded – Solid-state sensors: understanding gas-solid interface – Develop high temperature materials for sensors – Fundamental studies on electrochemical sensors	• Smart sensors for control and safety • In situ representative measurement of O_2, LOI (unburned carbon), NO_x and CO ✪✪✪✪✪✪✪✪✪✪✪✪✪✪ – Specific programs on high temperature NO_x sensing • Forget emissions – focus on control ✪✪ • In situ instrumentation for A/F ratio for individual burners (coal-fired power plants) • PM sensor size, loading and chemistry ✪✪✪✪✪✪

Emissions Measurement

TABLE 4.2-3. ACTION PLANS

TOPIC	APPLICATIONS: WHAT/WHERE (THINK CROSSCUTTING MULTIPLE APPLICATIONS	R&D PRODUCTS AND CHARACTERISTICS	CRITICAL STEPS	INTEGRATION: LOGIC, ALGORITHM, ACTUATORS, NETWORKS (THINK SYSTEMS)	RESOURCES: PEOPLE, LABS, TOOLS, INFORMATION	TEAMING LEAD AND COLLABORATION	DOLLARS AND SENSE
Sensors Materials Technology	• Coal combustors • Gas turbines • All materials based parameters • Reducing and oxidizing environments	• Fundamental studies on electrochemical sensors • Sensors in structures themselves • Smart materials, i.e., smart sensors • Develop high-temperature materials for sensors • Solid-state sensors: understanding gas-solid intex • Materials properties data base – Include what's already available • Mechanisms for selectivity (study them) understand basic science • Joining and lead out technology for high temperature (look at autos)	• Material compatibility or sensor design needs to be funded • Coordinated materials testing and exposure • Material field tests • All materials work should be relevant to nearer-term sensor devleopment • Ensure collaboration on materials issues with other program elements	• Use software to make measurements/ predictions	• ASME, ASTM – Use their databases	• Universities, national labs, federal agencies • Utilities/industry in advisory role	• 4-8 years (each project 2-3 years, DOE program 4-8 years) • $20 M

Emissions Measurement

TABLE 4.2-3. ACTION PLANS *(CONTINUED)*

TOPIC	APPLICATIONS: WHAT/WHERE (THINK CROSSCUTTING MULTIPLE APPLICATIONS	R&D PRODUCTS AND CHARACTERISTICS	CRITICAL STEPS	INTEGRATION: LOGIC, ALGORITHM, ACTUATORS, NETWORKS (THINK SYSTEMS)	RESOURCES: PEOPLE, LABS, TOOLS, INFORMATION	TEAMING LEAD AND COLLABORATION	DOLLARS AND SENSE
Fund Test Facilities for Sensors	• PM testing • Optical testing • In situ gas	• Pilot-scale facility • Utility to provide open test ports at their facility • Uniform test protocol and fixturing – standardization • Higher background level of instrumentation than normal • Ability to vary many parameters	• Greater collaboration and designing • Field tests need greater funding or reduced cost sharing burden • Industry input on test conditions • Place value on use of test facilities • Round robin tests – Same instrument tested at different sites • DOE identify available test facilities • Scale of facility is important • Piggyback testing is important • Small facility dedicated for sensor testing	• Qualification procedures for agencies used for conformance testing	•	• National labs, universities, industry, federal government • When someone in field is ready to test, people that have system to test need to be ready and vice versa	• Ongoing
Specific DOE Program on Sampling Interface Issues		• Optical access to systems • Interface will be different for each type of device • Methods of heating, cooling, cleaning, access, window material and cleaning	• Need an existing sensor you are trying to apply		• Test sites	• Regulating agency (if applicable)	• 1-2 years/project • 15-25% of project cost

Emissions Measurement

TABLE 4.2-3. ACTION PLANS *(CONTINUED)*

TOPIC	APPLICATIONS: WHAT/WHERE (THINK CROSSCUTTING MULTIPLE APPLICATIONS	R&D PRODUCTS AND CHARACTERISTICS	CRITICAL STEPS	INTEGRATION: LOGIC, ALGORITHM, ACTUATORS, NETWORKS (THINK SYSTEMS)	RESOURCES: PEOPLE, LABS, TOOLS, INFORMATION	TEAMING LEAD AND COLLABORATION	DOLLARS AND SENSE
In situ* Representative Measurement of O_2, LOI, NO_x, CO (Unburnt Carbon)** – ***Reduce NO_x – ***Improve combustion efficiency***	• Gas turbine emissions conformance • Combustion systems • NO_x and CO: In situ or optical non-invasive measurement in gas turbine combustor can • NO_x and CO: In situ, as close to combustion as possible. At least > 700°C in boilers	• Specific programs on high temperature NO_x sensing • For unburned carbon: in situ real time accurate measurement allows control changes to minimize unburned carbon • Continuous, online monitoring operator-independent, accurate	• What is the state-of-the-art of technology? • Identify methods for accurate detection • Identify sensor approaches that are viable • Acceptance of methods of measurements (conformances) • Must identify short-term market potential • Demo in simulated environments • Field testing for life, drift, etc. • Provide/establish sensor requirements • Consult with controls companies for specs • Include power systems reps	• Develop system-friendly interfaces • Determine "transfer function" between input changes and sensor outputs • Coordination of sensor mounting and fixturing	• DOD and other federal agencies • Consult with developers/users • EPRI • Automotive groups • DOE – Transportation – FE – Etc.	• Collaboration with combustion process developers/operators • University, national labs, users, academia, industry • Sensor OEM guide research • PIWG (Propulsion Instrumentation Working Group)	• Will need parallel projects – multiple sensors • 5 years for fully commercial product • $100 M

Emissions Measurement

TABLE 4.2-3. ACTION PLANS *(CONTINUED)*

TOPIC	APPLICATIONS: WHAT/WHERE (THINK CROSSCUTTING MULTIPLE APPLICATIONS	R&D PRODUCTS AND CHARACTERISTICS	CRITICAL STEPS	INTEGRATION: LOGIC, ALGORITHM, ACTUATORS, NETWORKS (THINK SYSTEMS)	RESOURCES: PEOPLE, LABS, TOOLS, INFORMATION	TEAMING LEAD AND COLLABORATION	DOLLARS AND SENSE
New Concepts for Sensing	• Any critical need in combustion system sensing • LOI, O_2, COS H_2S, NO_x, PM, NH3, CO, Hg, $SO_{2,3,}$ other heavy metals • Coal flow • Fuel gas heating value • Gas turbine airflow	• Wave technologies acoustics, electro-magnetics, NMR, etc. • Perform basic science – Basic principles, e.g., look at spectrum • Studies on applying existing basic principles from other applications	• Tomography – how sensors are used • Include power system representatives • Program milestone: stop/go technology demonstration • High temperature MEMS and NEMS (micro and nano) – Build on existing research • Identify key technical hurdles for promising technologies • High temperature optical	• Not considered at this stage		• Teaming – Scientists – Oversight committee • Target universities, national labs, small business • Research Centers • BES – Be sure to consult them – DOE/BES	• Each project will take around 3 years (max) to reach technology proof-of-concept • $10M (for proof-of-concept) • High risk area (1 out of 10 successful)

4.3 Condition Monitoring

Introduction

A substantial majority of the participants for the Condition Monitoring breakout session were industry representatives. In general, the inherent focus of the industry representatives leaned toward more near-term concerns rather than the longer-term, high-payoff approaches that are the primary target of advanced research. The group was encouraged to leap from within "the box" to assess opportunities for innovative, breakthrough technologies, including technology options that could have both near- and long-term payoffs. Accordingly, a significant amount of detailed information was gathered, in particular addressing the options and trade-offs between conventional and visionary approaches.

Participants
Condition Monitoring

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Heng Ban	University of Alabama at Birmingham
Kelly Benson	Woodward Governor Company
Jim Ciesar*	Siemens Westinghouse Power Corp.
Chris Condon	REM Engineering Services
Marc Cremer	Reaction Engineering international
Mike Drumm	Hood Technology
Dot Johnson	McDermott Technology, Inc.
Stephen Kimble	Southern Company Services, Inc.
Susan Maley	National Energy Technology Laboratory
Russ May	Prime Photonics, Inc.
Esmail Monazam	REM Engineering Services
Robert Murphy	ALSTOM Power
Gary Pickrell	Virginia Tech
James Roberts	Rolls-Royce PLC
Lawrence Ross	Siemens Westinghouse Power Corp.
Andy Suby	Iowa State University
John Telford	Los Alamos National Laboratory
Paul Wolff	EPRI I&C

*** Report Out Presenter**

FACILITATOR: ALICIA DALTON, ENERGETICS, INCORPORATED

Barriers and Issues

The group members brainstormed the barriers to condition monitoring, discussed and analyzed key ideas, and arranged them into major topical areas. They are: Harsh Environments, Interfaces, Policy, Strain, Other Measurements, Performance Testing and Design, Costs, Flow Measurement, Combustion Stability, Temperature/Emissions Measurements, and Materials.

Opportunities

To assure a focus on longer term, higher-risk opportunities, the group was asked to consider the issues associated with sensors and control systems and system integration rather than sensor development alone. In particular, the wide range of Vision 21 systems and configurations were to be considered. Accordingly, participants addressed topics such as non-intrusive measurement and monitoring devices as well as integrated suites of systems with predictive abilities. The responses identified R&D opportunities and/or needs to overcome the barriers to condition monitoring. The group organized the opportunities into the following categories: Instrumentation Technologies and Strategies, High Temperature Materials, Modeling, Materials Properties Databases, Vibration/Fatigue/Strain, Chemical Sensors, Testing, Thermal Barrier Coatings, and Miscellaneous Condition Monitoring. Each participant voted to indicate the highest priority R&D opportunities among the generated ideas. The four highest vote-getting opportunities were as follows, respectively:

- Flame monitoring and characterization method,
- Enabling materials for sensor development coupled to or concurrent with the development of engineered high-temperature materials,
- Test facilities, and
- Pyrometer measurement and monitoring for thermal barrier coatings.

Action Plans

Detailed action plans were developed for the four highest vote-getting opportunities. Participants identified information in each of the follow categories for each high priority opportunity: Applications, R&D Products and Characteristics, Critical Steps, Integration, Resources, Collaborations, and Dollars and Sense. In addition to these individual topics, participants addressed a number of crosscutting topics.

There was general acknowledgement that many of the sensors and control systems issues stemmed from a lack of suitable sensor materials. Enhancing the collaboration between the existing materials program and the sensors and control systems effort would help achieve maximum productivity. The traditional sensors emphasis also raised issues regarding the lack of focus on controls system and system integration. Group members repeatedly noted that the development of a control system follows the development of the sensor – and at present, it is the sensors that are needed. Upon identification of the system characteristics, an existing control system may be available for adaptation for the new sensors.

Market pull versus technology push was also a topic of discussion. The group noted that often within industry, advanced sensors and control systems are not considered until a more stringent regulation becomes eminent. Comparatively little emphasis is placed on the potential for efficiency gains from advanced control systems. In general, improved knowledge of the end users' needs must be coupled with the ability to convey the benefits of better measurement and monitoring systems.

The participants not only discussed at length the need for low-cost test facilities, but they identified the problems with traditional patterns of research, development, and testing. Industrial-scale facilities that could be used for full-scale testing are industry-owned. This translates into large investments of time and money as well as issues such as intellectual property and proprietary knowledge, the risk of disrupting operations, and the availability of facilities for long-term testing. Before adoption of sensors and control systems technologies occur, lengthy tests to verify life span are necessary. The group noted that although universities may in fact have the ability to conduct long-term tests, the scale of their test facilities is not sufficient to verify industrial use of the sensors. Many suggestions were noted regarding potential test sites and the resources that exist throughout the world, but the general consensus was the need for a national, standardized, pilot- or industrial-scale test bed.

Table 4-3-1 presents the detailed results for barriers and issues, Table 4-3-2 presents the opportunities, and Table 4-3-3 presents the action plans.

Condition Monitoring

Table 4.3-1. What are the Barriers to Advanced Sensor Systems for Condition Monitoring?

Harsh Environments	Interfaces	Policy	Strain	Point Measurements Relative to the Big Picture	Other Measurements	Performance Testing and design	Dollars
• High temperature environment and ash deposition for condition monitoring • Gasification tars • Sensor stability	• Control system interface • Friendly operator interface • Lack of bi-directional data networking "sensor intelligence"	• Lack of proper regulatory incentives • A third party such as EPRI or DOE needs to issue a report on reliable, accurate, measurement equipment, e.g., NO_x analyzers	• In situ strain measurements • Lack of turbine strain measurement	• Lack of ability to describe not just local conditions, but also distributions • Point level sensors suitable for high pressure (and temperature) letdown of char (approx 9 lb/ft^3 capacitance) does not work • Sensors cannot focus on all the different parts of turbines	• Need models to relate observables to system states (conditions) • An online monitor to detect moisture in coal is needed	• Test facility costs • Design cycle too long • Lack of opportunities to test on complex turbines • Lack of well-defined performance/ cost goals • Lack of affordable test facilities • Lack of conclusive tests • Scaling-system size • Trying to anticipate turbine design changes • Intrusion into gas path	• Customers still buy on first cost and won't pay for sensors/ controls. Need to educate customer/ outreach. • Development costs prohibitive

TABLE 4.3-1. WHAT ARE THE BARRIERS TO ADVANCED SENSOR SYSTEMS FOR CONDITION MONITORING? *(CONTINUED)*

FLOW MEASUREMENT	COMBUSTION STABILITY	TEMPERATURE/EMISSIONS MEASUREMENTS	MATERIALS
• Lack of reliable iso-kinetic sampling • Lack of solid flow measurement in transport reactor • Bulk solids mass flow measurement at 300 psi dense phase and dilute phase capable of 1850 F reverse flow survival • Non-mechanical valve in the hot unit solid flow • Fuel materials handling issues • Lacking measuring capabilities for shear measurement in the gas-solid system	• Need dynamic pressure measurements at high temperature • Sensing combustion dynamics • No way currently to control lean pre-mix combustor flash back/detonation detection/control	• Until high temperature combustion barrier for sensor • Gas path temperature profiles at combustion exit/turbine entry • Turbine blade surface temperature mapping/monitoring • Thermal barrier coating temperature measurement • Lack of reliability of existing sensor systems • Sensing and emissions in the combustion • There is a need for ammonia analysis • Lack of in situ analysis of syngas of 300 psi 1100^{o}F	• Need robust materials • Materials performance limitations • Failure due to harsh environmental conditions • High temperature thermowells for harsh conditions, erosion, corrosion, reducing atmosphere suitable • Very high temperatures • Ability to withstand harsh conditions • Lack of high temperature materials • Temperature ratings of fiber optics • TBC condition monitoring: lack of integrated conductivity • Sensors for turbine environment don't exist

Condition Monitoring

TABLE 4.3-2. WHAT ARE THE R&D OPPORTUNITIES TO OVERCOME THE BARRIERS?

✪ = VOTE FOR PRIORITY TOPIC

INSTRUMENTATION ENABLING TECHNOLOGIES AND STRATEGIES	HIGH TEMPERATURE MATERIALS	MODELING	MATERIALS PROPERTIES DATABSES	VIBRATION/FATIGUE/ STRAIN	CHEMICAL SENSORS	TESTING

• Working group of turbine experts to consult for sensor developers ✪
• Non-proprietary integration of all systems
• Rules/Elimination of rules to ensure plants maximize efficiency while reducing emissions [standardized] ✪✪✪
• Develop fast response transient capable bulk solids mass flow measurement suitable for 300 psi. Must withstand 1850 F and reverse flow ✪
• High temperature FT-transmitting optical fiber
	• Development of enhanced high temperature materials ✪✪✪✪✪✪✪
	  – Material to withstand gas temperature without cooling
	• Enabling materials (for sensors) development ✪✪✪✪✪✪✪✪
	• Develop materials for erosive, corrosive, reducing, high temperature environments ✪✪
	• Development of high temperature corrosive environment temperature sensor
		• Accurate/Robust numerical models
		• Development/verification and use of models to describe distributions of properties ✪✪✪✪
		• Develop lifing data for turbine parts - predict remaining life
		• Accurate multi-phase flow measurement technique
		• Learn how to better equate thermal cycles to steady state hours
			• Centralized data bank for sensor, system data ✪
			• Standard communication protocol for sensor interface ✪
			• Develop lifing data for turbine parts - predict remaining life
				• Non-contact strain measurements
				• Real time calculation of strain in turbine blades; measure and model
				• Real time detection of low cycle fatigue cracking ✪
				• Bearing health monitoring from rotating frame; tot bearing race of bearing vibration; temperature ✪✪
				• Technique for in-service blade vibration monitor especially high pressure turbine ✪✪✪
				  – Real time turbine blade resonance measurement
				• Sensor to measure tip clearance and tip temperature at same time ✪✪
					• Mercury sensor ✪✪✪✪
					• HCN sensor
					• Ammonia sensor ✪✪
					• Develop sensors to measure composition of combustion products, in basket, at full temperature ✪✪
					• An in situ system that can identify combustibles in a selection catalatic reduction (SCR) ✪
					• Develop high temperature high pressure in situ gas analysis system ✪✪
					• Sensors for fuel hydrogen equivalence ratio
					• On line fuel characterization (coal, etc.)
						• Power plant owners that allow sensor development on their turbines
						• Clear definition of cost/performance targets ✪
						• Low-cost test facilities ✪✪✪✪✪✪
						• Pilot to full scale testing of sensors
						• Better access to existing pilot scale and larger systems
						• Measurable, well-defined performance objectives
						• Independent and confidential test facility; incubator for sensors for harsh environments

Condition Monitoring

TABLE 4.3-2. WHAT ARE THE R&D OPPORTUNITIES TO OVERCOME THE BARRIERS? *(CONTINUED)*

✪ = VOTE FOR PRIORITY TOPIC

MISCELLANEOUS CONDITION MONITORING	THERMAL BARRIER COATINGS	VISIONARY OPPORTUNITIES
• Accurate, low cost flow sensor ✪✪✪ • Btu content sensor for fuel stream ✪ • Solid flux radial monitor ✪ • Single fiber high temperature optical sensor for mass and velocity ✪✪✪✪ • Instruments that can withstand high moisture environment, e.g., wet electrostatic precipitation (ESP) • On line corrosion monitoring/measurement ✪✪✪ • Uncooled dynamic pressure sensor for high temperature use ✪✪✪✪ • High temperature eddy current probe • A "tri-corder" for turbines; external measurement; non-intrusive ✪✪ • Flame monitoring and characterization method ✪✪✪✪✪✪✪✪✪✪✪ • High temperature, stable, temperature sensors ✪✪✪✪ • High temperature "through the case" sensor for carbon particles ✪ • High temperature pressure sensor ✪ • Develop reliable point level measurement for hot fluffy char ✪	• Pyrometer for measuring and monitoring thermal barrier coating ✪✪✪✪✪ • Develop sensors to sens, on line, "blistered" thermal barrier coating at 2700°F • Method for monitoring TBCs	• Data/Sensor fusion: sensors with multiple uses • Life estimation of rotating parts based on multiple sensor input • Data mining opportunity (we may have to learn how to use the data) • Predicting maintenance systems – combine sensors with lifing models • Integrated physical models for advanced control systems • Life cycle model component and system • Predictive/adaptive control • Fault detection diagnostics • Need a better "big picture" view; better definition of entire system • Smart burner system; burner sensor(s) send signal to control system, automatic adjustments are made • Failed or marginal sensor detection system with calculated value substitution • Control systems for solid fuel flow • Process monitoring to optimize plant operation (includes sensor data validation) not a control system • Systems integration; integration of sensors, actuators, various plant components • Define (anticipate) actuator needs and requirements • Develop dynamic models of Vision 21 plants • Learning based plant controls • Develop integrated control/sensor/diagnostic suite – give owner $ weighted options for operation at max revenue • Intercommunication between multiple sensors (quorum sensing) • Intelligent sensors with decision rules embedded • Purge ports for transport reactor that self clean and use very little purge gas • Index to measure effectiveness of diagnostic or efficiency improvements • Remove source of variation rather than sensing when something's wrong

Condition Monitoring
TABLE 4.3-3. ACTION PLANS

TOPIC	APPLICATIONS: WHAT/WHERE (THINK CROSSCUTTING MULTIPLE APPLICATIONS)	R&D PRODUCTS AND CHARACTERIS-TICS	CRITICAL STEPS	INTEGRATION: LOGIC ALGORITHMS ACTUATORS, NETWORKS (THINK SYSTEMS)	RESOURCES: PEOPLE, LABS, TOOLS, INFORMATION	TEAMING: LEAD AND COLLABORATION	DOLLARS AND SENSE
Flame Monitoring and Characterization Method	• Application – pulverized coil boilers • Application – gas turbines • Location – place where the flame should be • Location – place where the fame should NOT be	• Measure combustion efficiency/stability • Measure fuel/air equivalence ratio • Special analysis of flame • Temperature/combustion efficiency characteristics • Needs to last for service interval of engine/plant • Chemical species, emissions	• Buy the commercially available systems, see if they work • Identify high temperature material necessary	• Measurement and control of fuel and air streams (sticking point)	• Laboratory combustion facility needed • Independent testing organization to validate • Siemens Westinghouse burner test facility	• OEM • National Labs • Vendors • Universities for basic research • End users • Technology developers	
Enabling Materials for Sensor Development and Development of Engineered High Temperature Materials	• Pulverized coal • Thermal well • Turbine • Combustor • Coal gasifier	• TW for coal gasifier 1850-2100°F corrosion reducing atmosphere 350 psi – 900 psi • Corrosion and erosion resistant • Point level probe suitable for 350-900 psi 450°F dielectric ≈1.2-1.6 hot fluffy char 9 lb/ft^3 • Primary stage for slagging gasifier 2600°F • Gas turbine combustor probes need 4000°F and 600 psi	• Independent verification that probe/sensor works as claimed	• Material database • Combustion neural net with RPMBC for allowing extrapolation, quick training and user feedback • Characterization is an issue must be able to model it	• National labs • Materials prep (Ames Lab) • Universities • Sandia DOE labs, LANL • Sensor materials research labs • Materials test facility • University materials labs and staff • Solid state labs thin film technology	• Universities do fundamental research then license • National labs	• \$100 M • 5-8 years

CONDITION MONITORING
TABLE 4.3-3. ACTION PLANS *(CONTINUED)*

TOPIC	APPLICATIONS: WHAT/WHERE (THINK CROSSCUTTING MULTIPLE APPLICATIONS)	R&D PRODUCTS AND CHARACTERIS-TICS	CRITICAL STEPS	INTEGRATION: LOGIC ALGORITHMS ACTUATORS, NETWORKS (THINK SYSTEMS)	RESOURCES: PEOPLE, LABS, TOOLS, INFORMATION	TEAMING: LEAD AND COLLABORATION	DOLLARS AND SENSE
Low Cost Test Facilities	• Combustion • Component test facilities • Pilot or large scale system testing • Large scale combustion	• Large scale combustion test facility ~40 MW thermal • PSFD for gasification and turbine combustion testing • "Consumer Report" independent center for technology testing	• Survey existing test facilities • Specify lab requirements • Data base of test facilities and capabilities	• Coordination of tests – lots of experiments on one "test build"	• Program instrumentation working group for piggyback (PIWG) testing of new sensor technologies • Southern Company for pulverized coal system testing via vision 21 • Kingston via DOE/EPRI for pulverized coal • ALSTOM Power for industrial scale test facility • University AL at Birmingham/ Southern Research Institute, Pilot coal combustion • University of Utah PC test facility		• $10 M to build pilot • $200 M for PC

TABLE 4.3-3. ACTION PLANS *(CONTINUED)*

TOPIC	APPLICATIONS: WHAT/WHERE (THINK CROSSCUTTING MULTIPLE APPLICATIONS)	R&D PRODUCTS AND CHARACTERIS-TICS	CRITICAL STEPS	INTEGRATION: LOGIC ALGORITHMS ACTUATORS, NETWORKS (THINK SYSTEMS)	RESOURCES: PEOPLE, LABS, TOOLS, INFORMATION	TEAMING: LEAD AND COLLABORATION	DOLLARS AND SENSE
Pyrometer Measuring and Monitoring for TBC	• Location – turbine blades; as many as you can; 1st and 2nd coated • Turbine blade coating monitor • Combustor tiles and liners	• Pyrometry of TBC enables both surface temperature measurements and TBC integrity monitoring in real time • 8-10 microns fiber optics stop at 2 • Life in service • 1500°C • 15% Oxygen • 3% Steam • Need optical access, ¼”	• Develop reliable solid-state detector • Develop mid-IR optical fibers	• I-D vs. 2-D data?	• Can test at a power plant on a newly installed guinea pig turbine • Component testing • PIWG • Westinghouse Plasma can do testing • PWIG and government advisors (NASA, AFRI, DOE, ORNL) ranked surface temperature and TBC health monitoring as high, priority needs	• Air force DOD are interested and involved aero turbine	• $½ million over 3-4 years

APPENDIX A

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