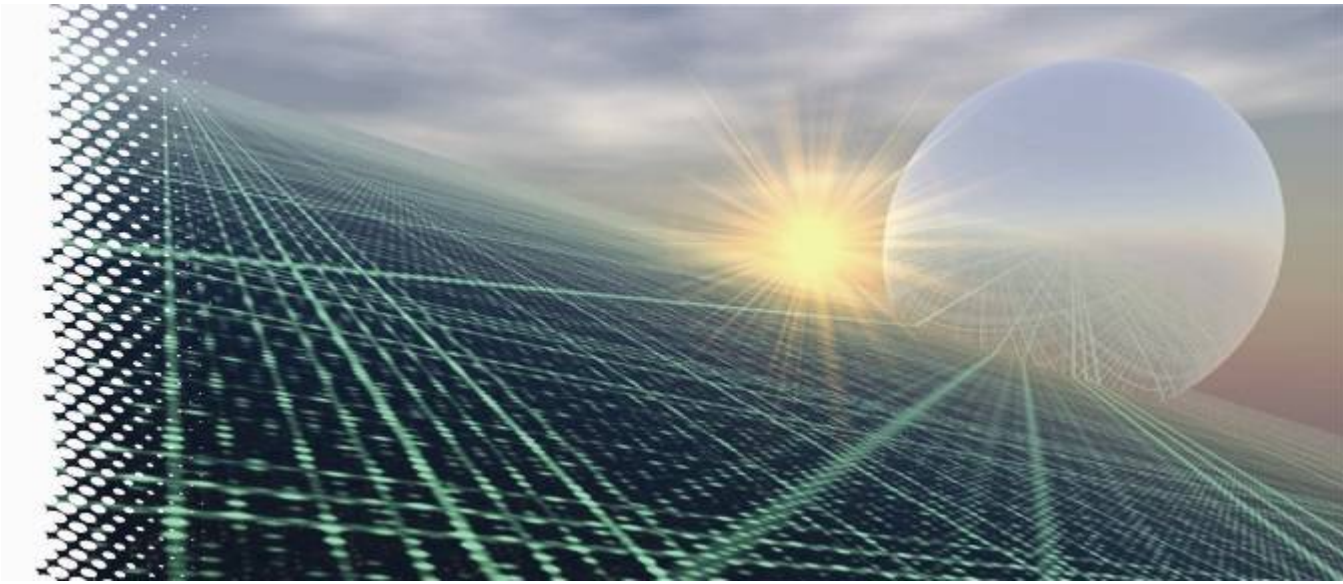
NATIONAL ENERGY TECHNOLOGY LABORATORY



Development of Harsh Environment Sensor Platform for Fossil Energy Applications

Robert R. Romanosky

Advanced Research Technology Manager

Overview

- About NETL
- The importance of power
- Technologies for clean power
- Sensing and Control for power generation
- Sensor development for harsh environments
- Sensor networks for advanced control
- Computational approaches
- Conclusions

National Energy Technology Laboratory

- **Only DOE national lab dedicated to fossil energy**
  - Fossil fuels provide 85% of U.S. energy supply
- **One lab, five locations, one management structure**
- **1,200 Federal and contractor employees**
- **Research spans fundamental science to technology demonstrations**

Alaska

Oklahoma

Oregon

Pennsylvania

West Virginia

Partners in Innovation and Implementation

DOE Offices

Technology Developers and Vendors

Universities

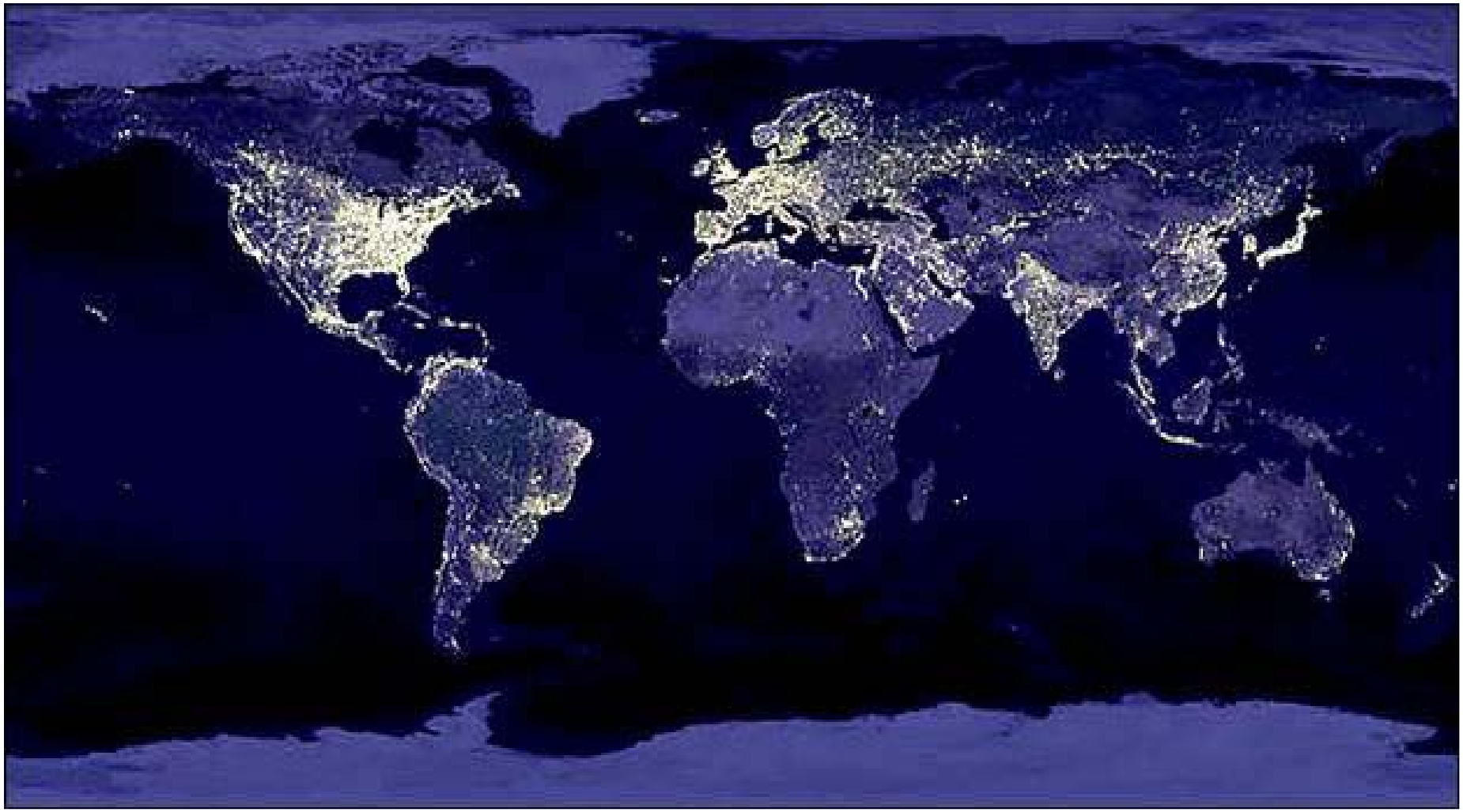
Small Business

Other National Laboratories

Other Government Agencies

Power Industry

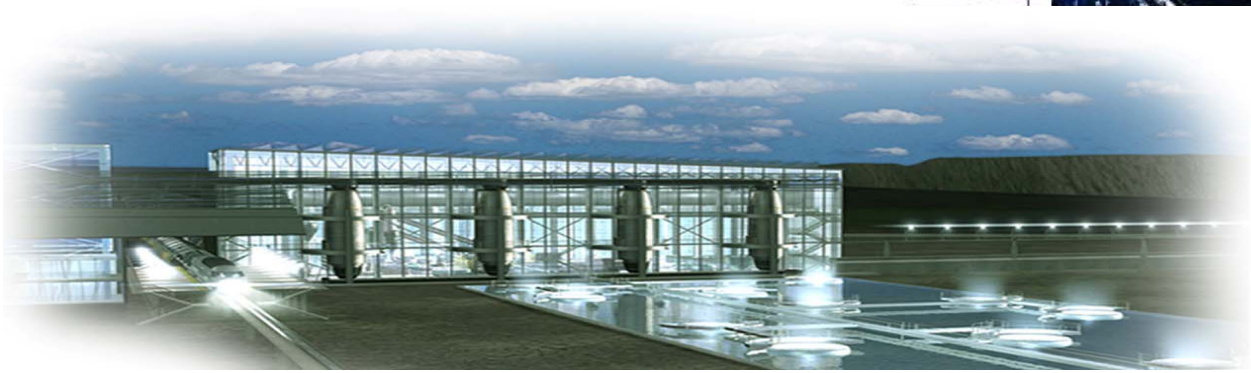
Distribution of Power: Worldwide



Target for Sensor and Controls

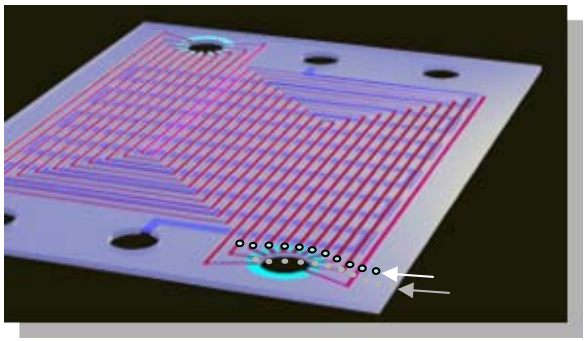
Seamless, integrated, automated, optimized, intelligent power and fuel production facilities

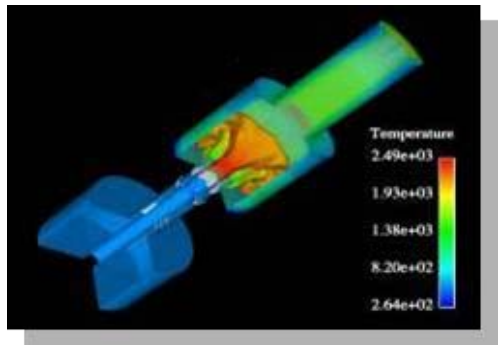
Identify and execute research and development for sensing and advanced process control to help ensure that key technologies will be available to meet the needs of future near zero emission power systems



Advanced Research Program

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





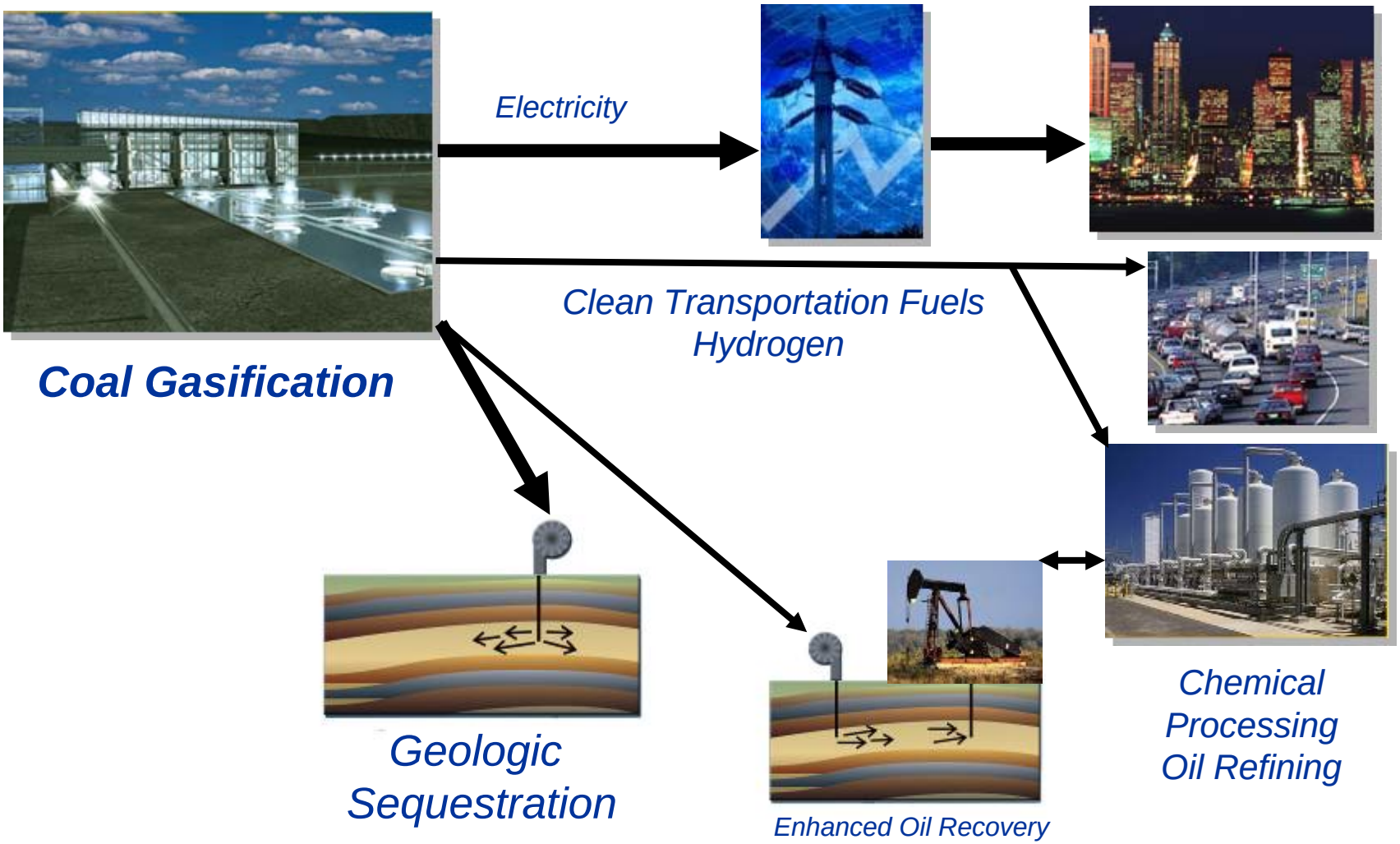
Bridge the gap between fundamental and applied technologies

Reflective of industry needs and responsible for driving new technologies

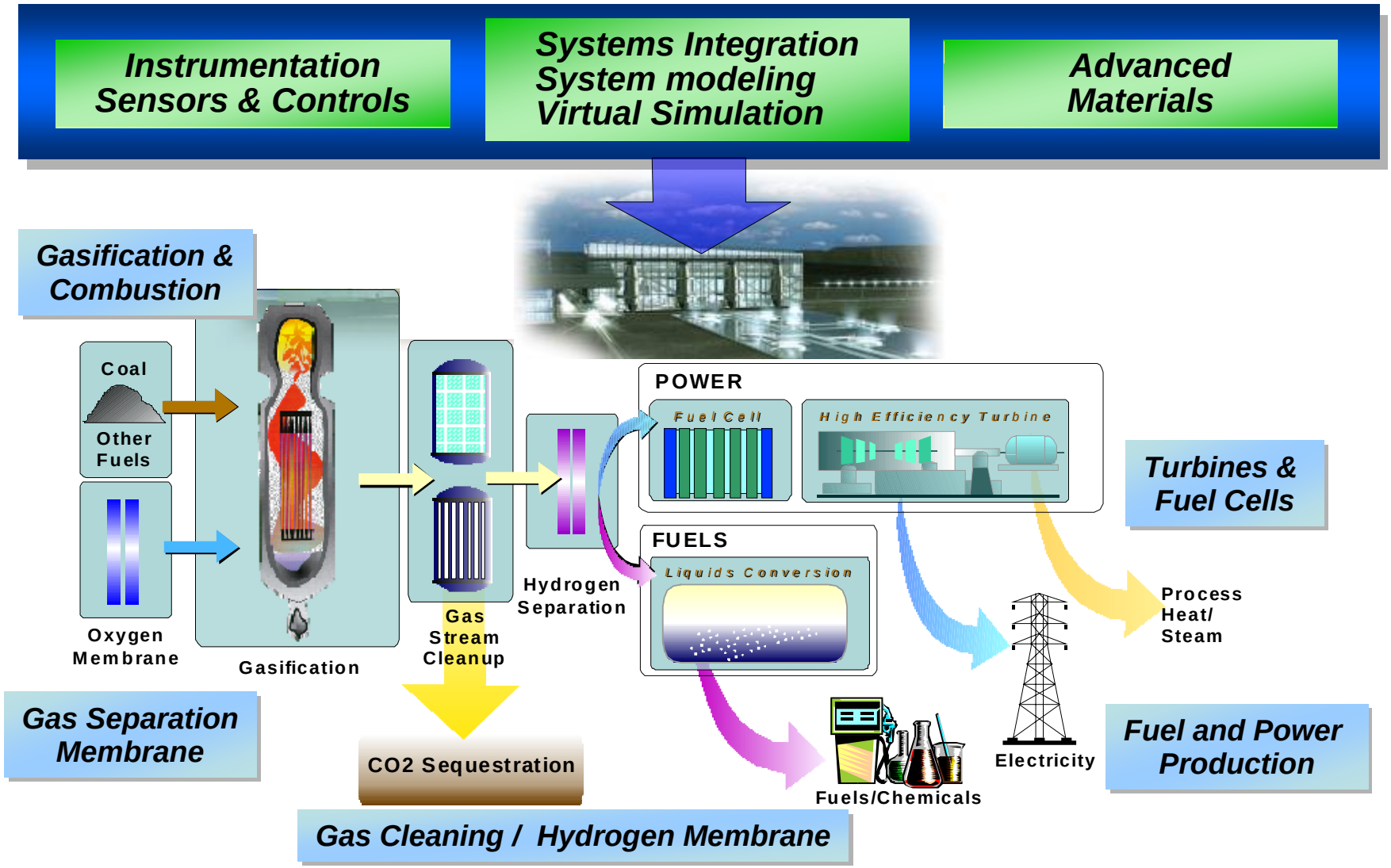
Develop technologies that address critical needs for Fossil Energy

Advanced Power Generation

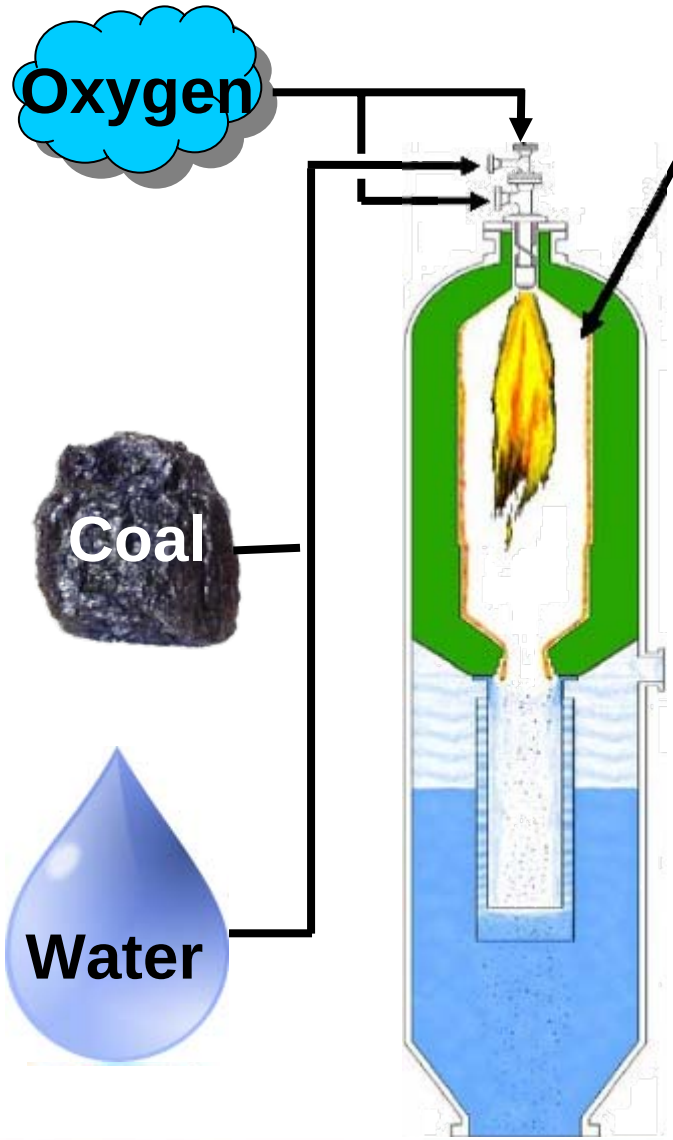
Multi Product Capability



Ultra-Clean Energy Plant



What is Gasification?



Extreme Conditions:

- 1,000 psig or more
- 1450 °C
- Corrosive slag and H_2S gas

Products (syngas)

CO (Carbon Monoxide)

H_2 (Hydrogen)

[CO/H_2 ratio can be adjusted]

By-products

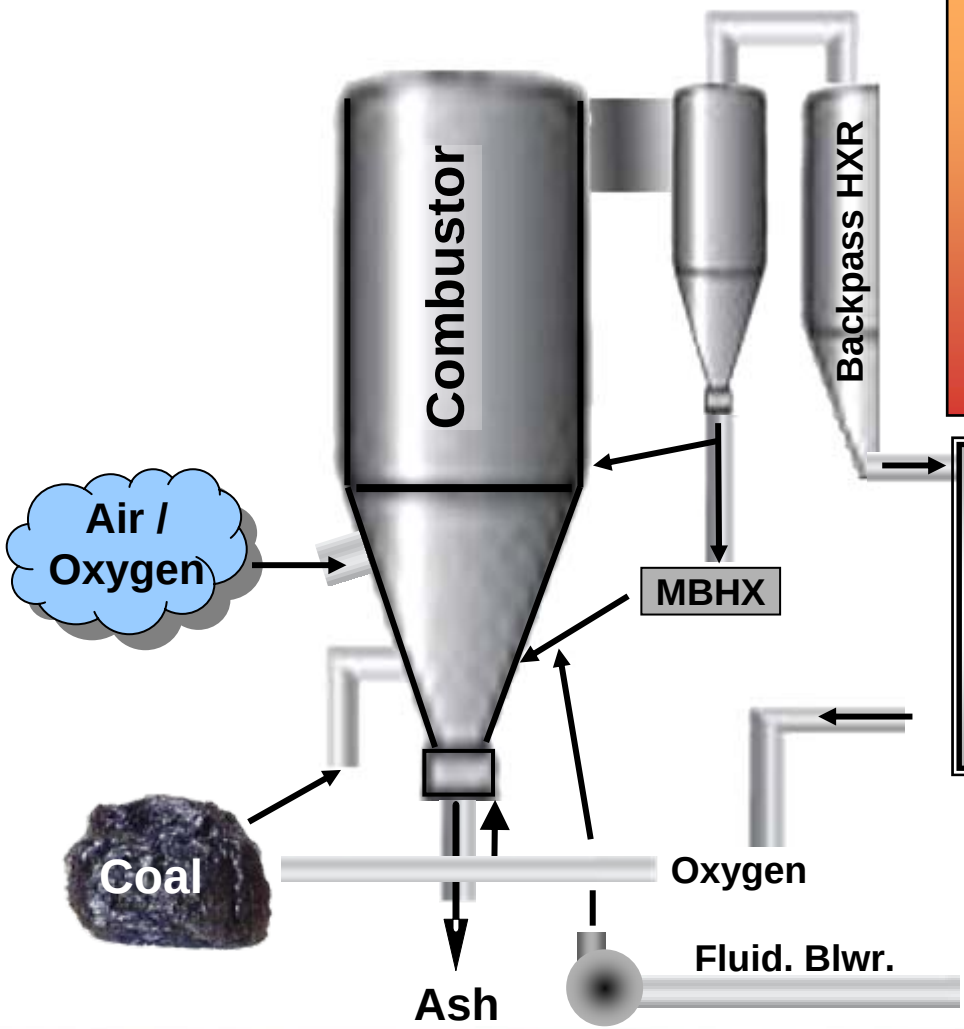
H_2S (Hydrogen Sulfide)

CO_2 (Carbon Dioxide)

Slag (Minerals from Coal)

Gas Clean-Up Before Product Use

What is Advanced Combustion?



Steam Side Conditions

- Up to 760 °C
- Up to 5,000 psi
- Material issues

Combustion Side Conditions:

- Flame temperatures near 2000 °C
- Atmospheric pressure

Combustion Products

CO_2, CO
NOx, SOx
Ash
Trace metals (Hg)

→ To Gas Clean-up

What are Fuel Cells and Turbines?

Solid Oxide Fuel Cells

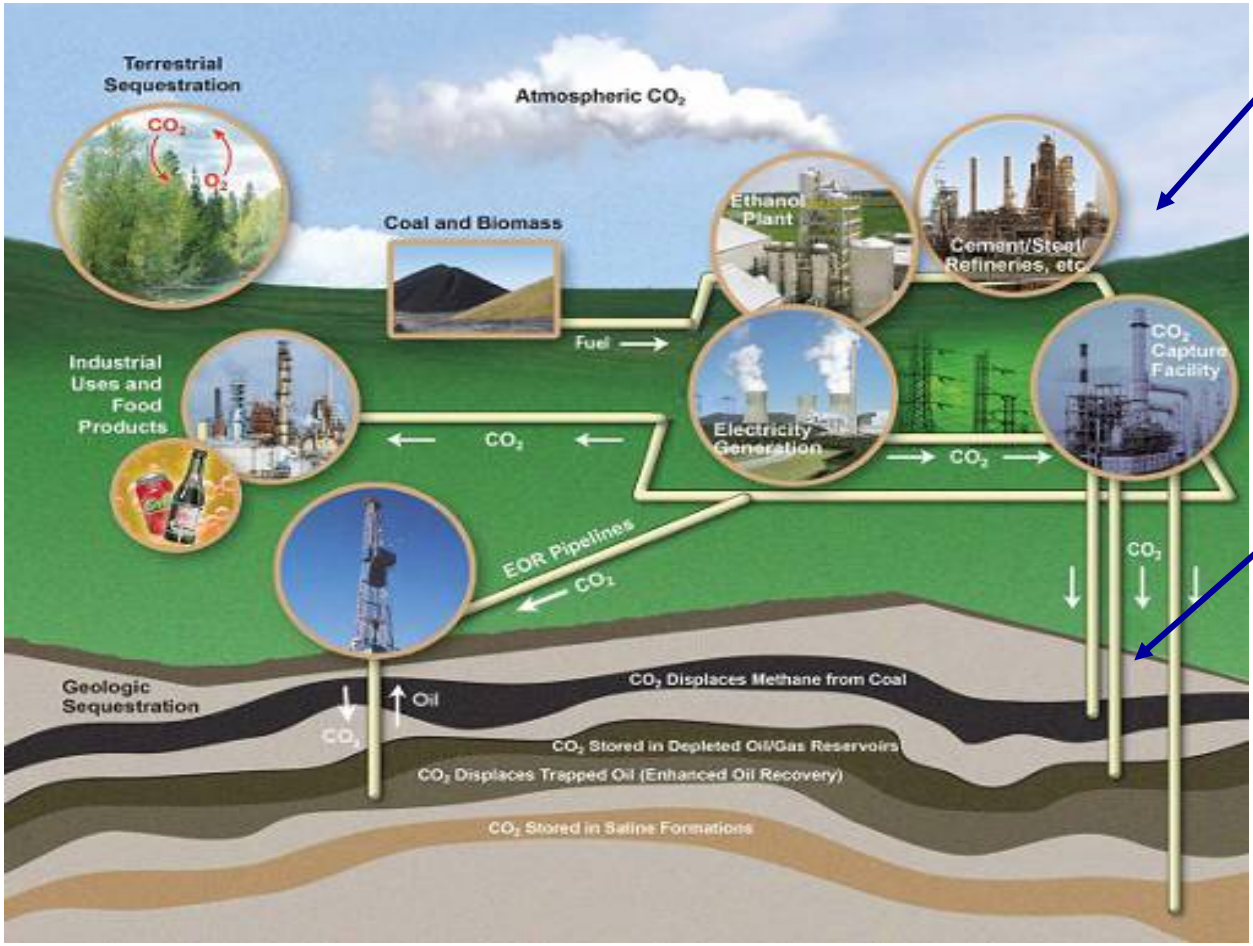
- Utilizes Hydrogen from gaseous fuels and Oxygen from air
- 650 -1000 °C temperature
- Atmospheric pressure

Advanced Combustion Turbines

- Gaseous Fuel (Natural Gas to High Hydrogen Fuels)
- Up to 1300 °C combustion temperatures
- Pressure ratios of 30:1

What Is Carbon Sequestration?

Capture and storage of CO_2 and other greenhouse gases that would otherwise be emitted to the atmosphere



Point Source Capture

Power plants

Ethanol plants

Cement, steel, refineries

Natural gas processing

Geologic Storage

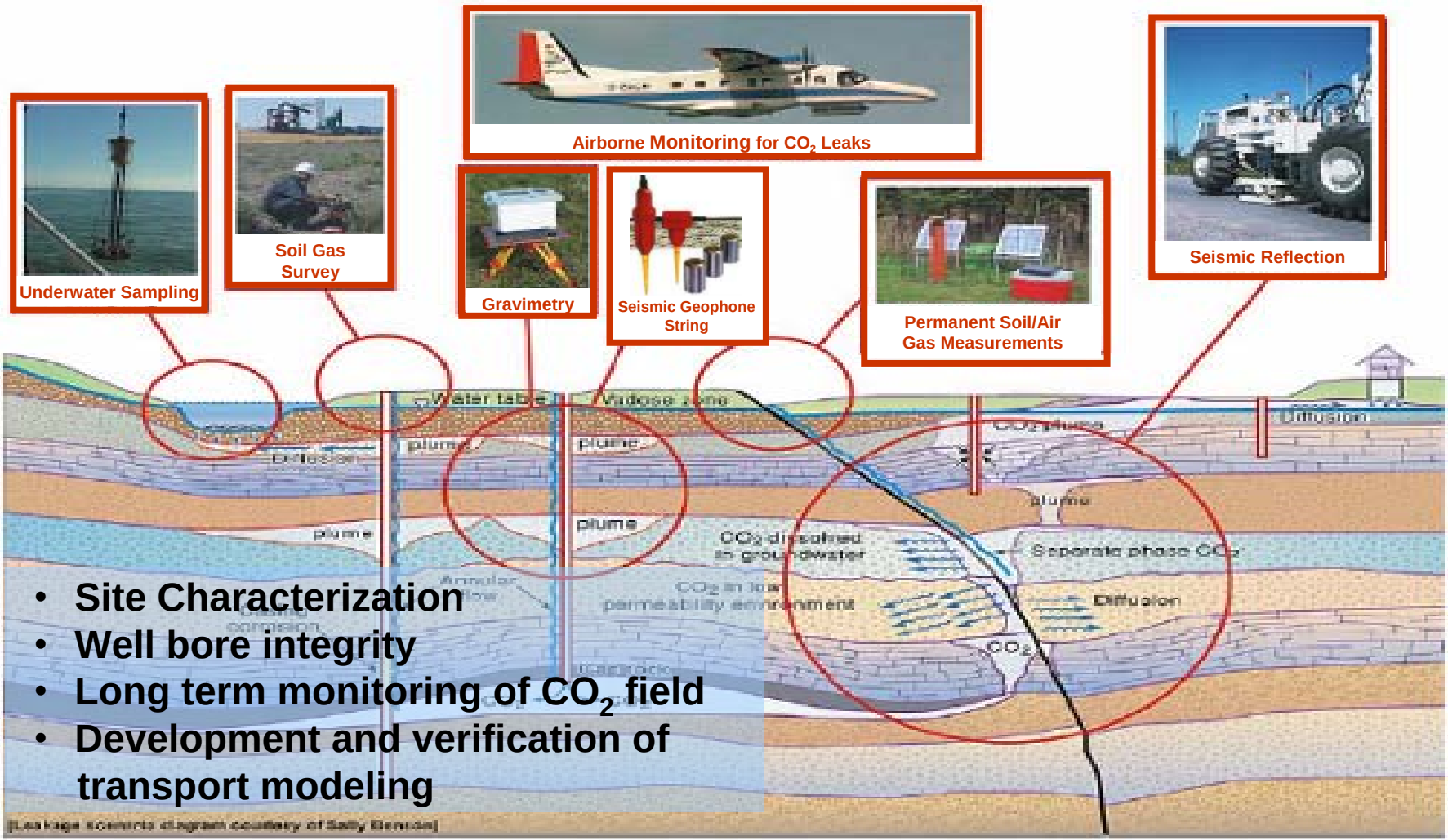
Saline formations

Depleted oil/gas wells

Unmineable coal seams

Basalts, shales, other

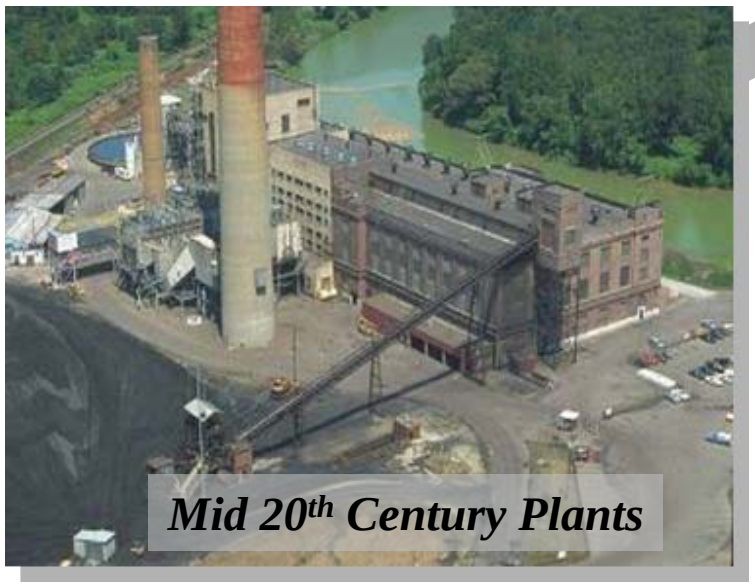
Monitoring, Mitigation, and Verification Needs for Carbon Sequestration



- Site Characterization
- Well bore integrity
- Long term monitoring of CO_2 field
- Development and verification of transport modeling

Technology Challenges

- Zero emissions
- Integrated systems
- Controllable and reliable designs
- Tight tolerances & operating margins
- High temperatures & pressures



- Plant design
- Process modeling and control
- Operations monitoring
  (efficiency, emission, equipment)
- Dynamic & transient mode management
- Materials for harsh environments

Large Scale Central Power Systems Sensors and Controls Needs

Controls

- Supervisory control
- Integrated control
- Neural nets
- Predictive, adaptive control
- Modeling

Advanced Materials

- High temperature Micro sensor materials
- Nano-derived materials

Gas Purification / Separation Environmental Control

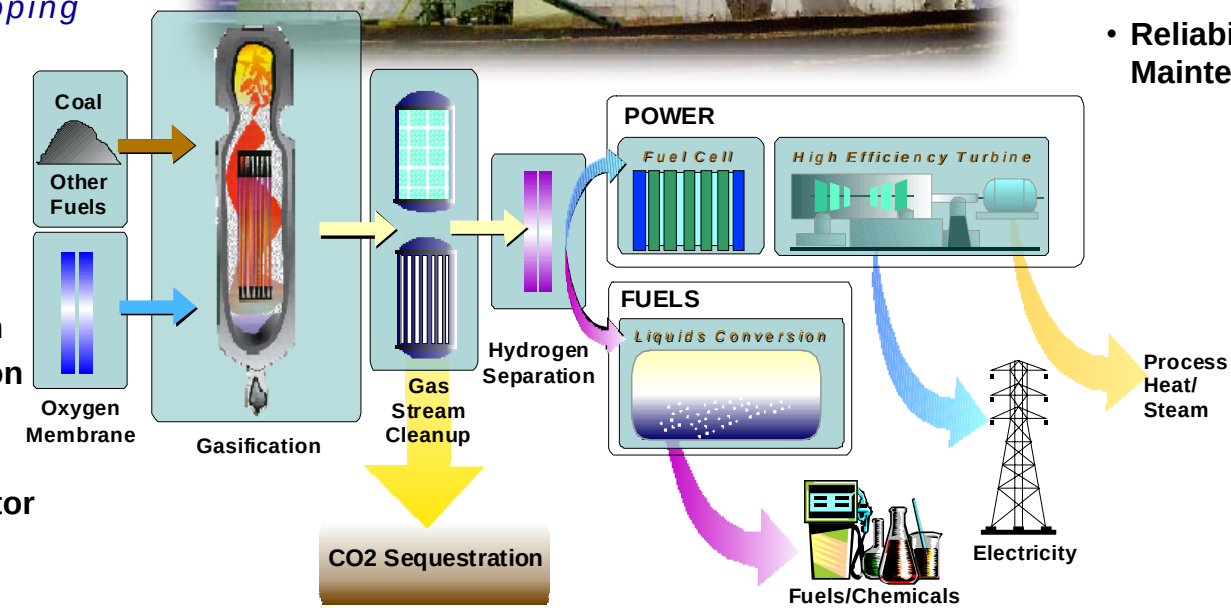
- Mercury Trace Metals
- NOx, SOx
- Ammonia
- CO_2 Monitoring

Turbines

- Temperature
- Fuel Quality
- Dynamic Pressure
- Thermal barrier coating
- Hydrogen
- Fast response
- Lean combustion control
- Reliability and Predictive Maintenance Monitoring

Gasification Chemical Looping

- Temperature
- Gas Quality
- Fuel / air ratio control
- Robust sensors
- Feed flow and Characterization
- Particle Detection
- Standardized signaling
- Corrosion monitor
- O_2 control



Fuel Cells

- Catalyst and electrode monitoring
- Sulfur
- Reformate Quality
- Flow & Pressure
- Diagnostic Capability

2007 Workshop Results

R&D Categories for the Advanced Process Control (APC)

- **Diagnostics/validation- Development of sensor networking, sensor validation/data quality for on line systems, soft or virtual sensors, diagnostics & prognostics, excitation of systems for validation of sensors and controls, and condition monitoring**

- **On-line sensors- Measurement of state variables (temperature, pressure, etc), solids flow, solids state or composition, wear/corrosion/lifetime, steam quality, and gas composition**

- **Computational intelligence- Development of control algorithms, adaptive methods, controls intelligence for complexity management and expert decision systems**

- **Model-based control- Address interface issues with mathematical models, models designed for use in control systems, and development of standard models for public dissemination to facilitate more R&D in this area**

Drivers for New Sensing Technology

- **Advanced Power Generation has harsh conditions through out a plant that need to be monitored with new instrumentation and sensor technology**

- **Target development of critical on line measurements**
  - Sensor materials and designs are aimed at up to 1600 °C for temperature measurement and near 500 °C for micro gas sensors

- **Reduce Total Cost of Ownership of plants / systems by developing and supporting control algorithms and condition monitoring technologies**
  - Focus on improving the reliability, availability and maintainability of existing and future power systems
  - Enable coordinated control for advanced power plants including carbon capture

Contribution from Sensors and Controls

Value Derived for an Existing Coal Fired Power Plant

FUEL COSTS
$39 Million/Year @ 9,500 BTU/kw-hr, $1.25/million BTU's

Non Fuel O&M COSTS
$6 Million/Year (10 - 20% of total costs)

Total Fuel + O&M Budget
$45 Million - Avg. 500 MW Unit

Gaseous emissions

POWER

3,285,000,000 kw-hr/yr @75% Capacity Factor

Solid wastes

Analysis for Year 2000

- **1% improvement in EFFICIENCY**
  - $390,000 savings in fuel
  - $4.1 million for entire installed fossil capacity
- **Approximately 1% REDUCTION in greenhouse gases and solid wastes**

- **1% increase in AVAILABILITY**
  - Yields 33 million kw-hr/yr added generation for a 500MW plant
  - Approximately $2 million in sales (at $60/1000kw-hr)
  - An additional 5,000 MW of power for entire installed fossil capacity

Delineation of Sensor Development

- **Physical Measurements**
  - Temperature, Pressure
  - Flow, Strain/Stress
  - Harsh environment
- **Solid and Gas Measurements**
  - Coal Quality
  - Syngas (H_2, CO)
  - >500 °C targeted

- **Sensor Materials**
  - Fiber optics & substrates
  - Active sensing layers
- **Sensor Design**
  - Selectivity
  - Survivability
  - Responsiveness
- **Sensor Packaging**

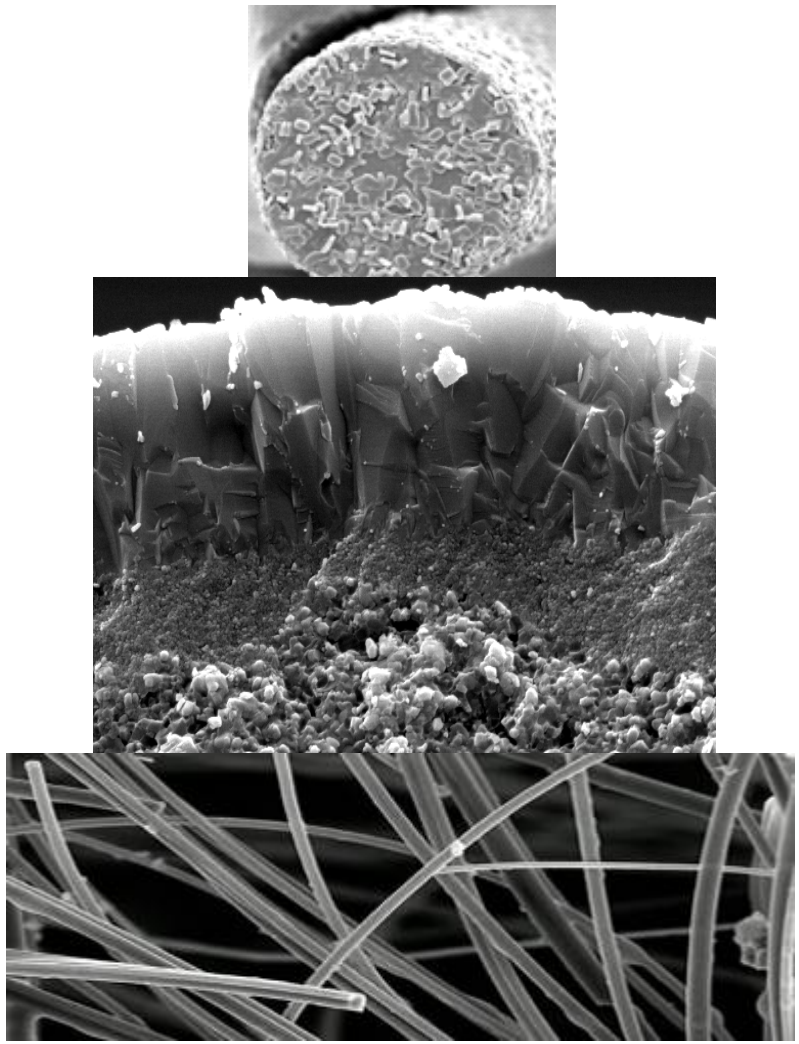
General Sensor Requirements

Fuel Quality	• Coal – Heating Value (C,H, O), Minerals and ash
Fuel Quality	• Natural Gas – CH_4, other hydrocarbons including high MWHC, fast response (seconds) • Synthesis Gas – H_2 (~26%), CO (~37%), byproducts (CO_2) and contaminants (H_2S), ~ 500 °C, up to 800 psi
Exhaust Gas	• NOx – 2-5,000 ppm, SOx 3-5,000 ppm, particulate, Mercury (ppb), CO (ppm-%), CO_2 (%)
Temperature	• 1000 - 1700 °C, highly erosive and corrosive • Packaging for gasifier and turbine applications
Pressure	• Up to 1000 psi, high temperature, erosive & corrosive • Dynamic pressure for turbine applications
Materials Assessment	• On-line refractory for gasifiers, thermal barrier coatings for turbines, piping and tubes for combustion stress/strain, corrosion, cracking

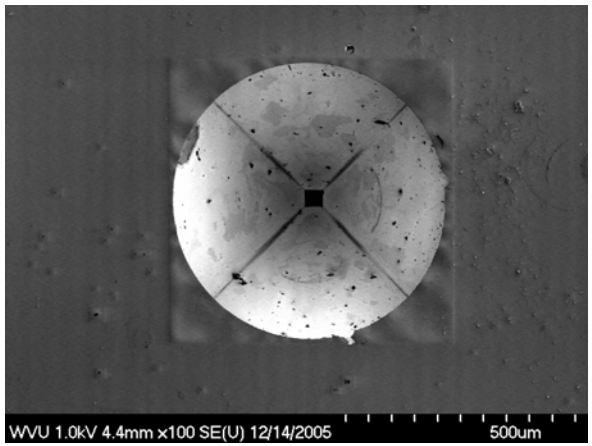
Materials for Sensing in Harsh Environments

(Optical and Micro Sensors)

- Sapphire
- Alumina
- Silicon Carbide
- Doped Silicon Carbide Nitride
- Yttria stabilized zirconia
- Fused/doped silica for certain process conditions
- Active/doped coatings
- Nano derived high temperature materials and structures
- Novel materials for high temperatures (1000 °C)

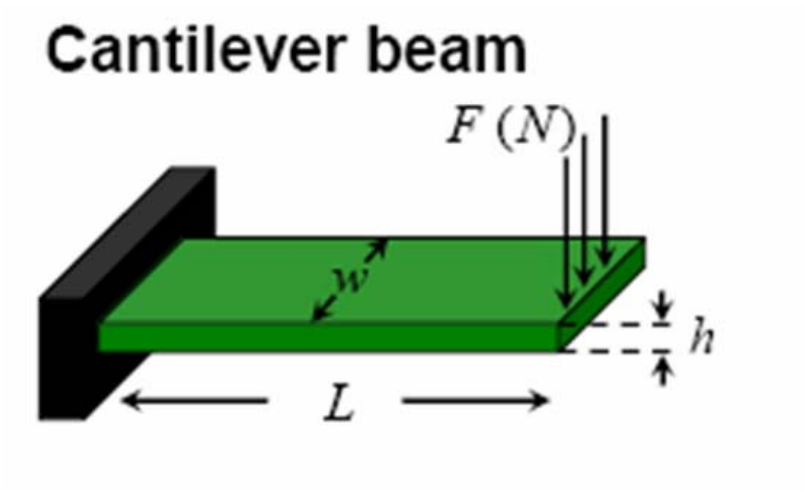


High-Temperature Piezoelectric Materials

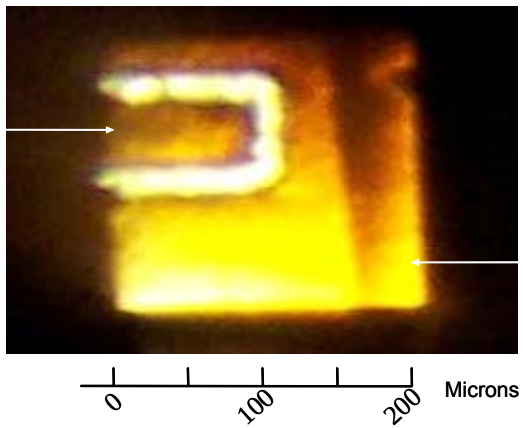


AlN material (WVU)

- **Investigate Piezoelectric properties of Aluminum Nitride at high temperatures (1000 C)**
- **Assess potential for high-temperature actuators and sensors**
- **NETL and West Virginia University**



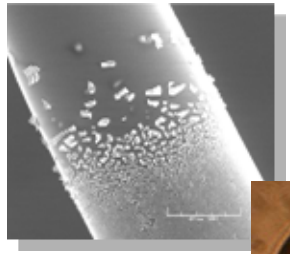
Cantilever Fabricated from a Freestanding AlN/SiO_2 Diaphragm using Laser Ablation



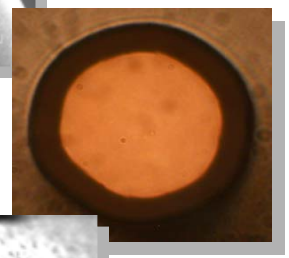
AlN/SiO_2 Diaphragm

Fiber-based Sensor Material Development

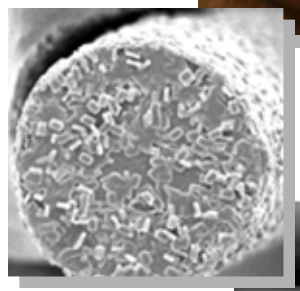
- **Using silica-based fiber sensors to develop distributed and selective gas sensing by depositing active sensing layers onto novel gratings**
- **Driving sapphire materials development for single and multipoint sensing**
  - Targeting coating materials to improve wave guide properties
  - Developing techniques for creation of Bragg and Long period gratings onto sapphire fiber
- **Using silica and sapphire to create radially directed holey fibers for gas sensing**
- **Program participants include VT, Prime Research, UMiss, NMT, UMR, UC, ASU and GE**



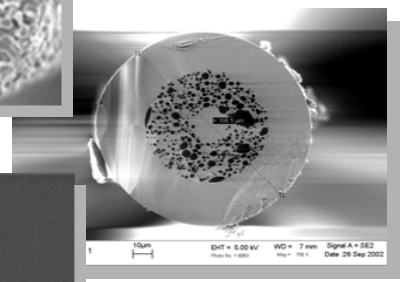
Coated Silica fiber (NMT, UMR, ASU, UC)

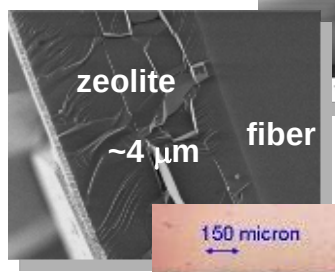


Coated Sapphire Fiber (Prime)



Holey Fiber (VT)

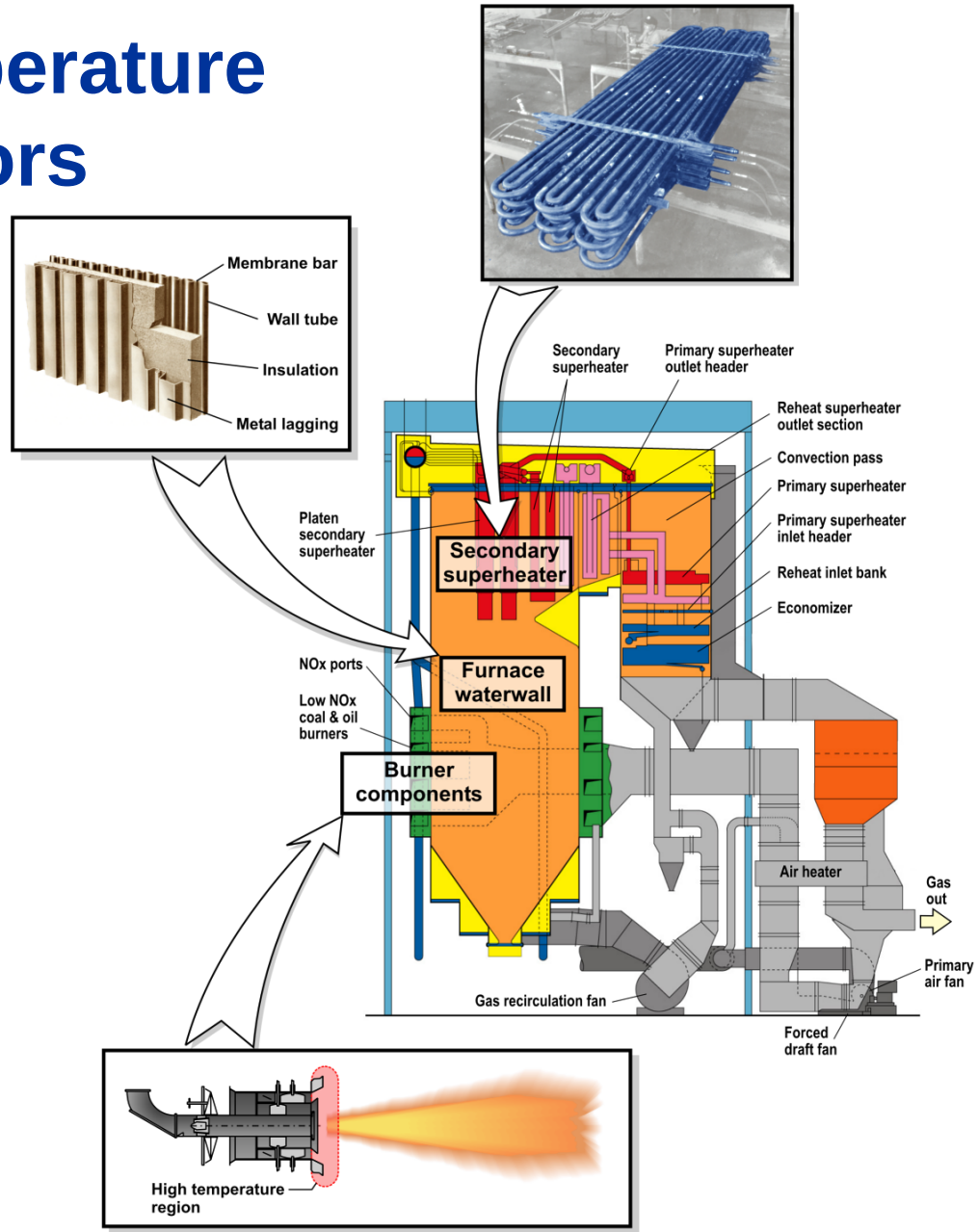




Grating in Sapphire Fiber (PSU)

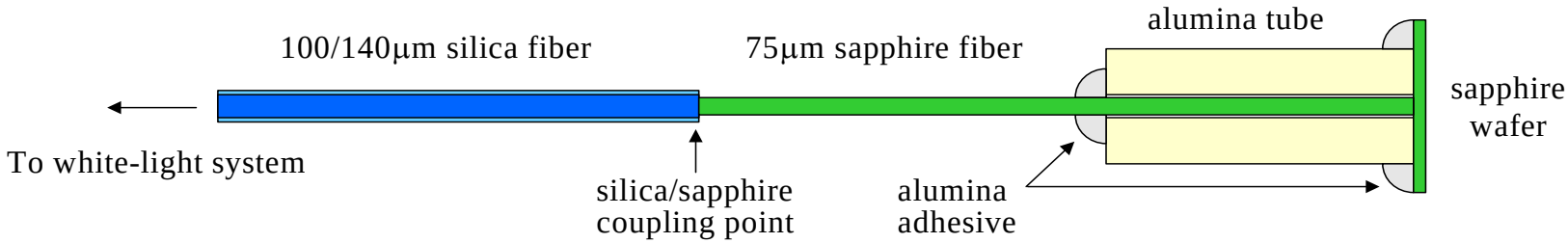
High Temperature Sensors

Specified areas where fiber optic sensors would enable measurements not previously possible

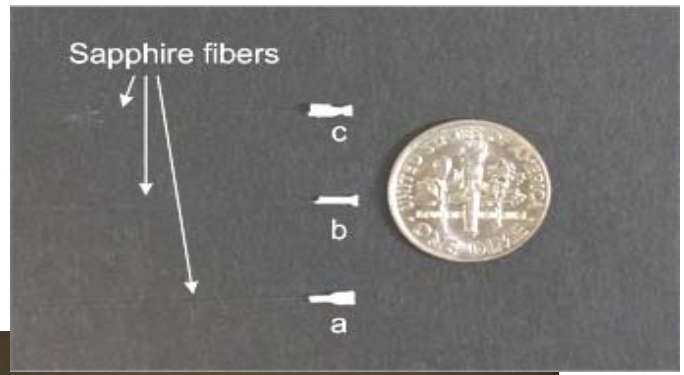


Single Point Sapphire Temperature Sensor

Fabry Perot Sensor System



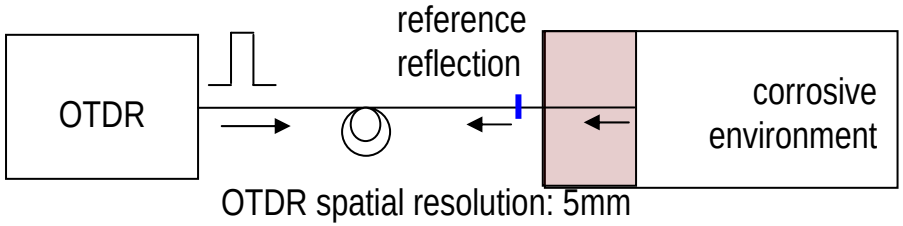
- **Measures temperature up to 1600 ºC**
- **Methods, fabrication, designs, packaging under development since 1999**
- **Full scale testing at TECO**
  - 7 months of operation
- **IP and licensing being evaluated by Virginia Tech**
- **Considering testing on turbines (combustor section)**

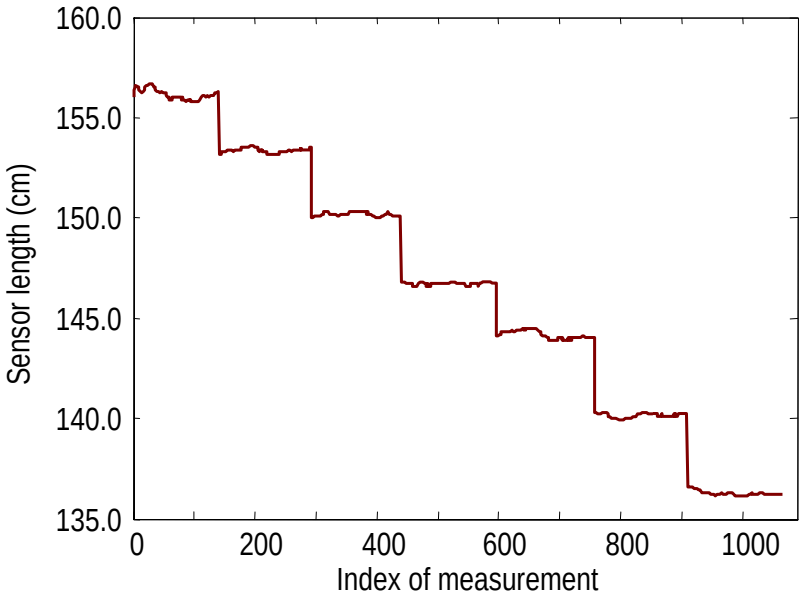


Concept for Refractory Monitoring

Refractory thickness monitor

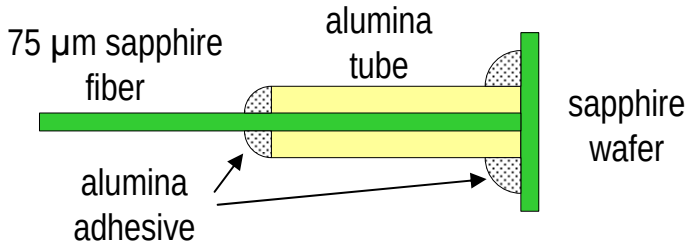
Optical Time Domain Reflectometry

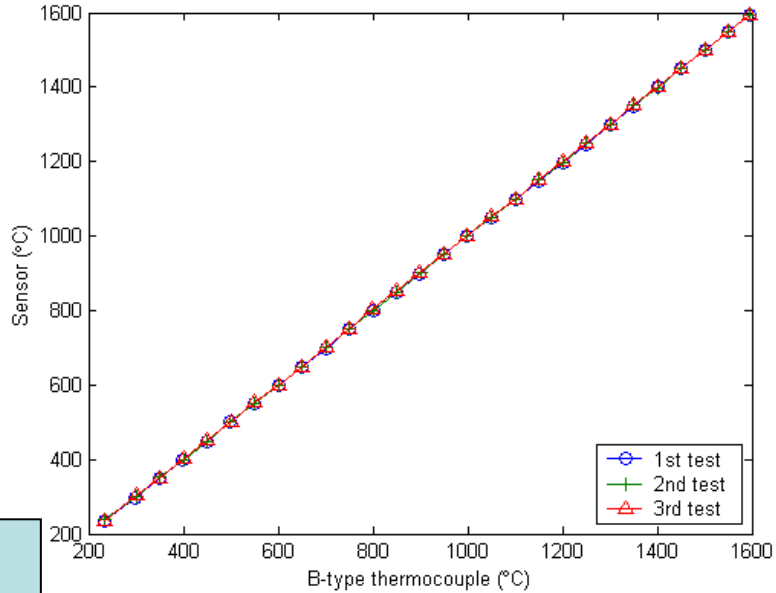




Extreme temperature sensor

Fabry-Perot Interferometry





Fiber length measurement results at 600°C as the sensor was shortened by 180mm in discrete cuts.

Micro Sensor Design

- **Targeting in situ gas sensors for high temperature environments**
  - Target gases for fossil energy environments include NOx, SOx, NH_3, CO, CO_2, H_2, H_2S, and Hydrocarbons around 500°C
  - Silicon carbide, YSZ, etc for substrate materials
  - Metal oxides, precious metals, etc for active sensing materials
  - Sensor arrays, backside heaters, reference elements, etc contribute to robust design
  - Low cost for routine replacement
- **Targeting micro sensors for physical measurements such as temperature and pressure**

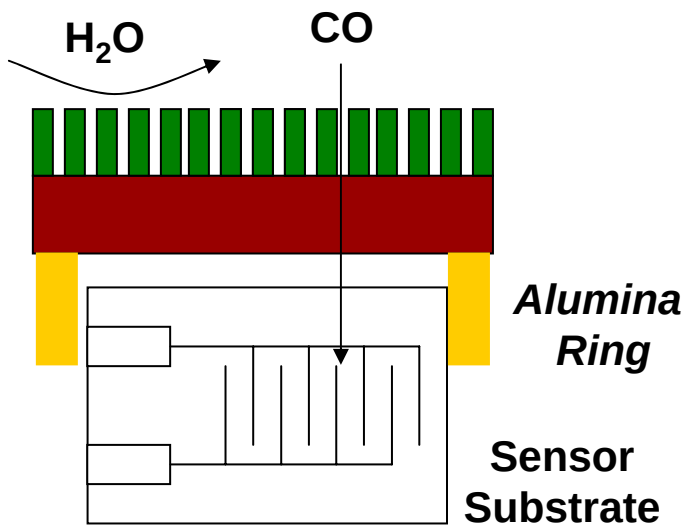
- **Program participants include, SRD, OSU, MSU, Sporian MicroSystems, University of Utah, University of Florida, NETL**

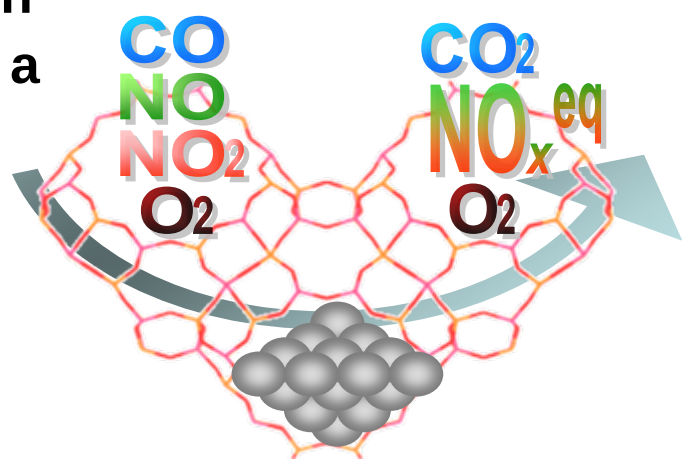
Metal Oxide Gas Sensor Array (SRD)

H_2 Pt/SiC Prototype Sensor (MSU)

Development of Active Sensing Materials

- Enhance selective gas sensing through use of nano derived materials
- Charge exclusion
- Size exclusion
- Layering of materials
- Application of fundamental understanding of material/gas interaction
- Success is in the application of forming a complete sensor structure and the demonstration of the sensor's performance over time
- Nano derived material applications by OSU, UMR, ASU, UC, and GE

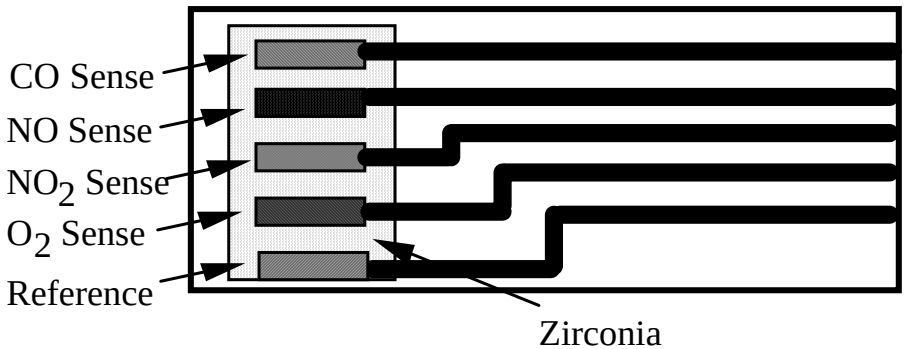


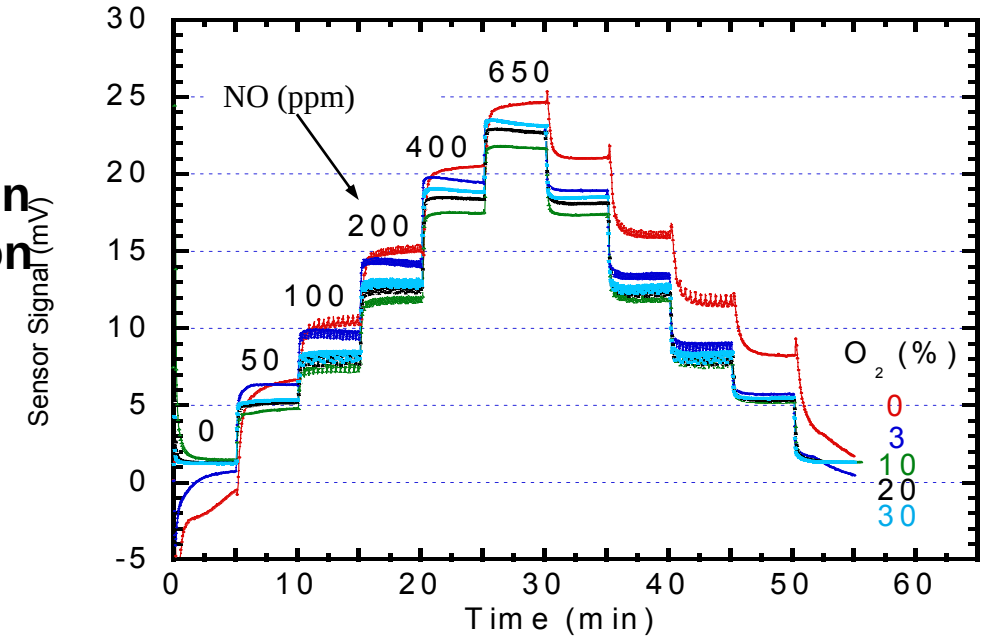


University of Florida

Solid State Micro Sensor Arrays

- **Multifunctional $NO/NO_2/CO/O_2$ solid-state sensors**
  - based on conventional automotive sensor technology
- **Fundamental sensing mechanism based on catalytic/material properties**
- **Demonstrated 1 ppm resolution (e.g. CO) and *selective* detection**
- **Commercializing technology**
  - Licensed technology
  - Developing prototypes



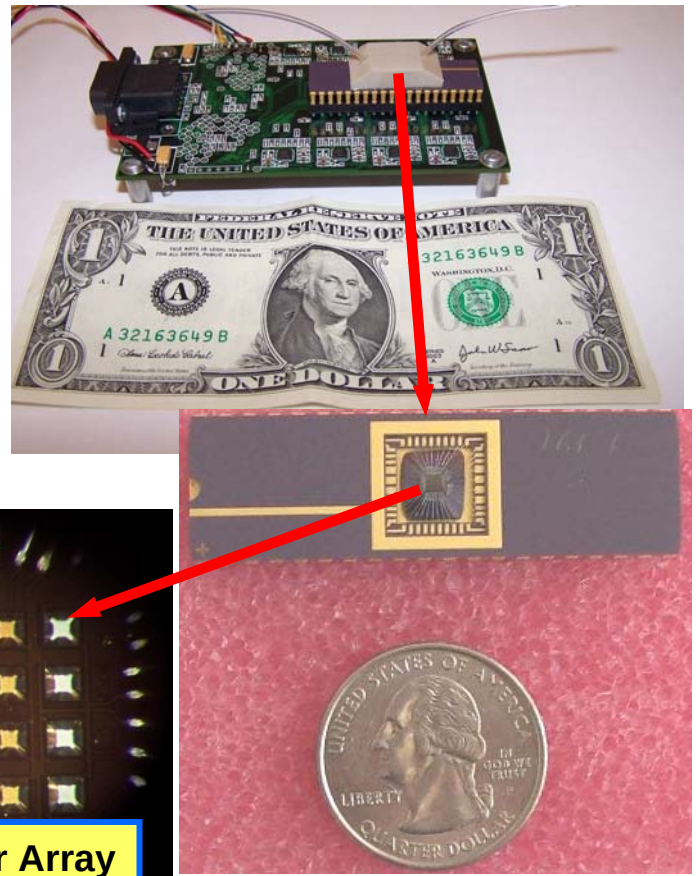


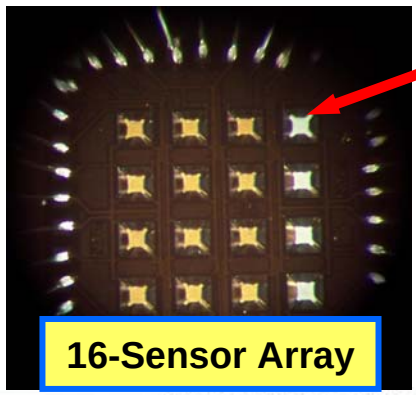
Selectivity: Response to NO in varying O_2 exhaust gas

Sensor Research and Development Corporation

Semi-Conductor Metal Oxide Sensor Arrays

- **Develop continuous, real-time, *in situ* sensors for the detection, identification, and measurement of coal-fired combustion gases**
  - Robust (high temperature < 400°C, corrosive, etc.)
  - High sensitivity (ppb – ppm)
  - Selective detection: CO, CO_2, NO, NO_2, SO_2, NH_3, HCl
  - Customized devices for a targeted gas suite
  - Multiyear sensor element lifetimes in lab conditions
  - Algorithms for gas identification and quantification





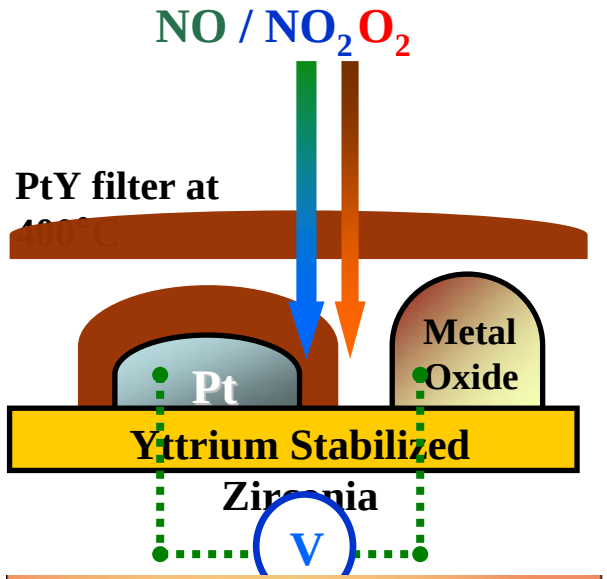
16-Sensor Array

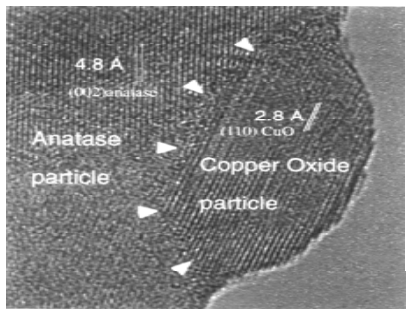
Sensors for Advanced Power Systems

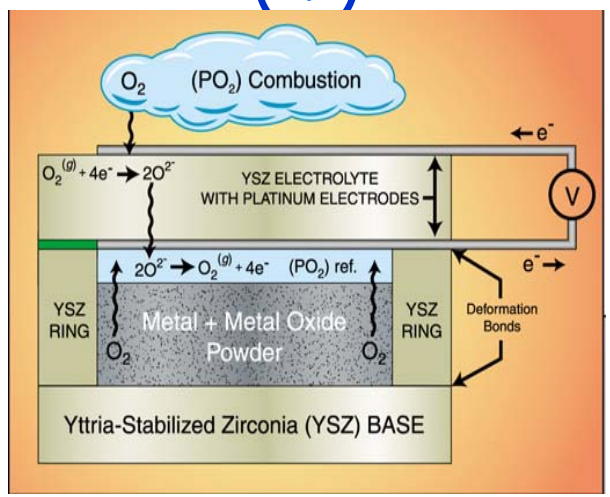
(High Temperature MicroGas Sensors)

- **Ohio State University**
  - CO sensor : 1-10,000 ppm
  - CO2 sensor : 1-10,000 ppm
  - O2 sensor :1-21% air reference free
  - Total NOx sensor :ppb-10,000 ppm
  - Excellent gas selectivity and repeatability
  - Good operation in the 400-800 ^{o}C range

- **R&D 100 Awards (2)**



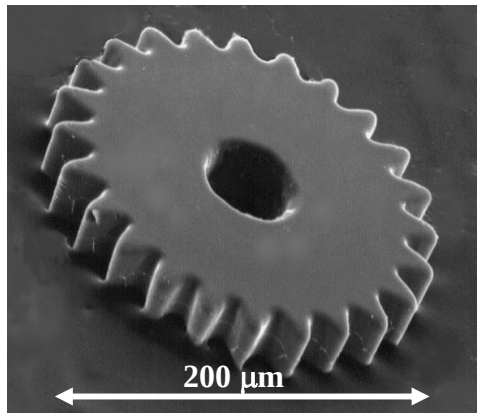


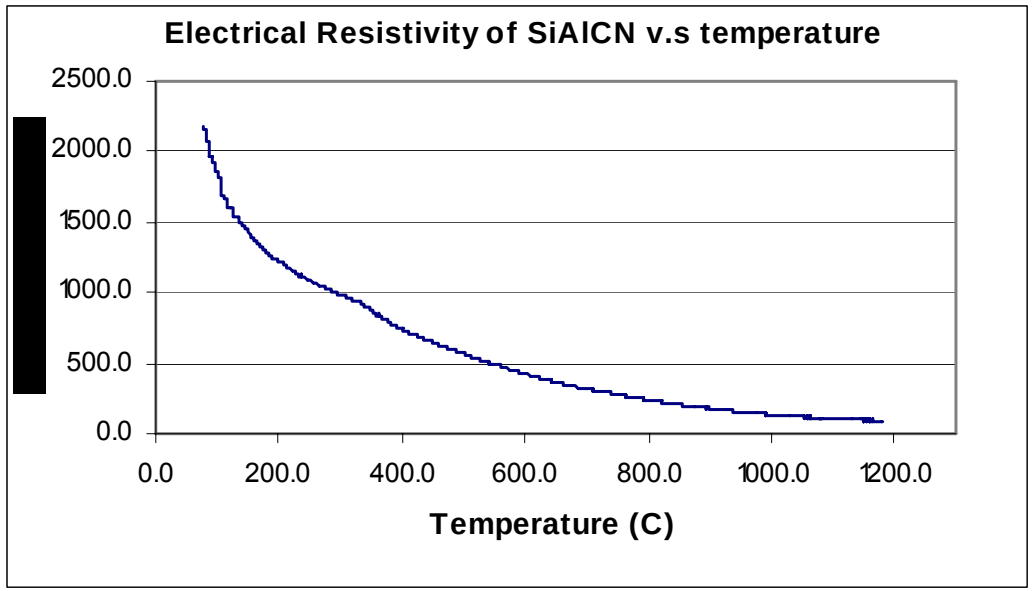


Sensor Materials

SiliconCarbideNitride

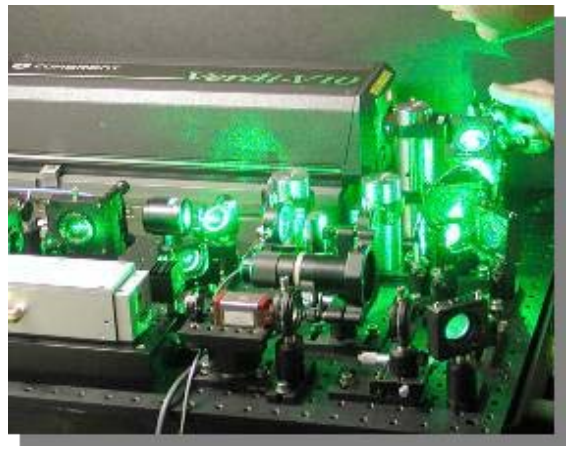
- **Developing conductive/ non-conductive SiCN sensor element for integrated T&P measurement up to 1000 ºC and 1000 psi**
- **Material shows high temperature stability and corrosion resistance**
- **Capitalizes on mature MEMS sensor concepts for low cost fabrication**
- **First to make SiCN-x Ceramic Foam**
- **Sporian Microsystems, University of Central Florida, Sandia National Lab, Siemens**
- **PIWG support for SBIR project**





Optical and Laser Based Techniques

- **Novel approaches for temperature and gas species monitoring**
  - Optical materials, new light/laser sources
  - Detection in pressurized vessels
  - Trace level detection
  - (NO_X, SO_X, particulate, Hg, CO, CO_2, etc)



- **Advantages with these techniques**
  - Non-intrusive, rapid, continuous measurements
  - Readily adapted for regulatory monitoring
  - Relative ease in calibration

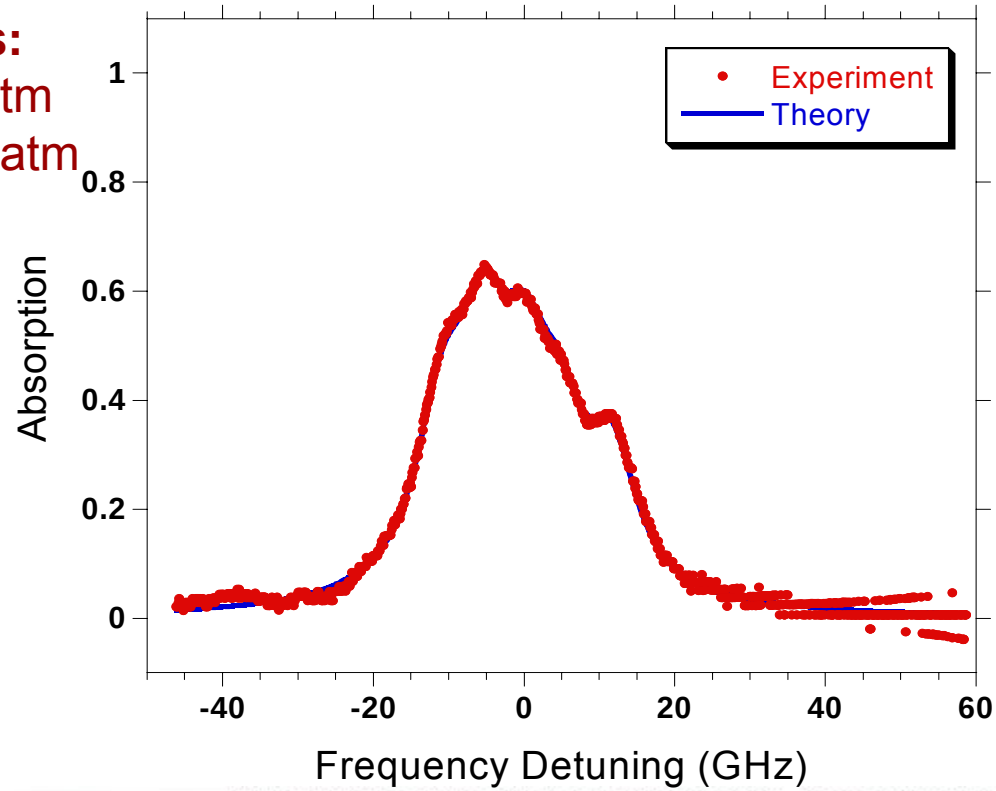
- **Challenges with these techniques**
  - Optical access
  - Rugged, compact, field ready systems

- **Participants include SNL, Nuonics, Purdue, NETL**

Purdue University

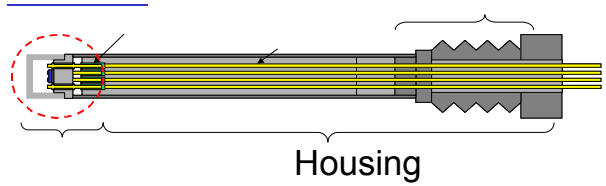
Diode Laser Sensor for Atomic Mercury

- **Optical absorption measurements of mercury made using 253.7 nm using ultraviolet light generated by sum-frequency-mixing of 784-nm DFB diode laser radiation and 375-nm ECDL radiation**
- **Unaffected by SO_2 and other broadband absorbers or scatterers**
- **Atomic Hg detection limits:**
  - 0.1 ppb-m at 300 K, 1 atm
  - 0.3 ppb-m at 1000 K, 1 atm
- **Laboratory Development**
  - Hg vapor in 1 atm of N_2
  - 109 ppb in 15 cm path
  - Pilot scale testing planned for 2006

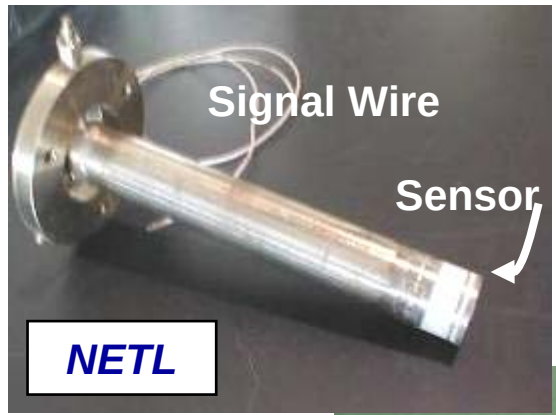


Sensor Packaging
(Design, Materials, Technology Transfer)

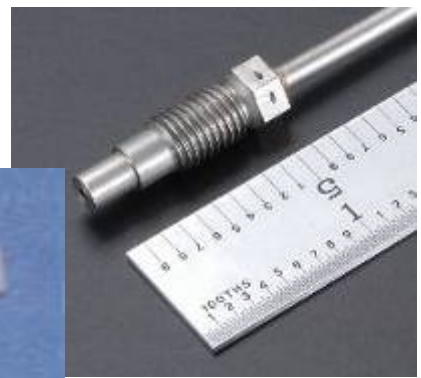
- **Package sensor to enable exposure to environment but protect for adequate performance**
  - Chemical exposure, electrical lead failure, mechanical thermal expansion considerations
- **Ease in handling, installation, replacement**
- **Barrier for technology transfer**



Sporian

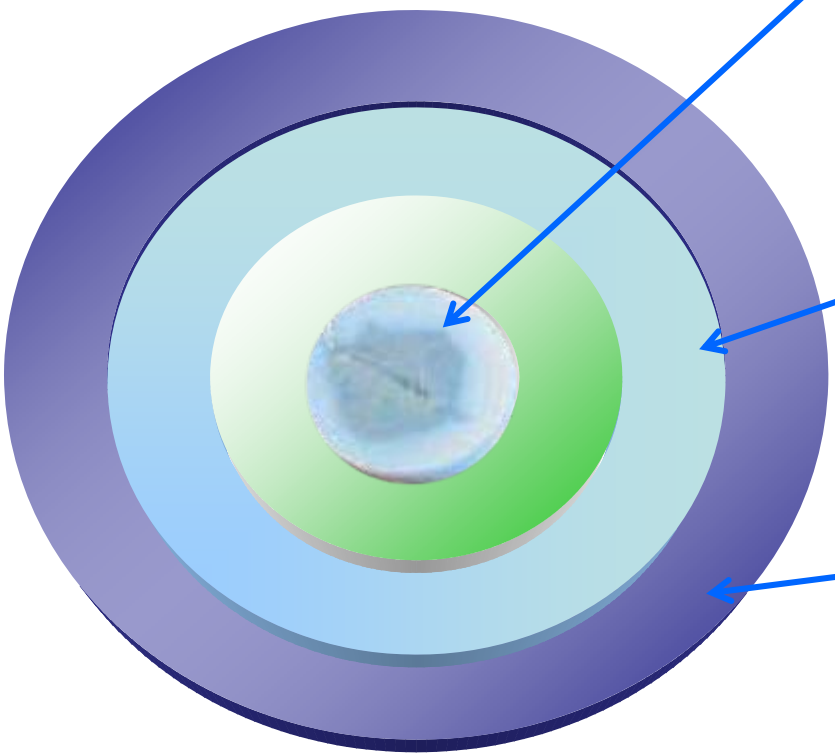


Prime OSU



Sensor Development

Targeting Development of Commercially Viable Sensor Technologies

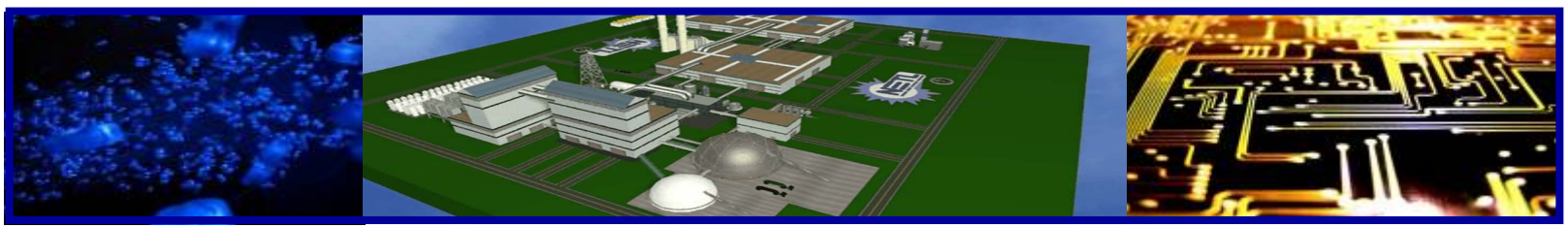


- ***Feasibility / Proof of Concept***
  - *Materials*
  - *Basis for sensing*
  - *Fabrication of device*
  - *Selectivity*
  - *Accuracy*
  - *Identification of failure mechanisms*
- ***Demonstration of Sensor Performance***
  - *Sensor design*
  - *Sensor packaging*
  - *Survivability followed by performance*
  - *Portability, connectivity, ease of use*
- ***Technology transfer / Commercialization***
  - *Commercialization plan (license vs. sell)*
  - *Testing*
  - *Ability to manufacture*
  - *Letting go of the technology and embracing the business*

High Density, Heterogeneous, Massive Sensor Nets for Process Systems

- Sensors are small, inexpensive and thinking
- Massive real time data sets - “data storm”
- Current sensing and control strategies don’t work
- A new sensor/control network strategy is envisioned
- Computing is highly capable and ubiquitous
- Complexity - almost unmanageable but is the new frontier

- Utilize and extend capabilities of virtual engineering
- Build and test various sensor network strategies
- Principles of model integration can be extended to sensors based on engineering objects
- A physical sensor is just a special type of object in the virtual engineering world



Use of Virtual Engineering

- Study interactions between individual components and plant performance
- Optimize plant components from the subcomponent level to the plant performance level
- Integrate sensor strategies into virtual power plant and evaluate
- Aid in engineering decision making including design, construction, operation, and maintenance
- Explain to the public and other nations how this technology works

Conclusions

- **Challenges require innovation at all levels**
  - Creation of low cost reliable, zero emission power and multi product large scale plants utilizing domestic resources will require advanced sensors and controls for operation and achievement of performance goals

- **Value in reduction to practice**
  - Development of individual S&C technologies, including enabling technologies, are required but value is derived from integrating, adapting, networking, packaging for systems and plant level operation and control

Working with NETL

- **Competitive Solicitations (Open, University, Small Business)**
  - Option to waive patent rights to recipients
- **Cooperative Research and Development Agreements (CRADAs)**
- **Bench Scale Test Facilities**
- **Partnering with NETL and Industry for testing of sensors on full scale systems**

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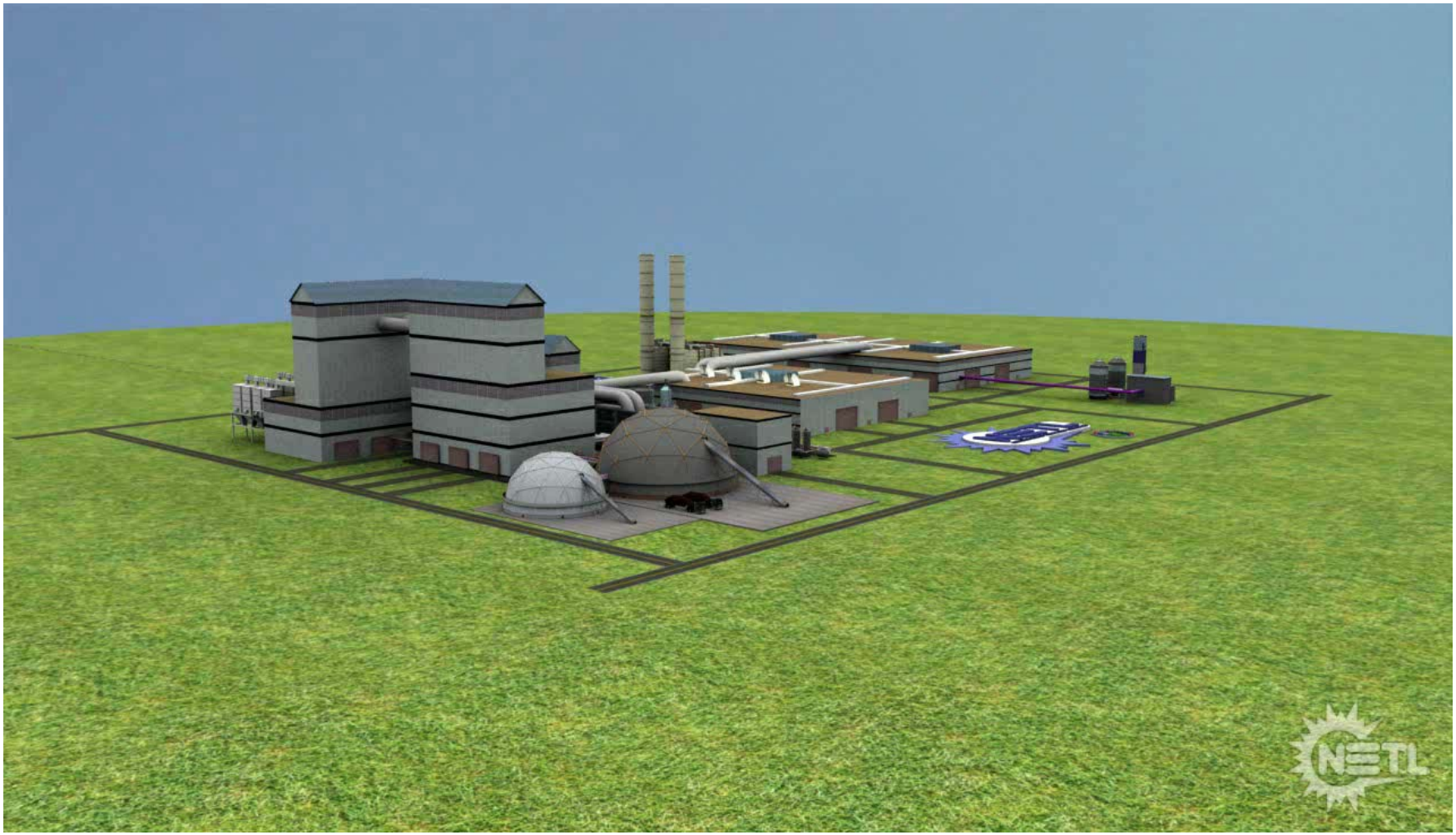
Virtual Power Plant with Carbon Management