Sensors and Controls Workshop
Summary Report

by

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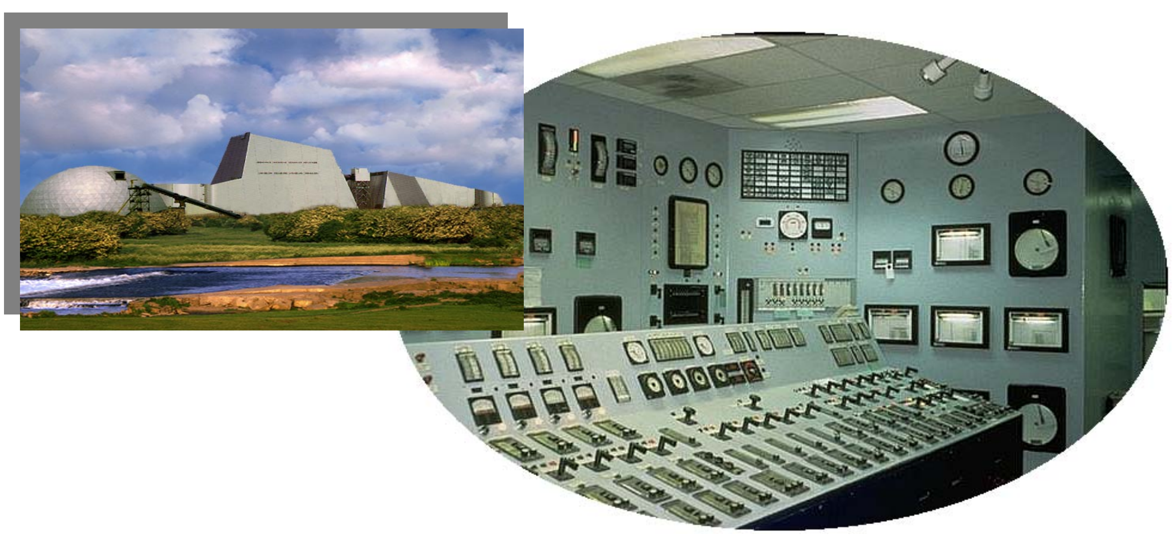

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Disclaimer

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Executive Summary

Higher operating efficiencies, emission reductions, improved reliability, and lower operating costs are benefits that the power industry can realize with the utilization of sensors and controls. However, for the power industry to derive the maximum benefit from sensors and controls, improvements in existing technologies and novel approaches to challenging measurements are needed.

Recognizing the importance of sensors and controls, the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) sponsored a sensors and controls workshop on April 17 to 18, 2001, in Washington, DC. The workshop focused on identifying technology needs in sensors and controls for existing fossil-energy power plants as well as future facilities conceived under the Vision 21 Program. Forty-six experts from 29 organizations, including private industry, research laboratories, academia, and government agencies, attended the workshop.

The meeting opened with keynote speakers from NETL and the private sector. NETL officials spoke of the Vision 21 and advanced research programs. Speakers from the Electric Power Research Institute (EPRI) and Delphi Automotive Systems Research Laboratory discussed the improvements realized with their respective operation through the use of sensors and controls.

NETL keynote speakers Robert Romanosky and Carl Bauer emphasized that developing sensor and control systems plays a critical role in DOE Office of Fossil Energy Vision 21 Program, clean coal activities under the Power Plant Improvement Initiative, and the proposed Clean Coal Power Initiative. The Vision 21 Program is aimed at providing technologies for ultra-clean fossil-fuel-based energy production with 60- to 75-percent efficiencies and near zero emissions. The program also uses a modular approach to present opportunities to not only generate power, but also co-produce clean fuels, chemicals, steam, and other useful products. The ultra-high efficiency and environmental performance goals of the Vision 21 Program mean that facilities must operate at optimum conditions, while adapting in real-time to changes in load and feedstock. These are challenging performance goals. They will require advanced control and sensing systems that can be adapted and optimized in real time. To improve the overall plant performance of existing power plants, one of the most cost-effective methods is to update the sensor and control systems.

Robert Frank, Director of the Instrumentation and Control Center for EPRI, presented the results of a demonstration project that retrofitted the Tennessee Valley Authority (TVA) Kingston Station Power Plant Unit 9 with updated sensors and controls. Benefits derived from that project included improvements in heat rate, reduction in loss-on-ignition and nitrogen oxides (NO_X) emissions, and improved plant reliability and responsiveness. Mr. Frank also discussed potential benefits available to existing U.S. fossil-based power systems. It was estimated that a 1-percent improvement in efficiency gained from a controls-and-sensors retrofit would result in

$409 million in annual fuel savings. A 1-percent increase in availability, as a benefit of improved control and accurate sensing, would result in an additional 5,000 MW of capacity without the addition of power generation equipment.

Galen Fisher of Delphi Automotive Systems Research Laboratory discussed the benefits—improved efficiency and reduced emissions—that sensors, controls, and diagnostics have brought to the automotive industry.

Parallel discussions were held on advanced combustion/gasification, turbines, fuel cells, and environmental controls to identify and prioritize near-term (0–5 years) and long-term (5–15 years) needs. Near-term needs may improve existing power-plant performance as well as meet Vision 21 Program goals. Long-term needs are aimed primarily at supporting the Vision 21 Program. Following identification of prioritized needs, breakout sessions were held on emerging sensor and control technologies.

Workshop participants recommended that sensors need to be developed or improved for on-line or in-situ applications under harsh conditions (high temperature, high pressure, corrosive environment, and presence of particulate). Sensor development needs to focus on robustness and accuracy, while balancing longevity with cost. Self-diagnostic and drift quantification capabilities of individual sensors will be an essential feature of new “smart” sensors.

Balancing the fuel/air ratio in 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 was identified as a long-term need for use with advanced control systems. As 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.

Accurate monitoring of the physical conditions within combustion and gasification systems remains a high-priority need, because current on-line technologies cannot withstand the harsh conditions, particularly those found inside gasifiers and turbines. While the specific applications for a gasifier and turbine differ, the primary need is to develop materials and technologies capable of accurately detecting gas path and surface temperatures (as high as 3,000 °F for gasifiers and 4,000 °F for turbines) in high-pressure corrosive environments.

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 (size and concentration). While some of these methods are commercially available, most measurement tools have been designed for stack monitoring and need to be improved for use near the combustion zone.

The development and implementation of advanced controls were discussed in every session and were identified as important needs for both existing and future power generation facilities. Participants recognized that existing facilities could benefit substantially from implementing advanced computerized control systems that are commercially available. Identified areas of interest included integrated control for total plant optimization, improved modeling of combustion and instability, standardization, and dynamic controls. To facilitate DOE's Vision 21 Program with its modular yet interdependent components, an umbrella approach was deemed appropriate. A high-level control system may also be used to track feedstock supply, system output, maintenance, and cost. At the individual modular-system level, the need to develop smart feedback or feed-forward controls utilizing neural networks and predictive models was discussed. Validation of models was also deemed an important feature of advanced controls development.

Valuable information was gained from the participants' input at the workshop. Information sharing was viewed as mutually beneficial for NETL's sensors and controls program as well as the participants. The information compiled in this report will assist in aligning NETL's Advanced Research Program development efforts in sensors and controls with both the DOE Vision 21 Program and future funding considerations. While it is recognized that more discussions are needed, particularly in the areas of advanced controls and emerging sensor technology, the information contained in this report may serve as a basis for the research and development community to focus its efforts more effectively in the higher priority areas.

I Introduction

The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is the nation's largest fossil-fuel research organization. NETL leads DOE's efforts to develop cleaner, more efficient, and more cost-effective technologies for fossil fuel uses. One of these efforts is the development of advanced process control strategies and technologies, including advanced sensors and intelligent controls, so that power generation equipment operates in a safe, efficient, and environmentally sound manner. NETL has recognized that innovations in sensors and controls are needed as a concurrent effort to foster the full-scale implementation of new, more efficient power generation technologies. In addition, existing power plants benefit greatly with installations of new sensors and controls. Retrofits of this kind replace outdated instrumentation and controls of limited capability and result in many high value benefits at comparably low costs.

Specific benefits for both existing and future power generation facilities include lower operating and maintenance costs, higher efficiencies, reduced emissions, enhanced responsiveness to market and load fluctuations, and increased availability. These benefits are significant, especially in a deregulated market with high demands for power.

An example of the benefits obtained from upgrading instrumentation and controls is the Tennessee Valley Authority (TVA) Kingston Plant Unit 9 where a distributed control system and modern instrumentation increased the heat rate, improved loss on ignition (LOI), reduced nitrogen oxides (NO_X), and led to overall improvement in plant performance.

Improved performance leads to significant savings and profits. Approximately $409 million can be saved annually in existing fossil-based power plants in the United States by implementing advanced sensor and control technology. This estimate, provided by the Electric Power Research Institute (EPRI), was based on a 1-percent increase in efficiency. Other benefits include improved plant availability and enhanced responsiveness to load changes. A 1-percent increase in availability will make an additional 5,000 megawatts (MW) of capacity available without major capital investments. Higher efficiency will improve control of NO_X and carbon monoxide (CO) emissions and reduce greenhouse gases and solid waste. Increased efficiency reduces fuel costs for individual plants, which positively impacts the facility' s competitiveness in the open market. For a 500 MW unit similar to the Kingston Number 9 Unit, approximately $390,000 can be saved in fuel per year with a 1-percent increase in efficiency through the use of advanced sensor and control technology. A 1-percent increase of availability for the same plant will generate an additional profit of $1.5 million at a retail price of $0.06/kWh.

To tap these potential benefits, NETL is supporting advancements in sensor and control technology, including sponsoring a 2-day workshop on April 17 to 18, 2001, in Washington, D.C. The workshop aimed to identify and prioritize sensor and control needs for power generation technologies. The purpose was to identify those needs that enhance the performance of existing facilities and enable the full-scale implementation of Vision 21 power generation technologies. Short-term (0-5 years) development priorities would support existing and future facilities, and a long-term (5-15 years) goals would primarily support the Vision 21 Program.

A summary of the general session is provided along with information from seven individual breakout sessions. Four sessions focused on the sensor and control needs for advanced combustion and gasification, turbines, fuel cells, and environmental control technologies. Follow-up sessions focused on the relevant technologies and issues in (1) physical measurement and diagnostic sensors, (2) chemicals and emission sensors, and (3) advanced controls.

NETL's Power Systems Advanced Research Program, in the Office of Coal and Environmental Systems, will use the information to shape their program in sensors and controls. This program is aimed at supporting novel or revolutionary technologies that will drive advancements in sensors and controls. The program will also capitalize on NETL's ability to screen and accept risk associated with novel technologies as well as the ability to deploy successful sensor and control technologies concurrent with advanced power generation technologies.

II General Session Summary

General session presentations provided an overview of NETL's programs and outlined the benefits derived from implementing advanced instrumentation sensors and controls. Robert Romanosky, Product Manager for Power Systems Advanced Research at NETL, and Carl Bauer, Associated Director for the Office of Coal and Environmental Programs, introduced NETL and the DOE Vision 21 Program. The importance of advanced sensors and controls with respect to the Vision 21 Program, and the opportunities for novel approaches through the Advanced Research Program, were discussed. Robert Frank, Director of EPRI's Instrumentation and Control Center, described current activities in instrumentation, sensors, and control deployment. He presented the benefits from retrofitting TVA's Kingston 500-MW unit with advanced controls and instrumentation. Galen Fisher, of Delphi Automotive Systems, described the sensors and controls used in automobiles to improve the fuel efficiency, reduce emissions, and enhance diagnostic capability. The four presentations illustrated the importance of sensors and control research, and gave the attendees useful background information for the breakout discussions.

Robert Romanosky conveyed the goals of the workshop and the roles that sensor and control development plays in the Power Systems Advanced Research (PSAR) and Vision 21 programs. The PSAR program is crosscutting research and development (R&D) that bridges the gap between fundamental science and advanced engineering by supporting research that overcomes technical barriers and explores innovative concepts. NETL's instrumentation, sensors and controls systems (ISCS) programs will collaborate and crosscut other areas to develop technologies applicable to power generation and environmental control technologies. The PSAR program also encompasses programs in coal utilization science, materials, metallurgical processes, bioprocessing, university coal research, historically black colleges and universities (HBCU), and small business innovative research (SBIR). The Vision 21 Program is a long-range, industry-driven effort to develop ultra-clean, fossil-fuel-based energy plants with unprecedented efficiency. Sensors and controls have been identified as an enabling technology for Vision 21 plants.

Carl Bauer introduced NETL's missions and programs, emphasizing the dramatic growth in world energy use. To meet the growing need for affordable, clean energy, the abundant U.S. coal resources need to tapped. The environmental issues related to fossil-energy power systems will continue to be addressed. Technology efforts like those at NETL have helped to significantly reduce pollutant emissions since 1970, including sulfur oxides (SO_X), NO_X, and particulate matter from coal powered plants. Current programs are aimed towards multi-pollutant control, including fine particulates ($PM_{2.5}$) and mercury, and greenhouse gas reduction.

The time-phased and market-driven strategy consists of the following three phases:

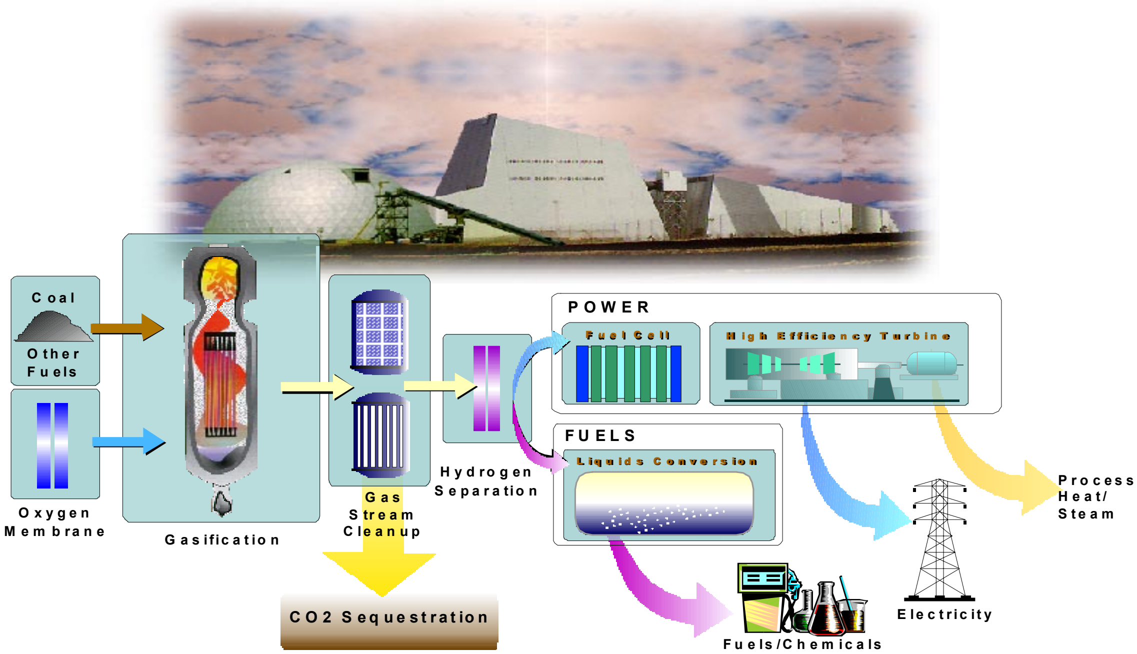
1. Develop environmental control and efficiency improvement technologies for existing fleets by 2005;

2. Develop next generation gasification, advanced combustion systems, improved materials, and advanced sensors and controls for retrofit/re-powering markets by 2010; and

3. Integrate advanced enabling technologies, including gas separation, carbon dioxide (CO_2) capture, fuel cells, advanced turbines, novel gasifiers for Vision 21 plants, and carbon sequestration by 2015.

Robert Frank described the research and development activities at EPRI's instrumentation and control (I&C) center at the Kingston Fossil Plant near Knoxville, Tennessee. The I&C center participated in retrofitting TVA's Kingston Unit 9 with a distributed control system (DCS) and upgraded the instrumentation. The retrofit significantly improved heat rate, reduced loss on ignition (LOI), and reduced NO_X emissions. The improvements generated financial and environmental benefits. To illustrate the potential benefits obtained from sensors and controls, Mr. Frank said that a 1-percent improvement in efficiency will yield over $390,000 in savings in fuel costs for an average 500-MW plant. A more significant benefit is the improvement of plant availability and agility. A 1-percent increase in plant availability will generate $1.5 million in additional gross profit for a 500-MW plant at a retail price of $0.06/kWh. Other benefits include reduced emissions, solid waste, and disposal costs.

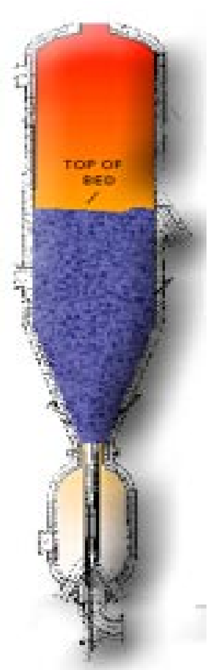
Galen Fisher of Delphi Automotive Systems discussed the improved fuel efficiency and emission performance obtained through the integrated use of advanced sensors and controls. The automobile's integrated control and sensor system may serve as a reference for other industries that convert fossil energy to power. Approximately 12 different sensors are utilized in the power train of today's automobiles to keep the air and fuel ratio at an optimum range. Sensor outputs for airflow, temperature, fuel, and oxygen content in the exhaust gas are fed to a control system to maintain an optimum air/fuel (A/F) ratio while driving. Sensor and control systems are also important for emission performance: a three-way catalytic converter that reduces CO, NO_X, and hydrocarbon emissions. Because the three-way catalytic converter for reducing emissions only works at a very narrow range in A/F ratio, the successful reduction of all three pollutants depends critically on the accurate closed-loop control of the A/F ratio. The automobile's electronic control module and sensors provide this accurate closed-loop control of the A/F ratio.



Virtual Schematic of Vision 21 Energy Plant

III Breakout Session Summary I
Power Generation Technologies

III.A Sensor and Control Needs for Advanced Combustion and Gasification

Sensor and control needs for advanced combustion and gasification include existing and future facilities. The discussion focused on systems that utilize coal as the primary feedstock. The needs identified for advanced combustion and gasification are similar, but sensor specifications and applications differ, since conditions in a gasifier are more severe than those found in a boiler. General instrumentation and sensor needs are outlined in Table 1. Table 2 outlines participant feedback for advanced controls. The data were not assigned a priority because of time limitations.

R&D on diagnostics and distributed sensing were identified as needs; however, these points were not discussed in detail because of time limitations and lower priority. The session concluded with the following general recommendations from the participants:

- Rugged, robust, and reliable sensors are essential for the complex and harsh environment of advanced, Vision 21 combustion and gasification technologies. Instrumentation and sensors should (1) include self-calibrating capabilities and have high reliability and longevity; (2) be designed for and operate at high pressures and high temperatures; and (3) be corrosion resistant. However, cost should be balanced with performance and longevity.

- Development of combustion stoichiometry controls and required sensors for air and fuel staging are necessary for the near term and long term.

- Solid and gas fuel flow actuators must be developed to close feedback loops.

- DOE needs to work with industry to develop standards for sensors and controls. Such standards will facilitate modularity.

Table 1: High-Priority Sensor Needs for Advanced Combustion and Gasification

Sensor Need	Purpose	Time Frame	Comments
Flame Imaging Sensor	Flame image is an important indicator of combustion status. It can be used to check the A/F ratio for improved efficiency and lower emissions.	0-5 years	• Optimal sensor should be spatially resolved and provide a three-dimensional account of the flame. • May monitor one or all characteristics, including species, temperature, uniformity, flame shape.
Particulate Sensor On-line Particle Measurement Instru-mentation	Particulate sensors are used for both pre- and post-combustion processes. Pre-combustion applications: • Monitor fuel particle size for complete combustion. • Improve fuel sizing operations. • Monitor particulate in gas stream to protect turbines. Post-combustion applications: • Fine particulate ($PM_{2.5}$) monitoring and control (also see Table 4). • Dust/soot control (e.g., diesel soot).	0-5 years and 5-15 years	• Sensing/determining particle size is a high priority. • Measuring/determining particulate concentration is a high priority. • Particle velocity is another important property. • Low-density stream for post-combustion applications, and dense stream for pre-combustion applications. • Flue gas application for combustion (also see Table 4). • High temperatures, elevated pressures, and corrosive conditions expected in gasification applications.
Solid Feedstock Flow Measurement On-line Solid Feedstock Analysis	Solid feedstock flow is another important quantity to be measured to control A/F ratio, so that better efficiency and lower emissions can be achieved. Feedstock analysis will further quantify the Btu and other components in the fuel stream for efficient combustion and effective emission reduction. Analysis is also important for fuel blending to facilitate usage of opportunity fuels.	0-5 years 5-15 years	• Must withstand high temperatures. • Must be an on-line measurement. • Coal is the primary solid fuel for flow measurement. • Alternative fuel flow measurement is a long-term need. • Improvement to solid level indication is also needed. • Btu, composition, water/moisture, contaminants are properties for on-line feedstock characterization. • Monitor on-line fuel contaminants such as mercury.
Emission, Toxic, Contaminant Sensors	Emission control is a major concern for combustion and gasification. In addition to analyzing feedstock as discussed above, measurement of the combustion product (also see Table 4) is required to control combustion/gasification. Other contaminants (such as alkali) will cause equipment deterioration: e.g., fouling, deposition, and corrosion.	0-5 years	• On-line sensors for real time monitoring and control. • Ability to operate under harsher conditions than in the stack. • Detect total mercury and speciated forms. • Combined flue gas sensing (e.g., NO_X, SO_2, Hg). • On-line gaseous alkali monitor for gasification. • Detect carbon content in ash. • Tar monitor.

Table 2. High-Priority Control Needs for Advanced Combustion and Gasification

Control Need	Purpose	Time Frame	Comments
Fast Boiler Control and Lean Burn Control	Fast boiler control can accommodate changes in demand and feedstock. Lean burn control is aimed at minimizing NO_X emissions.	0-5 years	• Response time for actuators is a limiting factor that should be addressed. • Some commercial packages for fulfilling this purpose need be examined.
Solid Flow Control	Controlling solid flow is an important component in adjusting and maintaining the A/F ratio.	0-5 years and 5-15 years	• Solid feedstock and coal flow splitter by metering or actuation. • Achieve homogeneous gas/particle flow.
Closed Loop A/F Control and Optimi-zation	Closed loop control can more accurately control A/F ratio to enhance efficiency and reduce NO_X emissions.	0-5 years	• Similar to needs listed above. • Improve overall system control by controlling A/F ratio and NO_X emissions. • Downstream systems will perform better. • Closed-loop control will require actuators with fast response time and high accuracy.
Signal Standardi-zation	Signal standardization will permit open communication and systems integration.	0-5 years and 5-15 years	• Standardize signals to control system for entire plant.
Neural nets, Dynamic Controls, And Predictive Control	More advanced controls are aimed at making the system more adaptive to changes in load and feedstock.	0-5 years and 5-15 years	• Capture operator's knowledge. • Smart logic-based controls and real-time optimization. • Simultaneously respond to rapid changes in feedstock, load demand, and other transients. • Need adequate number of sensors or instrumentation to support advanced controls.

III.B Sensor and Control Needs for Turbines

The gas turbine breakout session discussed several sensors and control needs that were identified from previous reports or workshops. A discussion topic list, provided in Appendix C, was reviewed by the participants and prioritized with primary consideration for natural gas turbines.

Participants identified an overwhelming need to develop sensors that are in-situ, non-intrusive, or embedded to provide a real-time account of turbine operation and component status. However, one of the primary barriers is the limited access to penetrate the turbine with in-situ methods. Embedding sensors are a potential area for development, but the basic need is to develop materials, technologies, or approaches that can withstand high temperatures and respond rapidly. After overcoming the barriers of access and temperature, a total sensing approach is desired to enhance the operation and reliability of gas turbines. Although turbine manufacturers did not participate, participants acknowledged that implementation of in-situ or embedded sensors will likely proceed through manufacturers.

High-priority items were ranked as near-term goals to enhance the operation of existing turbines as well as facilitate the development of new turbines. (See Table 3 on the next page.)

III.C Sensor and Control Needs for Environmental Controls

New or significantly improved technologies, sensors, or controls are to facilitate the operation of environmental control technologies. For this breakout session, some of the environmental control technologies considered were electrostatic precipitators (ESPs) and

Table 3. High-Priority Sensor and Control Needs for Turbines

Sensor or Control Need	Purpose	Time Frame	Comments
Particulate Sensor	Monitor particulate in fuel and inlet flows to turbine.	0-5 years	• Low ppm level particulate sensor for fuel and air flows. • Used for general turbine operation and protection.
Fast Pressure Sensor	Monitor operation and performance of turbine.	0-5 years	• Millisecond response time needed. • Able to detect or measure absolute or differential pressure.
Air- and Fuel-Flow Sensors	To control individual nozzle or burner for system optimization.	0-5 years	• Couple with other sensors for closed-loop control. • Flow sensors are to maintain high efficiency and reduce emissions.
Flame Monitor	Needed to monitor and control combustion to maintain high efficiency and ensure reliability.	0-5 years	• Monitor combustion zone, flame stability. • High temperatures may be a barrier for some on-line continuous technologies.
Temperature Sensor	Temperature sensors give key information on working medium and equipment status.	0-5 years	• Monitor surface temperature (up to 4,000 °F). • Monitor gas path temperature (up to 4,500 °F). • Materials limitations.
Sensor to Monitor Thermal Barrier Coating	To protect turbine components.	0-5 years	• On-line monitoring of thermal barrier coating degradation. • Sensors will likely need to be embedded. • High temperature in the hot-gas-path region.
Control Algorithms and Software	Real time, rapid, and remote data collection and analysis to optimize operation and predict maintenance.	0-5 years	• Work is ongoing in this area but focused only on the turbine operation. • Transient conditions, startups, and shutdowns may also benefit from rapid data collection and interpretation.
Integrated Controls	Optimize turbine operation with balance-of-plant operations.	0-5 years	• Does not appear to be a technical challenge. • Should be examined further given the new plant construction and expected growth.
Diagnostic Sensors	To monitor health of turbine components.	0-5 years 5-15 years	• Off-line technologies are an option but on-line is preferred. • Specific diagnostics sensors other than those mentioned above need to be identified and prioritized. • Support a total sensing system for maximum performance.

selective catalytic reduction (SCR) systems for NO_X control. Protecting fuel cells from catalyst poisons was also discussed. The regulation and control of mercury and the potential for carbon dioxide management through carbon sequestration were discussed as evolving environmental control technology areas.

Specific areas of interest in sensors and controls for environmental controls are listed on the next page.

- Mercury
- NO_X
- Particulate
- Alkali
- Ammonia
- Flame quality
- Feedstock characterization
- Carbon monoxide, carbon dioxide
- Hydrogen, hydrogen chloride
- Integrated and predictive controls
- Ash quality
- SO_X
- Water quality

Table 4 (on the next page) lists the higher-priority sensor and control needs; however, the relative importance of these measurements may shift as developments in the technology progress. Ash quality, sulfur dioxide, and water quality were also identified, but were not assigned a high priority relative to the other sensor and control needs.

III.D Sensor and Control Needs for Fuel Cells

The following were identified as generic sensor needs for fuel cells:

- Flow within the fuel-cell stack
- Hydrogen (H_2)
- Carbon monoxide (CO)
- Hydrogen chloride (HCl)
- Oxygen (O_2)
- Sulfur species
- Stack temperature with rapid response times

Participants in this session referred to the report *Sensor Needs and Requirements for Proton-Exchange Membrane and Fuel Cell Systems and Direct-Injection Engines* published by Lawrence Livermore National Laboratory. They felt that the report addressed the needs adequately and provided specifications for the proton-exchange membrane (PEM) fuel cell. The session did not have the expected attendees, therefore participants opted to forgo a detailed discussion. It was concluded that while fuel-cell development is highly proprietary, sensor development is an opportunity for shared technology development between vendors and manufacturers. More discussion is needed on other types of fuel cells (e.g., solid oxide).

Table 4. High-Priority Sensor and Control Needs for Environmental Control Technologies

Sensor or Control Need	Purpose	Time Frame	Comments
Mercury	Mercury emission is expected to be regulated. Sensors and instrumentation are needed to monitor emissions and facilitate the operation of mercury control technologies.	0-5 years 5-15 years	• Proposed as a regulated constituent. Continuous emissions monitoring (CEM) system potentially required on power plants by 2007. • Mercury analyzers are being developed and offered commercially, but accuracy improvements are needed. • Quantifying the speciated forms of mercury (elemental, oxides, and chloride) is desired. • Mercury chemistry research is under way.
NO_X	An important regulated constituent. Monitoring NO_X near the combustion zone would provide real-time NO_X data to optimize NO_X control.	0-5 years 5-15 years	• Commercially available analyzer is an extractive stack measurement where conditions are moderate. • Develop accurate in-situ NO_X sensors for high temperatures and harsher conditions than stacks. • Use data for closed-loop control to optimize combustion and NO_X control systems.
Particulate	Regulation of fine particulate ($PM_{2.5}$) is expected, and reliable monitoring technologies are needed.	0-5 years 5-15 years	• Continuous on-line monitoring is desired but is a substantial challenge. • Detect particle size, distribution, and concentration. • Spatial resolution desired over point measurements.
CO, HCl	To protect the catalyst in proton exchange membrane (PEM) fuel cells.	0-5 years 5-15 years	• Concern for PEM fuel cells; develop concurrently. • Micro-sensor with high accuracy is needed. • Not a concern for solid oxide or molten carbonate fuel cells.
Integrated and Predicative Controls	Current environmental sensors and analyzers are used to monitor emissions at the stack only. Integration of real-time data into plant control is expected to be more efficient and effective.	0-5 years 5-15 years	• Integrate environmental monitoring systems with combustion and steam control systems. • Use sensors/controls for combustion system to predict emissions and guide operation of the environmental control technologies, such as SCR and selective non-catalytic reduction (SNCR) systems.
Ammonia	Ammonia is used for NO_X control technologies. A sensor is needed to reduce ammonia slip.	0-5 years	• Optimize operation of SCR and SNCR systems. • Combined with NO_X sensor for high-temperature operation for closed-loop control. • Prevent ash contamination.
CO_2	CO_2 sequestration technologies need sensors to monitor operation and leakage.	5-15 years	• Develop concurrently with carbon sequestration technologies. • Investigate technologies to further define need.
Alkali	Gaseous alkali is corrosive, and needs to be monitored to protect high-temperature systems.	5-15 years	• Measuring gaseous alkali would facilitate preventative maintenance. • Applicable to high-temperature systems, such as gasifiers and turbines.
Feedstock Characteri-zation	Controlling emissions would be better achieved by on-line feedstock characterization to track fuel variation, fuel blending, and A/F ratio.	5-15 years	• Supports Vision 21 Program and alternative fuel utilization. • On-line solid fuel characterization will be a challenge. • Can be used for predictive and dynamic control.

IV Breakout Session Summary II
Sensor/Control Technologies

IV.A Physical Measurements/Diagnostic Maintenance Sensors

Substantial improvements in basic physical measurements are needed in advanced power generation technologies where the environment is extremely harsh. While the specifications for a particular sensor vary with the power generation technology, the barriers associated with the measurements are similar. Hence, overcoming a barrier, such as high temperature materials, would benefit all applications irrespective of the specifications.

Previously identified sensor needs, listed below, are classified as physical or diagnostic measurement needs.

Physical Measurements

- • Temperature
- • Solids flow
- • Flame quality
- • Pressure

Diagnostic Measurements

- Corrosion
    - Thermal barrier coating failure
- Component degradation
    - Alkali
- Sensor self-diagnostic capability
- Refractory contouring

Because of time limitations, discussions focused on identifying emerging technologies for high-temperature measurement, solids flow, and flame quality. The general specifications for high temperature measurements outlined by participants are listed in Table 5.

Table 5. General Specifications for High-Temperature Measurement

Power Generation Technology	Temperature	Pressure	Other
Gasification	3,000 °F	600 psi	• Slagging and reducing environment, particulates present.
Turbine (gas path)	4,500 °F	400 psi	• Fast response, oxidizing environment.
Turbine (surface)	4,000 °F	400 psi	• Fast response, oxidizing environment .
Combustion	1,500 °F	100 psi	• Spatial resolution, oxidizing environment, particulates present.

These general specifications can be further defined to evaluate a specific technology and application. For any application, the measurement technology must (1) be able to quantify drift, (2) self calibrate, and (3) be highly robust. Longevity goals outlined for the power generation technology include

- years for combustion,
- 1 year for gasifiers, and
- 500 hours for turbines (near-term) and 1 year (long-term).

The primary barrier identified for high-temperature measurements is the temperature limitations of the materials themselves. Work is under way to develop new materials and approaches. Barriers for non-contact optical technologies used to measure temperature include dirty windows, penetration into vessels, optical path contamination, light pipe chemical degradation, black body interference, low emissivity, and high cost. Of these, the primary issue is fouling of the optical window or ports, followed by cost for full-scale implementation. Table 6 lists potential or emerging technologies for high-temperature measurements.

Table 6. Potential Technologies for High-Temperature Measurement

Technology	Type	Comment
Thermocouple	Contact	• Thermocouples extend to 2,054 °C (3,729 °F) in a benign atmosphere. Wires limited to 3,500 °F in inert atmosphere and 1,200 °F in oxidizing environment. • Need sheaths that resist corrosion and erosion. However, response times may be slow.
Sapphire Probe/Fiber Optics	Contact	• Sapphire probe/fiber optics can operate at temperature of 2,200 °C (3,992 °F) in a harsh atmosphere. • Issues for high-temperature gasification applications currently being addressed include corrosion, vibration, performance near upper temperature limitation, response in slagging environment. • Commercially available up to 1,200 °C (2,192 °F) in oxidizing atmosphere.
Other Contact Technologies	Contact	• Resistive transmission, resistance change, resistance temperature detector (RTD) 650 °C (1,202 °F) limit. • Thin film thermocouples, Johnson Noise.
Two-Color Infrared Absorption	Non-contact	• Gas path measurement performs well in clean gas atmosphere with black body interference. • Used in steel mill gas-stream application up to 3,000 °F, but is separated from a corrosive or reducing atmosphere and operates at ambient pressure. • Using mid infrared (IR) tunable laser.
Phosphor Thermometry	Contact	• Point, imaging, and surface measurement. • Up to 1,200 °C (2,160 °F) for surface measurement. • Current focus is to adapt technology for slagging gasifiers. • Hydrogen sulfide may poison the phosphor material.
Infrared Pyrometer	Non-contact	• Prototype developed by Texaco and tested to 4,500 °F at lab and pilot scale. • Being prepared for field testing at Tampa Electric's Polk Power Station.
Time Domain Refractometer	Non-contact	• Uses a probe and has length limitation, tested to 1 m.
Gas-Phase Acoustic	Non-contact	• Low frequency, not sensitive to particulate. Tested and used at temperatures ranging from 2,200 to 3,300 °F at atmospheric pressure. • Sensitive to types of gas, but material is not a barrier. • Relating acoustic data to temperature is application-specific.
Other Non-Contact Approaches	Non-contact	• FT/IR pyrometer , millimeter wave pyrometer, coherent anti-Stokes Raman scattering (CARS) system, and low-frequency pulse, broadband

Several types of flows and flow regimes exist in a power generation facility. The critical flows identified include flow in a fuel cell, steam flow at high temperature, multiphase flow, solids flow, and energy content flow. The focus of the group's discussion was limited to solids flow with interest in balancing the A/F ratio to individual burners. Potential technologies for solid flow measurement are listed in Table 7.

General specifications identified for solids flow measurement include:

- Temperatures ranging from 200 to 350 °F,
- Pressures ranging from 0 to 400 psi,
- Response time of 1 s to 1 min,
- Five percent relative accuracy,
- Up to 14 in. inside diameter (ID) and 20,000 lb/hr for individual burners, and
- Continuous measurement.

Table 7. Potential Technologies To Determine Solid Flow Rate

Technology	Comments
Microwave	• Relative measurement, sensitive to moisture and particle size. • Pipe geometry may affect measurement. Complex system to extract flow rate data. • Cost may be high. Being tested in the field. • No other competing technologies closer to commercialization.
Static Charge	• Particles gather static charge as they move. • Moisture and rank dependent; outside interference. • Problems with alternative feedstocks may occur. • Being field tested and may be a low-cost technology.
Passive Acoustic	• Uses accelerometer at elbow to provide a relative measurement. • Technique is under development and a potentially low-cost approach. • Frequency interference needs to be examined.
Active Acoustic	• Technology to measure velocity and density. • Doppler to measure velocity and ultrasonic (500 kHz to 1 mHz) for density. • Two measurements stand alone. A relative measurement. • Technology is not commercial. Potentially a low-cost approach.
Beam Deflection	• Measures momentum. • Material probe deflection. • Material and sampling issues. • Erosion is a problem.
Metering Valves	• Commercially available. • Size limitations and maintenance issues. Not flow responsive.
Optical Technologies	• Can be used for dilute phases. Not applicable to coal feed pipes. • Measure flow at the surface. These technologies require windows.

Temperature and flow are basic measurements needed to control and optimize processes. Monitoring the flame control in combustion and turbine processes is also a primary function that facilitates control and optimization. The goal associated with measurement is to collect real-time data on flame characteristics and provide closed-loop active control of the combustion process and individual burners. Because of the high interest in this area, technologies to monitor flame quality were discussed and are summarized in Table 8.

Several technologies appear to be available to extract information about the flame. However, translating the data (without manual interpretation) into meaningful signals for the control system needs to be addressed. In addition, experience with implementing, operating and maintaining flame monitoring systems needs to be collected to document the benefits and identify improvement areas.

Table 8. Technologies To Monitor Flame Quality

Technology	Comments
Flame Ionization	• Used to detect flashback in a turbine. Currently being tested on a turbine test rig. • Sensor is expected to be low cost, simple, and durable. • Technology is being investigated by NETL in-house researchers. • Efforts focus on relating signal to useful information for flame quality and control.
Chemi-Luminescence	• Commercially available at reasonable cost. • Barriers associated with the accessibility of the turbine.
Flicker (High) Frequency	• Commercially available at low cost. • More applicable to boilers. • Untried on turbines because of flame access issues.
Cameras CCD, IR, UV	• Commercially available. • Unclear about sampling rate and timely electronic data interpretation. • Software and models need to be developed or debugged. • Issues with port access, port location, and maintaining line of sight need to be addressed, but are application-dependent.
Photo-Acoustic Laser	• Commercially available, but at high cost. • Has been attempted. Can be coupled with laser excitation to gain information. • Wave guides can be used to "listen" and gather specific data. • Used in automotive applications to detect leaks. • Data interpretation is a barrier.
Passive Acoustic	• Has been attempted at an R&D level, but not on a full-scale combustion system. • Need to test on a single burner to develop pattern recognition. • Use chaotic processes and apply to neural net to relate acoustic data for control purposes. • Cost is expected to be low.

Micro-electrical mechanical (MEM) devices were also discussed briefly at the closure of the physical measurements/diagnostic maintenance sensors session. It was recognized that MEM devices have many useful applications and possibilities. However, the direct application of today's MEM devices for power generation systems may not be appropriate for the near term, primarily because of their temperature limitations (600 °C/1,080 °F). In some cases, the presence of particulate in a stream or gas sample precludes the use of MEM devices. It was agreed that they are an exciting and promising field and may prove to be very useful for diagnostic purposes in power generation technologies. For the near term, MEM devices will act as an enabling technology that may help to reduce the size and cost of other instruments. A long-term goal is to identify suitable materials that withstand the higher temperatures found in today's power generation systems.

IV.B Chemical/Emission Sensors and Instrumentation

The specific sensor needs for environmental controls were identified in a previous breakout session along with other chemical sensors that would benefit power generation technologies. In this session, several high-priority chemical and emission sensor needs were discussed and are summarized in Table 9.

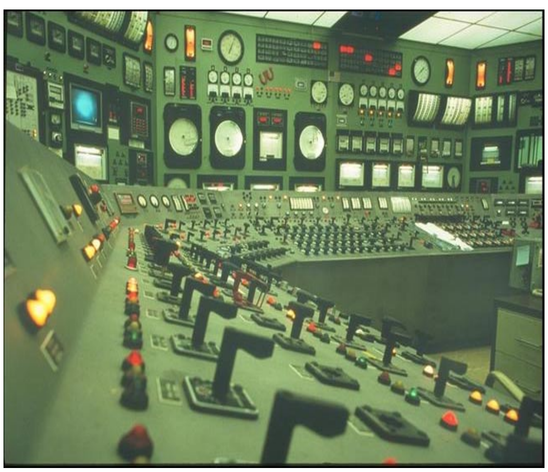
Table 9. High-Priority Chemical and Emission Sensor Technologies and Applications

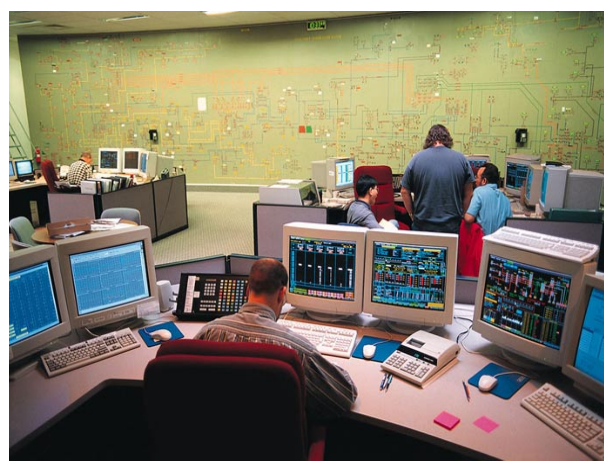
Mercury	Development Objective	• On-line or in-situ stack CEM for total mercury (0-5 years). • On-line/in-situ technologies to measure speciated forms of mercury (0-15 years).
	General Comment	• Total mercury expected to be regulated in the near term. • Mercury chemistry evaluation will help development of measurement technologies. • Detect mercury species (elemental, oxides, chloride) in addition to total mercury. • Mercury analyzers for feedstock contaminants is an option. • Measurement will help to develop mercury abatement technologies. • Performance of existing mercury analyzers is unproven.
	Status	• Laboratory technologies exist. • On-line technologies for total mercury are entering marketplace.
NO_X	Development Objective	• Reliable in-situ sensors suitable for stack emissions as well as accurate measurements close to the combustion zone.
	General Comment	• Regulated constituent. • In-situ sensors at stack remain a high near-term priority. • In-situ sensors to monitor the combustion zone (near- and long-term goal). • Combustion zone sensors will make SCR/SNCR systems more efficient. • In-situ sensors close to combustion zone can optimize combustion processes. • Combustion zone sensors need to withstand elevated temperatures (700-2,300 °F), particulate, and other potentially interfering combustion gases. • NO_X sensors are not commercially available or proven. • Instrumentation validation for emission reporting can be very challenging. • NO_X mapping helps staged combustion and special A/ F control. • Sensors can be used to monitor exhaust gases from turbine.
	Status	• Stack CEMs are commercially available. • Extractive systems most common.
Particulate	Development Objective	• Develop on-line technologies to measure particulate (2-10 μm) concentration and size distribution. Spatial resolution also desired.
	General Comment	• Need to detect/measure particle size, concentration, and size and spatial distribution. • Regulated emission. • Beneficial to monitor performance of filters used in gasification and other gas cleanup technologies. • Beneficial for turbine and fuel cell operation.
	Status	• Current technologies use filter collection that can only measure total particulate with batch measurement.
CO	Development Objective	• Detect low concentration levels of CO.
	General Comment	• Required to tolerate 1,500 °F, 200 psi, and oxidizing, reducing environment, and variable O_2 content. • High priority for low-concentration measurement in fuel cell operation. • Can be used to monitor boiler and gasifier operation.
	Status	• Extractive systems available.
HCl	Development Objective	• Detect low concentration levels of HCl.
	General Comment	• Required to measure at ppb level. • Needed in the inlet of fuel cells and to monitor syngas cleanup.
	Status	• Sensor not currently commercially available.
Alkali	Development Objective	• Detect concentration of gaseous alkali species.
	General Comment	• No reliable analyzer for low-level measurement currently exists. • Needed for high-temperature atmospheres present in gasifiers. • Help to protect turbine blades and facilitate preventative maintenance. • Enhance on-line diagnostic capability. • Sampling and analyzing gas at elevated temperatures is a barrier for accurate measurement.
	Status	• Currently not commercially available.

The following considerations were offered relative to the sensor needs outlined above and other gaseous species present in fossil-fuel based systems:

- Gas measurement sensors must be capable of operating at high temperature (3,000 °F).
- Monitoring hydroxy/methoxy (OH/CH) radicals for combustion controls should be included for temporal or spatial resolution.
- Spatially resolved sensors will provide the necessary data to validate models.
- Multi-component sensor arrays in a single sensing unit coupled with artificial intelligence to speciate and quantify gases is an emerging technology. Sensor-array electronic-noise-pattern recognition technologies could eliminate or minimize interference.
- Significant improvements in real-time gas analysis technologies have been made, but areas still open for improvement include tunable laser, robust in-situ probes, better sampling systems, low-cost gas speciation, and on-line solid fuel feedstock characterization.

IV.C Advanced Controls





The importance of advanced controls was discussed throughout the workshop. Controls are a component of a facility or a unit that interact with and affect all aspects of its operation. Thus, improving controls presents opportunities to influence cost, power output, and environmental performance.

Participants in this session touched on several key issues and offered a wealth of suggestions for both existing and future facilities. The discussion notes have been divided into three categories: Vision 21 systems, existing facilities, and general considerations. It was recognized that while a lot of information was gained in this session, more discussion is needed in the area of controls to develop the ideas and suggestions in greater detail, particularly for standardized communication and Vision 21 systems.

Considerations for Advanced Controls for a Vision 21 Modular Facility

- The Vision 21 modular system will require an advanced, multi-level control system with a high degree of integration and utilizing a master/supervisory control-system approach.

- Multi-level control systems need to include control of the individual devices, followed by unit, process, system, and plant.

- The master/supervisory control system should include cost, supply, maintenance, load demand, eco-factors, emissions, and efficiency.

- A whole system approach, which includes integrated, multi-level advanced controls, must also include the relationship of the sensors and actuation with the control system. Improvements in sensors and actuators need to occur to derive the benefit from using advanced controls. The use of advanced control logic can compensate for areas where sensing is not available or for slow response times of sensors and actuators.

- Evaluations of Vision 21 systems are needed to determine specific areas for control system development.

- Control system development needs to be broader than just fuel cells, turbines, gasifiers, or boilers.

- System development should define, develop, and characterize performance with the following characteristics: timely, flexile, capable of dealing with complex system, robust, algorithmic, and smart.

- Simulation and engineering models are needed so options for control can be evaluated effectively.

- Highly integrated, multi-level advanced controls will need standardized communication to sense, control, and respond in a timely fashion.

- Advanced control systems will need self-diagnostic capabilities.

- Predictive controls, neural networks, and other advanced controls will benefit from total sensing systems with temporal and spatial resolutions.

Considerations for Advanced Controls to Improve Existing Facilities

- There are many opportunities for current facilities to improve performance through control.
- Retrofitting is essential, and upgrades need to include digital controls.
- Several options for upgrading or replacing outdated control systems are commercially available.
- Unit upgrades are occurring along with installations of SCR and SNCR systems.
- Existing facilities need to evaluate their individual operations to determine specific improvement opportunities.
- The use of neural networks and other advanced control algorithms can prove to be highly beneficial for existing facilities.
- Universities are positioned for collaborative efforts to assist in system improvements, such as development of algorithms to overcome a specific problem.

General Considerations for Advanced Controls

- Technical and non-technical barriers associated with total system integration need to be evaluated.
- Integrating environmental monitoring into the operational control system should be considered. Emission measurement made closer to the combustion region will enable collection of real-time data so that it can be utilized by the control system in a timely manner, thus providing tighter emissions controls.
- Concurrent with sensor and control development, opportunities to improve actuation should be pursued. Without fast and accurate actuation, the benefits of an advanced control system will be less than expected.
- Controlling dynamics is important and universities are positioned to assist with these issues.
- Whole system simulators are a good stepping stone and benchmark for advanced controls.
- Shortcomings in high temperature and pressure measurements exacerbate control difficulties.

List of Abbreviations

A/F	air/fuel
CARS	coherent anit-Stokes Raman scattering (system)
CEM	continuous emissions monitoring (system)
DCS	distributed control system
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
ESP	electrostatic precipitator
FT	Fourier Transform
HBCU	historically black colleges and universities
I&C	instrumentation and control
ID	inside diameter
IR	infrared
ISCS	instrumentation, sensors, and controls systems
LOI	loss on ignition
MEM	micro-electrical mechanical
NETL	National Energy Technology Laboratory
NO_X	nitrogen oxides
OH/CH	hyroxy/methoxy
PEM	proton-exchange membrane
PSAR	Power Systems Advanced Research (program)
RTD	resistance temperature detector
SBIR	Small Business Innovative Research
SNCR	selective non-catalytic reduction
SCR	selective catalytic reduction
SO_X	sulfur oxides
TVA	Tennessee Valley Authority

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Appendix C. Workshop Agenda

Tuesday, April 17, 2001

7:00 - 8:00 am	Registration / Continental Breakfast
	General Session
8:00 - 8:40 am	*Welcome, Presentation of Workshop Goals, Overview of Vision 21* Robert Romanosky, Product Manager for Power Systems Advanced Research U.S. DOE, National Energy Technology Laboratory
8:40 - 9:10 am	*Current Research and Needs – Future Sensors and Controls Needs for the Power Industry* Rob Frank, Director EPRI Instrumentation and Control Center
9:10 - 9:40 am	*Automotive Sensors for Improved On-Board Control and Diagnostics* Galen Fisher, Principal Research Scientist Delphi Research Labs, Delphi Automotive Systems
9:40 - 10:00 am	*NETL's Perspective for Advanced Research in Sensors and Controls* Carl Bauer, Associate Director Office of Coal and Environmental Systems U.S. DOE, National Energy Technology Laboratory
10:00 - 10:20 am	Break - Adjourn to Breakout Sessions
	Breakout Sessions
10:20 - 12:00 pm	• Sensors and Controls for Advanced Combustion and Gasification • Sensors and Controls for Turbines • Sensors and Controls for Fuel Cells • Sensors and Controls for Environmental Controls
12:00 - 1:15 pm	Lunch (on your own)
1:15 - 3:45 pm	Breakout Sessions - Continued
3:45 - 4:10 pm	Break
	General Session
4:10 - 5:00 pm	Presentation of Results from Breakout Sessions
5:00 pm	Adjourn

Wednesday, April 18, 2001

7:00 - 8:00 am	Registration / Continental Breakfast
	General Session
8:00 - 8:15 am	*Welcome, Overview of Funding Opportunities for Sensors and Controls* Robert Romanosky, Product Manager for Power Systems Advanced Research U.S. DOE, National Energy Technology Laboratory
	Breakout Sessions
8:20 - 12:00 pm	• Advanced Controls • Physical Measurements/Diagnostic Maintenance Sensors • Chemical / Emission Sensors and Instrumentation
12:00 - 1:15 pm	Lunch (on your own)
1:15 - 3:00 pm	Breakout Sessions – Continued
3:00 - 3:15 pm	Break
	General Session
3:15 - 4:30 pm	Group Presentation and Recommendations to DOE NETL
4:30 - 4:45 pm	Acknowledgements, Adjourn

The National Energy Technology Laboratory

Sensors and Controls Workshop

Robert Romanosky, Advanced Research Product Manager

Workshop Objectives

- **Afford an opportunity for participation in the Sensors and Controls Program planning process**
  - Obtain perspective of industry, academia and government
  - Assist in formulating a roadmap for the Fossil Energy Sensors and Controls Program
- **Review and update the existing Vision 21 Sensors and Controls Roadmap**

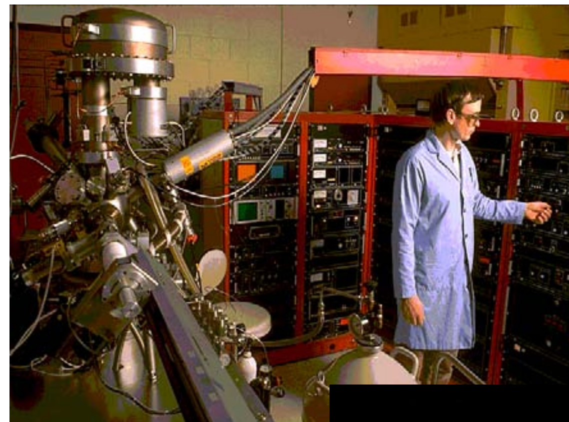
The How of Workshop

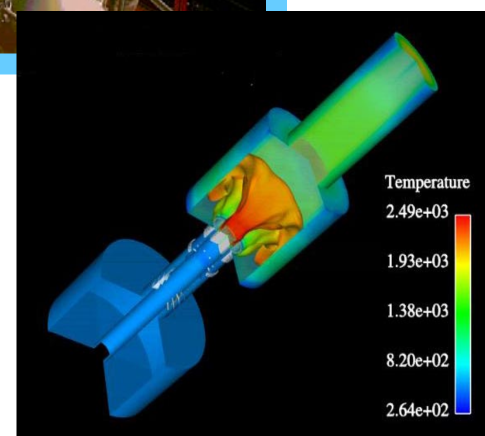
- Attendees will be divided into groups, according to technology needs
- Discussion of sensors and controls needs in each area will be discussed and formulated
- Prioritization of needs will be determined from groups' perspective
- Presentation of groups' findings will be presented to workshop
- Workshop findings will be incorporated into a fossil energy sensors and controls roadmap

Workshop Product

- **Produce document defining the sensors and controls R&D needs in each of the technology areas**
  - Prioritize the R&D needs associated with each technology area
- **Provide data needed for the next step in roadmapping the Fossil Energy Sensors and Controls area**
- **Update Vision 21 sensors and controls roadmap**

Advanced Research Program





Advanced Research - Power Systems

Ingenuity, innovation and implementation

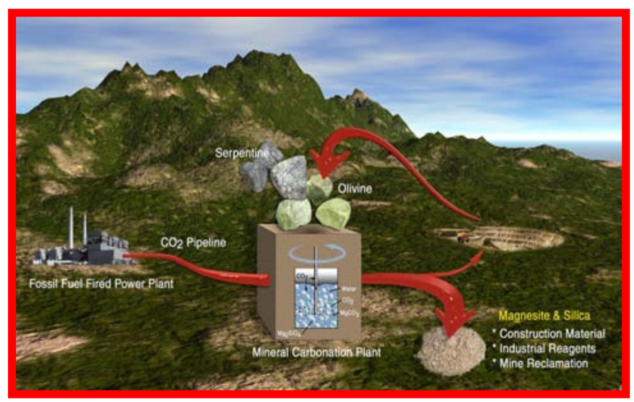
Goal

- 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

Uniqueness

- Bridge gaps between fundamental science and advanced engineering to overcome technical barriers encountered by R&D programs
- Stimulate advanced research in new directions--explore innovative concepts to enhance pace of fossil energy technology development



Mineral carbonation- NETL/ARC/LANL/ASU

AR Program Areas

- Coal Utilization Science (CUS)
- Materials
- Advanced Metallurgical Processes
- Bioprocessing
- University Coal Research (UCR)
- Historically Black Colleges and Universities/ Other Minority Institutions (HBCU/OMI)
- SBIR/STTR

Advanced Research - Power Systems

Near-term Emphasis

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

Advanced Research Plans for FY02

- **Initiate NETL Instrumentation, Sensors and Controls Systems (ISCS) Program through a solicitation to investigate and develop sensors and controls systems that crosscut all Product Lines for advanced power system market penetration**
- **Collaborate with NETL Materials Program to develop low-cost in situ sensors for advanced IGCC, other gasification and combustion systems**
  - **Develop sensors in parallel with gasifier and combustion technologies (instead as an afterthought)**
- **Development of reliable, robust, long-term durable and extremely low-maintenance front-end conditioning systems for established detection systems of selected continuous emissions monitors (CEMs)**

ADVANCED RESEARCH PROGRAM BUDGET TRENDS ($Million)

PROGRAM	FY 2000 APPR	FY 2001 APPR	FY 2002 REQ
AR			
• **Coal Utilization Science**	**6.3**	**6.3**	**6.3**
• **Bioprocessing**	**1.4**	**1.4**	**1.4**
• **University Coal Research**	**3.0**	**3.0**	**3.0**
• **Materials**	**7.0**	**7.0**	**7.0**
• **Center of Excellence**	**0.0**	**3.0**	**3.0**
Total AR	**17.7**	**20.7**	**20.7**
Advanced Metallurgical Processes	**5.0**	**5.2**	**5.2**
TOTAL ADVANCED RESEARCH*	**22.8**	**30.1**	**26.7**

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

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Why Sensors and Controls

- Fossil energy is critical to U.S. economy: 85% of energy use in the U.S. is supplied by fossil fuels; 53% of electric power is generated by coal.
- Deregulation demands lower electricity cost and improved grid connectivity.
- Infrastructure protection requires better monitoring.
- Increasing concerns on global climate change requires significantly higher efficiency and substantially lower carbon emissions.
- Environmental concerns mandate higher reductions in pollutant emissions.

How Do Sensors and Controls Help?

- BENEFITS: Improve reliability, reduce operating and maintenance costs, enhance grid connectivity, enhance efficiency, reduce CO_2 and other emissions, and support economic development.

- COSTS: Cost less than the capital intensive equipment used in power generation.

- PONTENTIAL: Compared to automobiles, airplanes, and defense applications, the sensors and instrumentation used in power plants appear to have room for improvement, indicating R&D opportunities exist.

Strategies

- Identify useful technologies
- Identify desired measurement
- Establish applicability of new technologies for the quantities to be measured (find a match)
- Identify key players
- Assemble the experts and stakeholders to discuss the findings
- Identify the key areas to start

Desired Measurement (temperature, pressure, composition, monitoring and control)

- Online gas species (O_2, CO, NO_x, SO_2, etc) and their distribution
- Ash/slag deposition and composition
- Monitoring ash deposition and filter status for gasification
- Nondestructive measurement for structural components
- On-line structural monitoring
- Intelligent power transmission and distribution through grid
- Temperature and pressure
- Trace element
- Wireless data transmission
- Process control and optimization

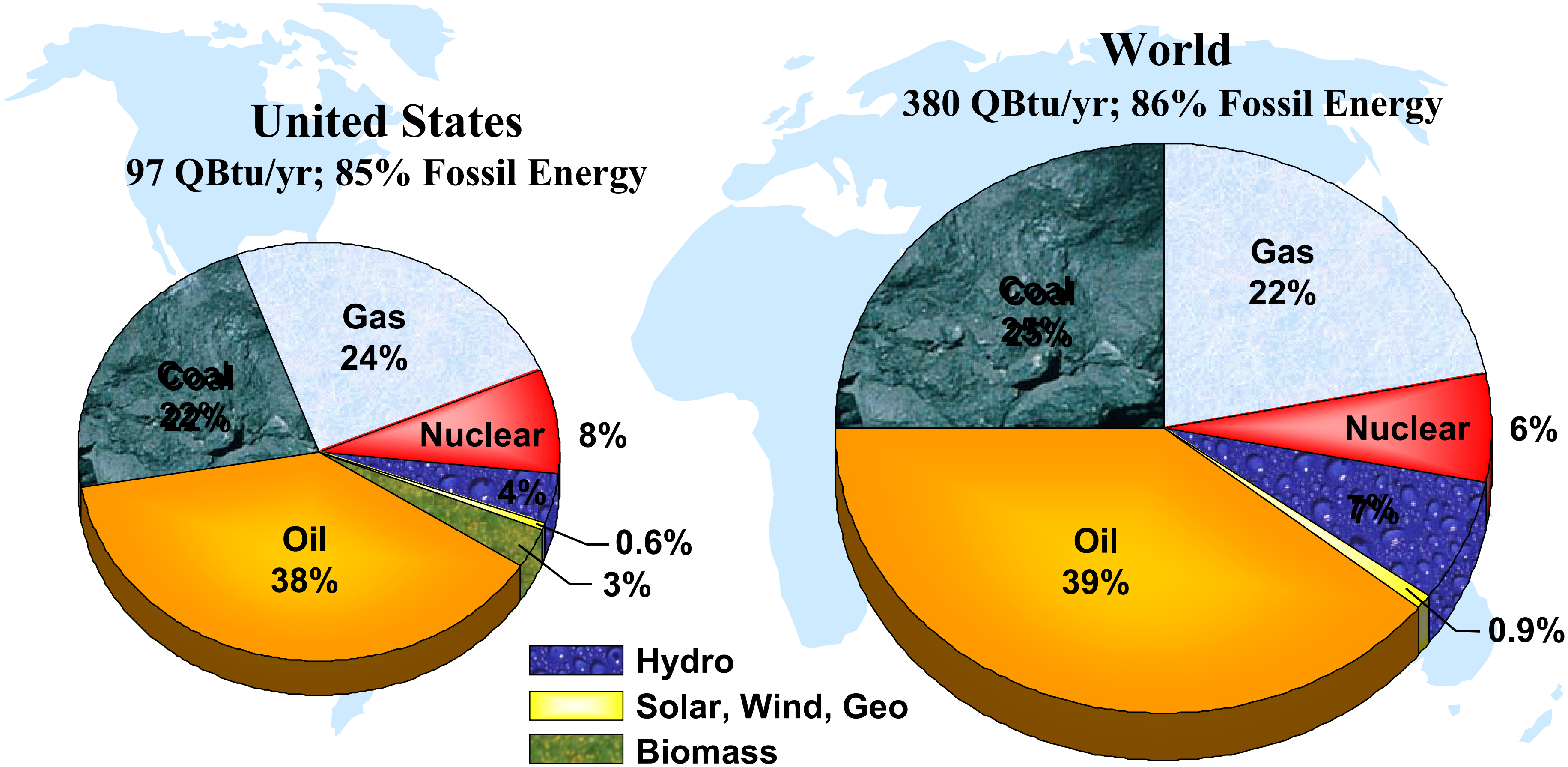
Challenges

- Harsh environment (fly ash, high temperature, etc)
- Vibrations
- Robustness
- Ease of operation by plant staff
- Reliability

VISION 21
Energy Plant of the Future

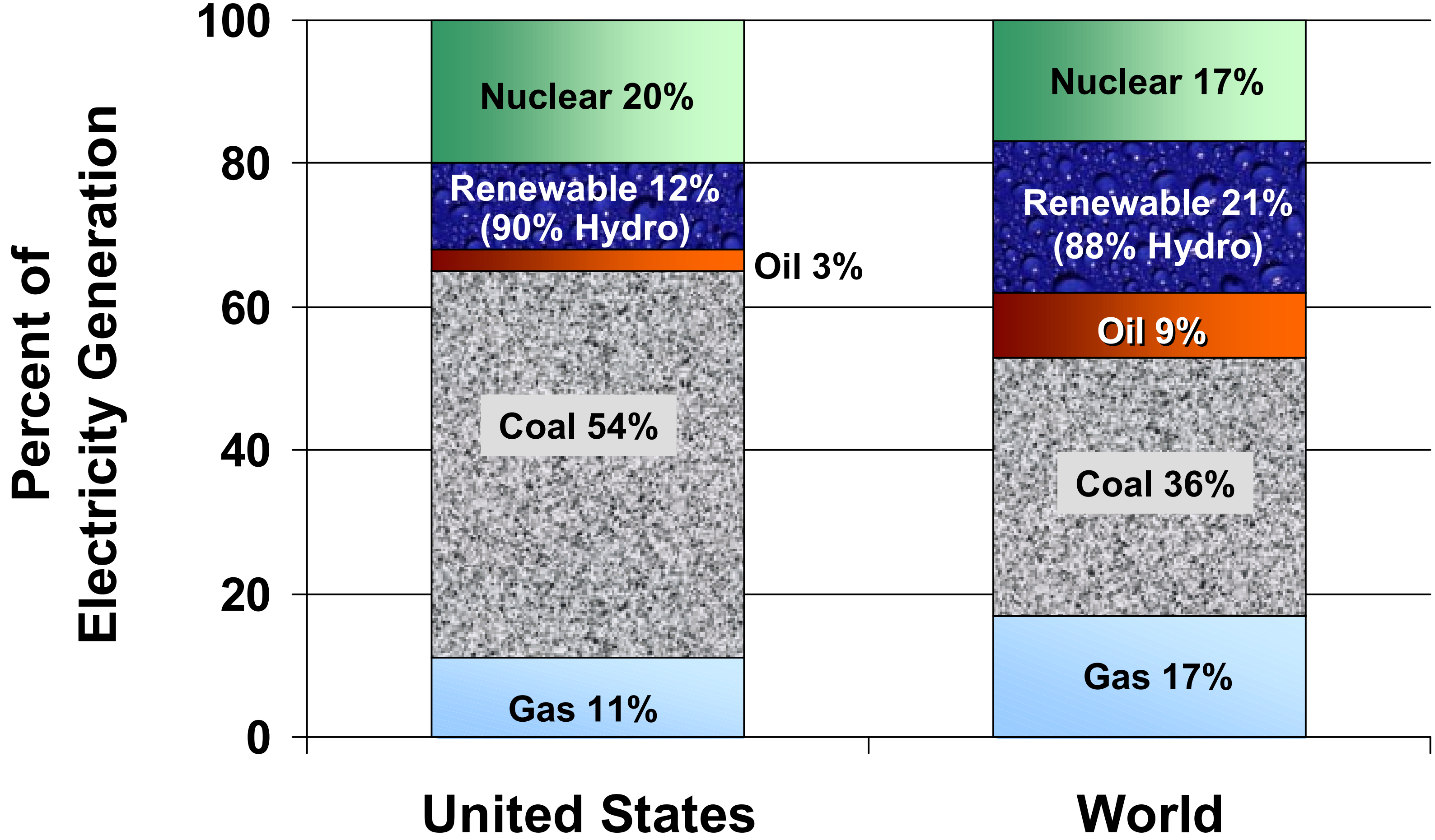
National Energy Technology Laboratory

Fossil Fuels Are the World's Dominant Energy Source



Word Data from EIA96. Does not include non-grid-connected biomass.
U.S. Data from Table 2 of EIA REA 97 & AEO98 Table A2

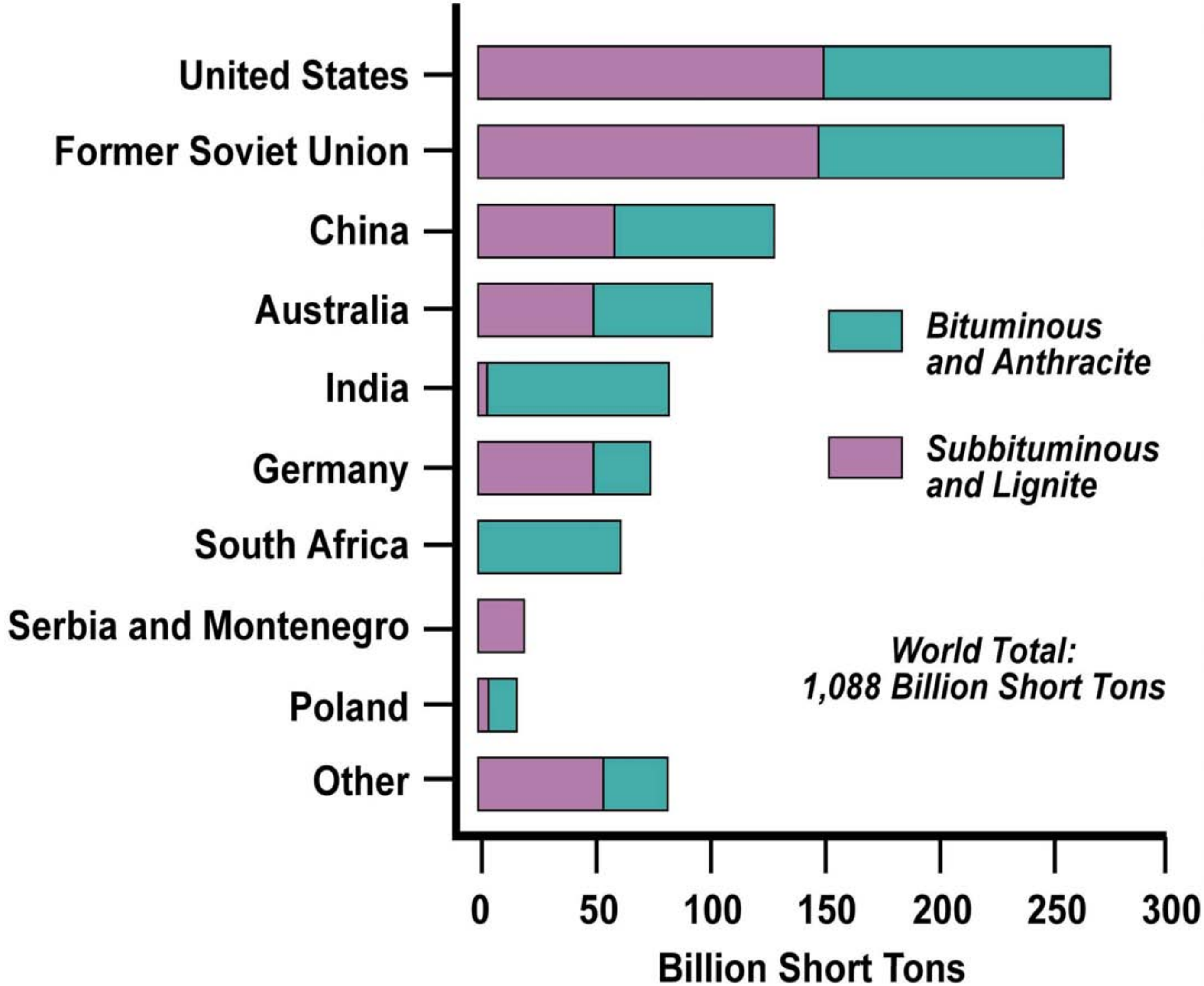
Fossil Fuels Dominate Electricity Generation



Data includes cogeneration. U.S. data is for fuel consumption for electricity
World data: IEO 2000, Table 21
U.S. data: AEO 2000, Table A2

NETL

World Recoverable Coal Reserves



The Vision

Effectively remove environmental concerns associated with the use of fossil fuels for producing electricity and transportation fuels (at competitive costs)

NETL

Drivers for Vision 21

- Recognition that fossil energy will be part of future energy mix
- Concern about environment, including global climate change
- Restructuring of energy industry
- Decreasing reserve margins and grid reliability issues
- Uncertain natural gas prices
- Recognition of value of “future options”

The VISION 21 Program

The Program

- **Long-range, industry-driven R&D program to develop ultra-clean, fossil fuel-based energy plants**
- **Government/industry/academia cost-shared partnership**
- **Stresses technology innovation and a diverse mix of energy resources**

The Challenge

- **Develop technology basis for Vision 21 energy plants with unprecedented efficiency and environmental performance**
  - Focus on technology "modules"
  - Apply systems integration knowledge
  - Satisfy market needs

Vision 21 Program Objectives

Capital & Operating Costs/RAM

- Vision 21 must be competitive with other energy systems with comparable environmental performance

Emissions

- < 0.01 $lb/10^6$ Btu SO_2 and NO_x
- < 0.005 $lb/10^6$ Btu PM
- <1/2 organic compounds in *Utility HAPS Report*
- <1 $lb/10^9$ Btu Hg

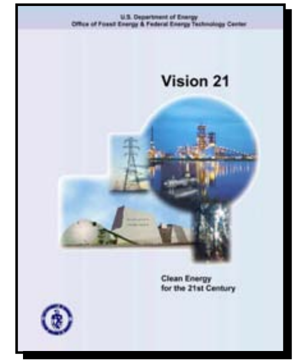
Schedule of Benefits

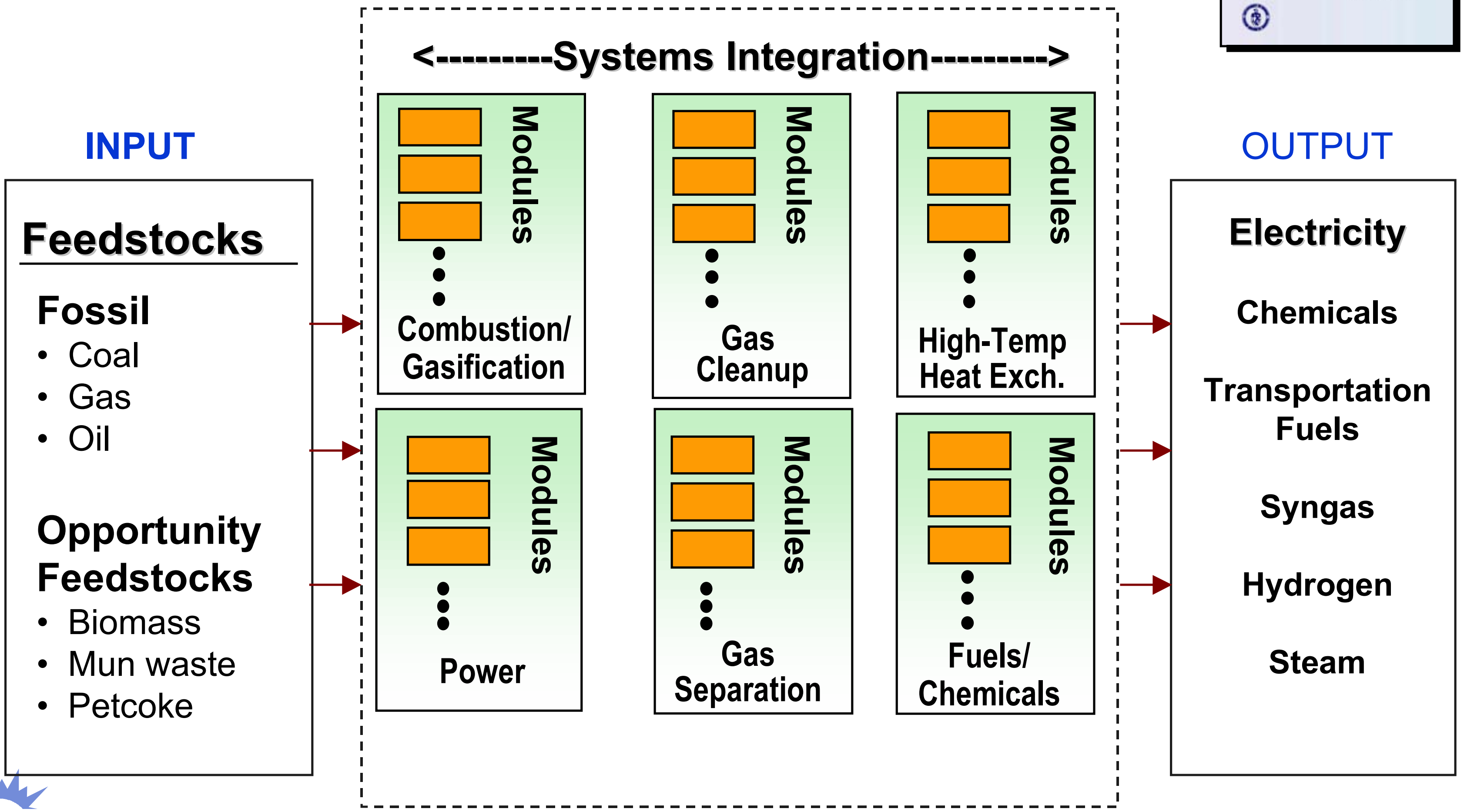
- Technology spinoffs by 2005
- Designs for modules by 2012
- Commercial plant designs by 2015

Efficiency

- Electricity generation
  - coal based 60% (HHV)
  - gas based 75% (LHV)
- Fuels only plants 75% (LHV)

VISION 21
Modular Technology





VISION 21 Technology Roadmap

Systems Analysis and Integration

Supporting Technologies

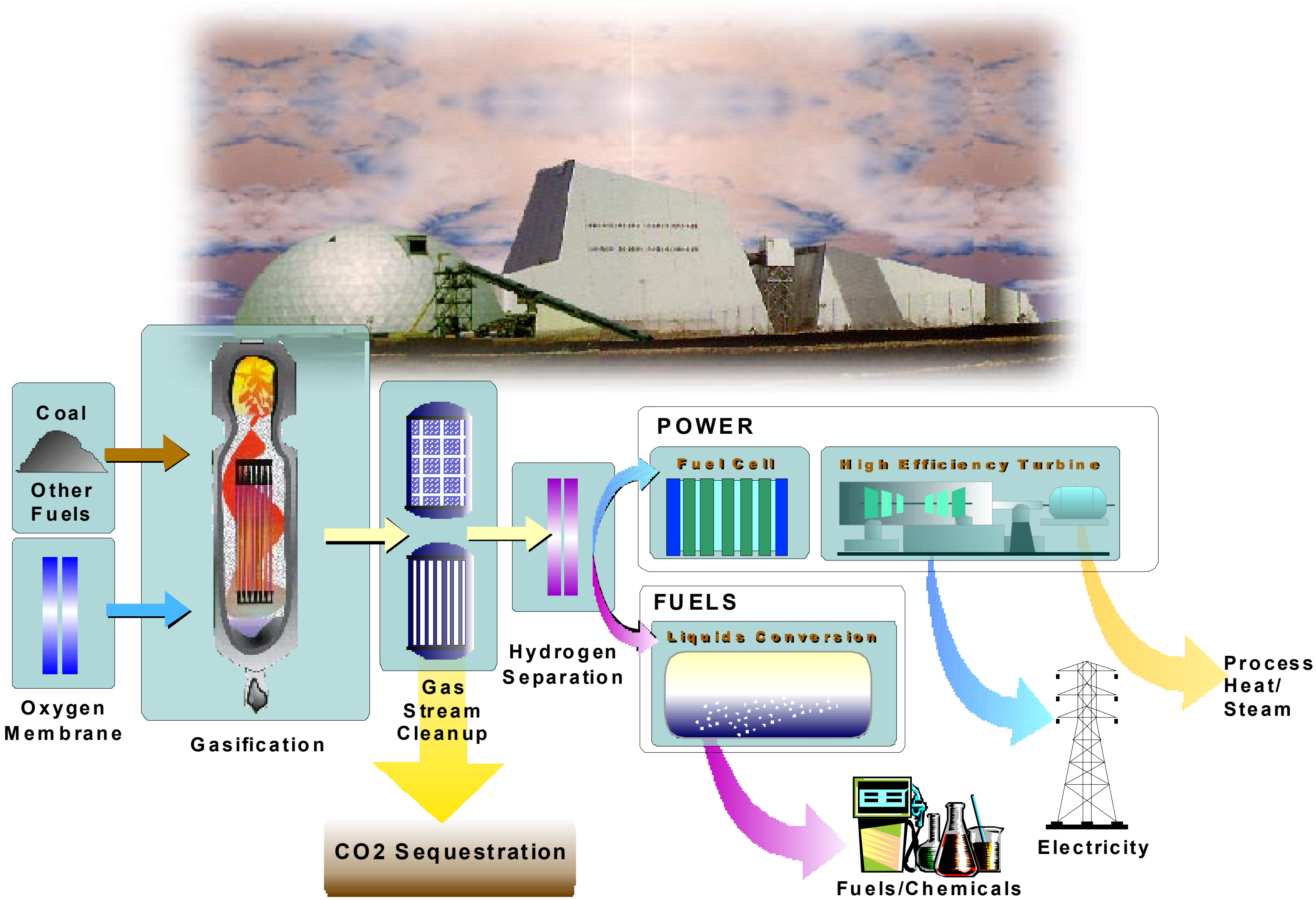
Enabling Technologies

1999 — 2015

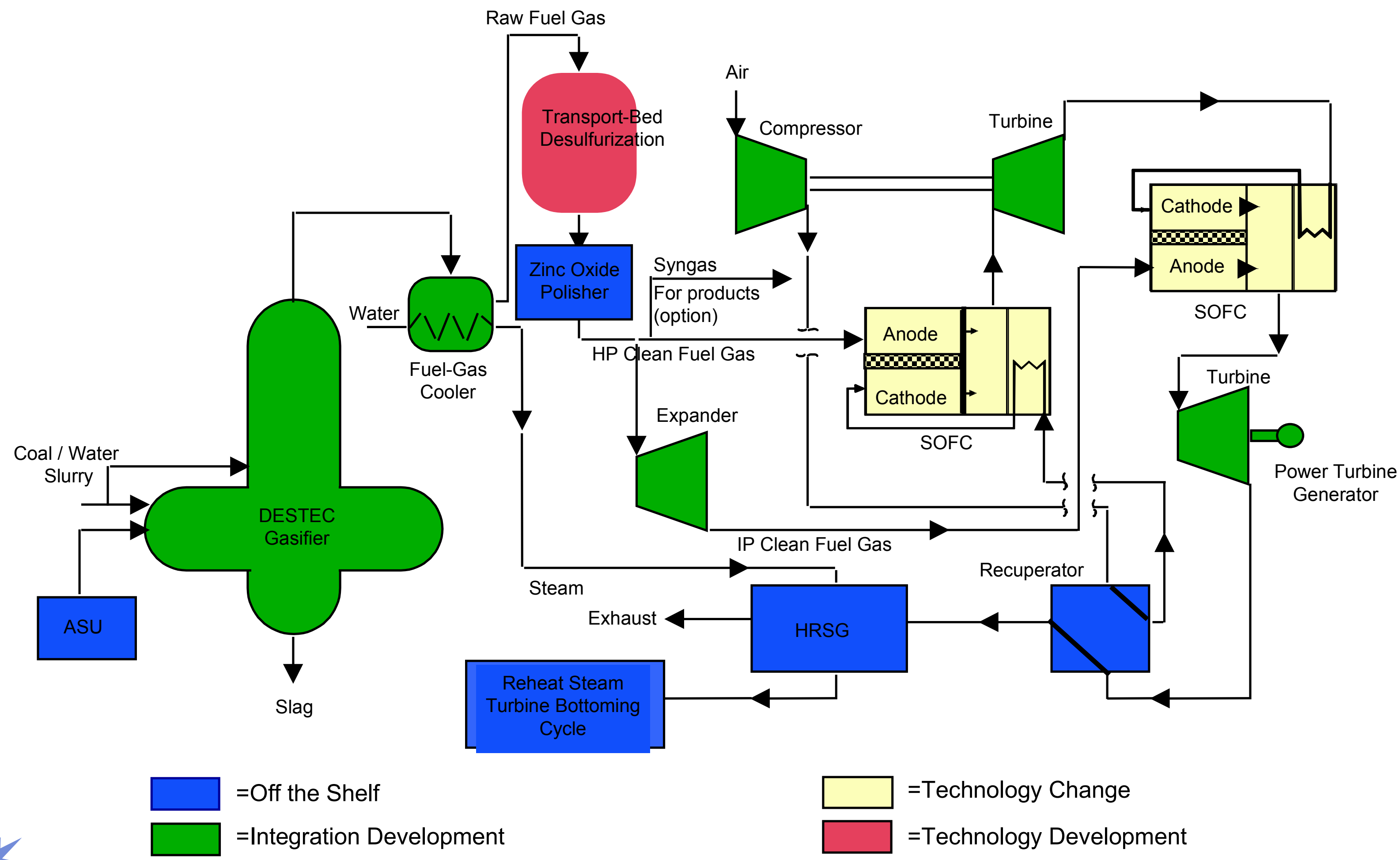
Enabling Technologies	Low-Cost Gas Separation/Purification High-Temperature Heat Exchange Fuel-Flexible Gasification High-Performance Combustion Fuel Cells Fuel-Flexible Turbines Synthesis Gas Conversion to Fuels & Chemicals
Supporting Technologies	Materials Environmental Control Technology Controls and Sensors Computational Modeling/Virtual Simulation
Systems Analysis/ Integration	Technical/Economic/Market Analyses Systems Engineering Industrial Ecology Dynamic Response/Control

NETL

VISION 21 ENERGY PLANT

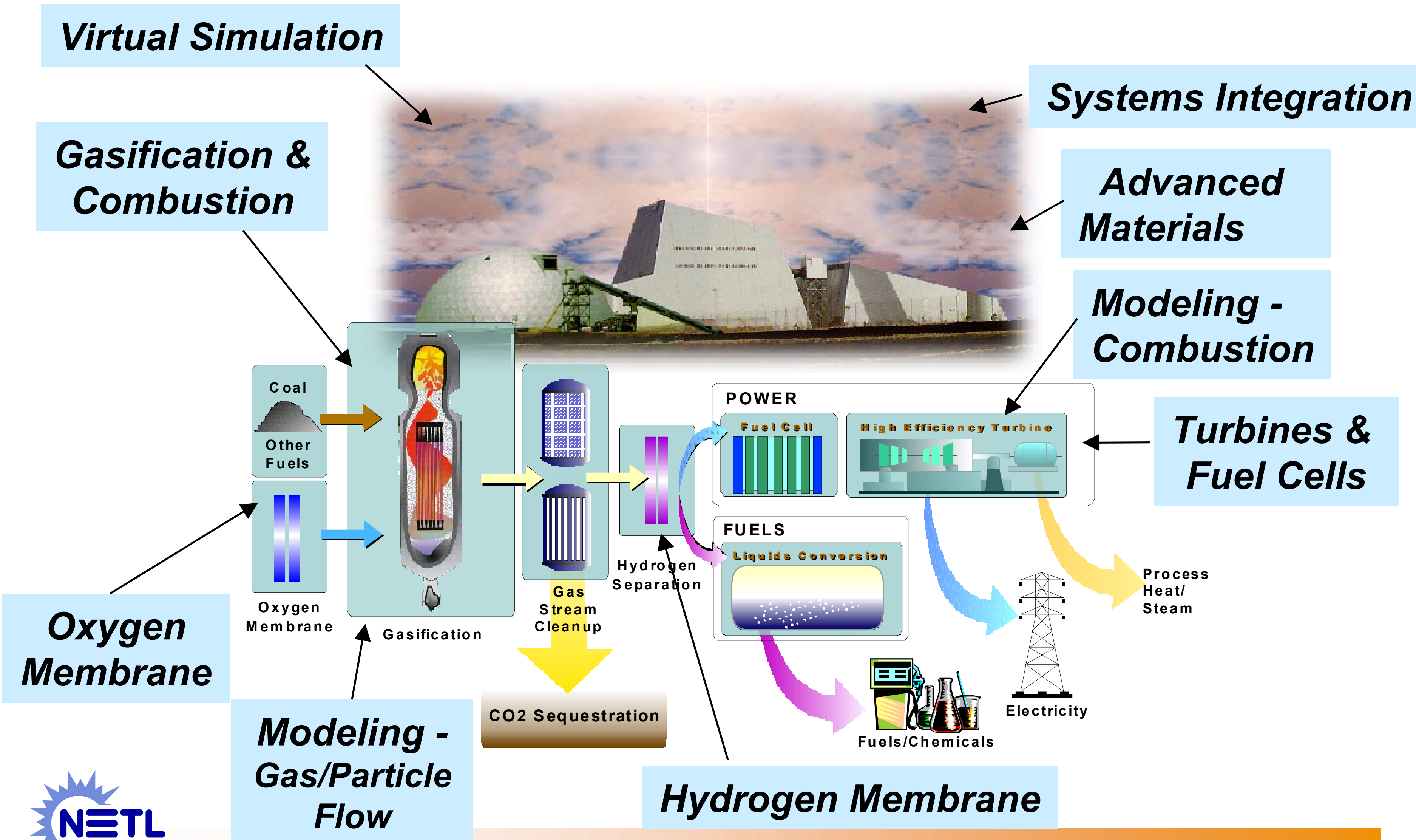


VISION 21 Fuel Cell/Gas Turbine Cycle



VISION 21 Program

New Projects Contribute to the Ultra-Clean Energy Plant



New Projects Contribute to Ultra-Clean Energy Plant

- **Systems Integration**
  - National Fuel Cell Research Center
- **Computational Modeling & Virtual Simulation**
  - Reaction Engineering International
  - Fluent, Inc.
  - Princeton University
  - CFD Research Corp.
- **High-Temperature Materials**
  - Huntington Alloys
- **Gasification & Combustion**
  - Foster Wheeler
  - GE Energy and Environmental Research Corporation
  - Clean Energy Systems
- **Turbines & Fuel Cells**
  - Fuel Cell Energy
- **Advanced Separation Technology**
  - Siemens Westinghouse
  - Eltron Research
  - ITN Energy Systems

What's Different About VISION 21?

Traditional Coal Plant

- Based on single technology
- Emission control "added on"
- Produces electricity only
- Single point design
- Reliability by overdesign
- Simple controls

Vision 21

- Integrates multiple technologies
- Industrial ecology
- Multiple products
- Defined design range
- Reliability by smart design
- Sophisticated controls

VISION 21

"The goals for the Vision 21 Program are very ambitious. If these goals can be achieved, Vision 21 technologies would offer the United States, and the world, a new method of coal-based power generation that would have significant advantages over current methods."

National Research Council

What's Important?

- Leapfrog performance improvement
- Near-zero environmental impact
- Zero CO_2 emission option
- Feedstock and product flexibility
- Industrial ecology
- Technology development focus
- Systems integration

TECHNOLOGY AREA: Sensors and Controls

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Sensors	• Sensors to understand component performance, real-time plant performance, and the "health of plant equipment • Sensors to support condition monitoring, non-destructive testing, and predictive maintenance tools	• Cost of sensors for condition monitoring and specific unit operation control is integral with the technology module cost • Cost of sensors for integrated plant operation is part of instrumentation and control. A reference I&C cost objective for an oxygen blown gasification plant for power generation is $35/kW	• Most power plants are not equipped with state-of-the-art sensing capability – on-line analyzers for performance, condition monitoring measurements • Sensors not currently available to meet Vision 21 plant needs	• N/A
Controls	• Information technology systems that permit real-time management of the power plant asset • Closed loop process optimization	• See above for cost perspective	• PC based process control technology entering power plants • Some open-loop process optimization ("advisory")	• Estimated I&C cost for oxygen blown IGCC plant of $40-50/kW

TECHNOLOGY AREA: Sensors and Controls

Technology	Barriers	Current Status	Approach 0-5 yrs	Approach 5-10 yrs	Approach 10-15 yrs
Sensors: Program considerations	*Program and Support Barriers* • Fragmented markets for advanced sensors resulted in inadequate private support for development efforts. • Conventional thinking tends to treat sensors as an add on in the design stage and failed to recognize the roles advanced sensors can play. (Sensors should be an integral part of design)	• Process developers consider sensors as an afterthought – Plan to utilize existing sensors rather than creating better ones – Leads to increased process development cost – Limits creativity and possible solutions. • Mismatch between current sensor capabilities and envisioned control requirements (e.g. speed and sensitivity)	YEARS 0-1 • Initiate an independent sensor development program to address known shortcomings. Focused workshop to identify sensor needs and requirements • . YEARS 0-3 • Extend sensor development program to meet defined needs – Model component and system performance to permit selection of measurement needs – Assess state-of-the-art of sensors and identify gaps – Define program, prepare solicitations, etc. YEARS 3-5 • Perform program	• Follow-up with workshops, communication between developers and users, and program support • Monitor component and plant needs and revise priorities based on review of needs • Demonstrate new sensors technology in operating plants	• Continue follow-up activities • Demonstrate new sensors technology in Vision 21 plant projects • Support Vision 21 plant design and operation activities • Assess the payback from DOE's sensors and control programs

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TECHNOLOGY AREA: Sensors and Controls

Technology	Barriers	Current Status	Approach 0-5 yrs	Approach 5-10 yrs	Approach 10-15 yrs
Sensor Technology	*General Technical Barriers* • Limited and constrained accessibility to utilize sensors • Harsh operating conditions • Material limitations	*Existing sensors have many limitations:* • Inadequate reliability, sensitivity, inaccuracy • Slow response • Complex and costly • Single point and single phase *Promising, but underdeveloped concepts exist, e.g. wave technologies* *Significant development required for each technology*	• Focus on in-situ, real time, fast response, field hardened, miniaturized sensors suitable for control (Interrogate and sense with energy only) potentially attainable with wave technologies – Optics – Acoustics - Electromagnetics • Develop sensors based on new concepts and using new technologies including nano-technology, MEM, etc.	• Continue supporting development of sensors based on new concepts • Test new sensors in operating plant environment • Incorporate new sensors into new control systems	• Continue supporting development and testing of new sensors • Demonstration projects

TECHNOLOGY AREA: Sensors and Controls

Technology	Barriers	Current Status	Approach 0-5 yrs	Approach 5-10 yrs	Approach 10-15 yrs
Sensor Technology (continued)		*NETL Initiatives* • Sensors for physical properties (T,P, flow, etc.): High temperature sensors and measurement development using infrared technology, coating, etc. is currently supported by NETL. This effort will help improve efficiency and performance in combustion and gasification. • Sensors for chemical species including emissions sensors**:** - NETL supported Sensors Research Corporation in developing advanced solid state sensors for measuring H_2S, NO_X, SO_X, and NH_3 - NETL has an active program of mercury measurement, and this R &D has laid a foundation for sensor development • Particulate sensors: Off-line and batch • Facilities Diagnostics and maintenance sensors:	• Continue current program initiatives e.g. test high temperature sensors, in-line testing of SRC chemical sensing technology • Continue near term work using existing wave technology in extractive or bypass configurations • Identify/evaluate applications for other emerging sensing technologies	• Continue supporting development of sensors based on new concepts • Test new sensors in operating plant environment • Incorporate new sensors into new control systems	• Continue supporting development and testing of new sensors • Demonstration projects

TECHNOLOGY AREA: Sensors and Controls

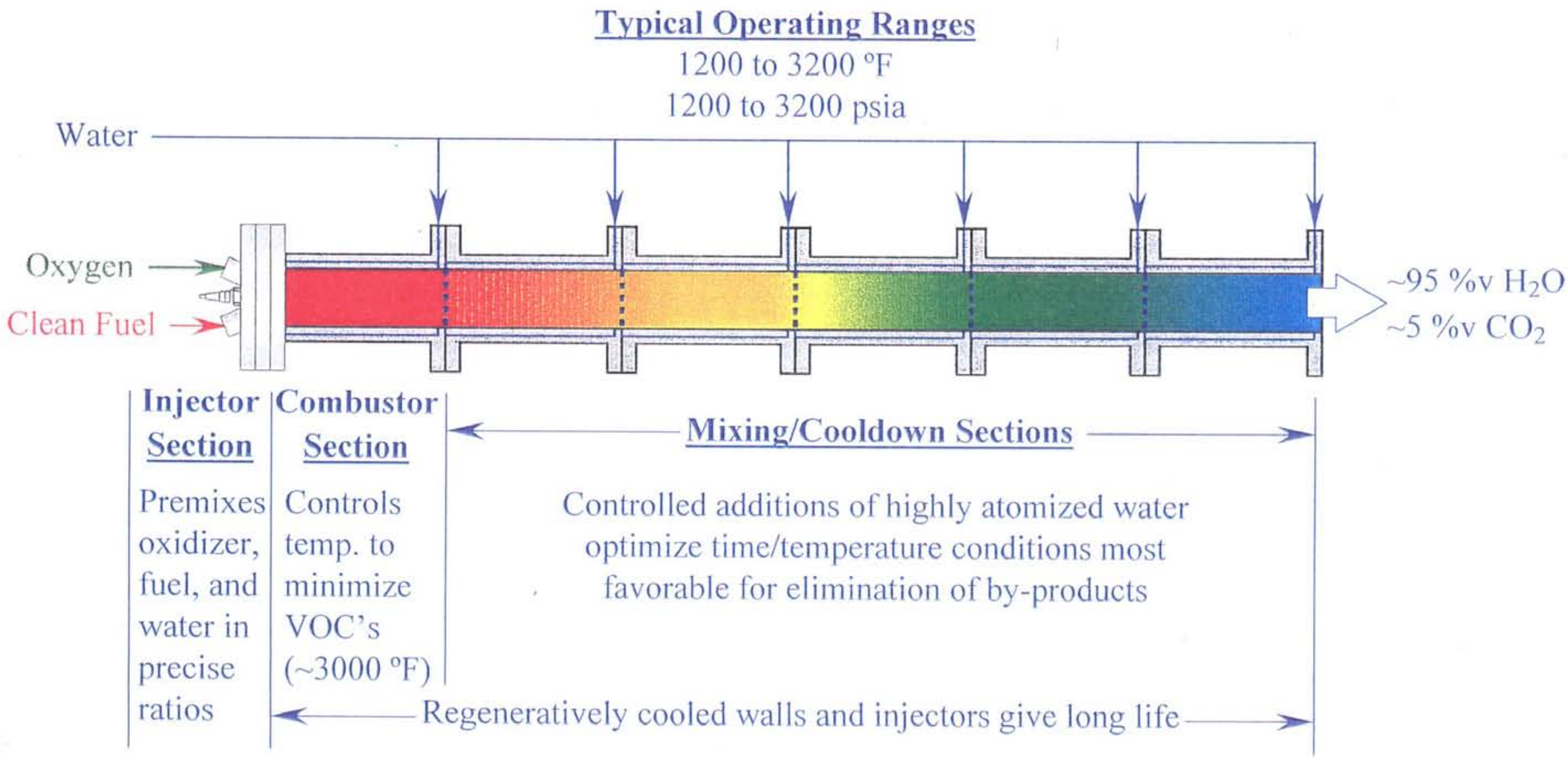
Technology	Barriers	Current Status	Approach 0-5 yrs	Approach 5-10 yrs	Approach 10-15 yrs
Controls	• Developing advanced controls is under-funded compared to other areas • Some hardware has long response time such as valves • Knowledge of failure modes and operability problems needs to be improved • Knowledge of some processes such as NO_x generation and destruction, fate of trace elements, and predicative modeling need to be improved	• Generic NO_X Control Intelligent System (GNOCIS) developed by Southern Company Services under NETL funding using neural net based control technology lowers NO_x emissions while maintaining plant performance • Point solutions are being (have been) developed for specific (currently available) systems • Some dynamic process simulators are available such as used on gasification, fuel cell, and hybrid systems • Advanced process controls for other applications are well developed (e.g. automobiles)	• Define process control needs required to meet the performance and reliability objectives for Vision 21 plants • Evaluate state-of-the-art control technologies: Example control technologies to be reviewed include Regulatory Control Algorithm, Supervisory Optimization, Control Numerical Methods, Inferential Sensing, and Predictive Maintenance • Define program to meet Vision 21 plant objectives – coordinate with component technology initiatives • Direct plant and component development programs toward intelligently controllable systems (example: automotive engines) • Identify key data and models, and components in control systems required to develop advanced control strategies • Implement programs to show benefit of advanced controls and predictive maintenance	• Direct development of components and plants to leverage advanced control and predictive maintenance • Update program to reflect new plant needs and technology development • Implement program • Continue review of Vision 21 plant needs and monitoring control technology state-of-the-art	• Demonstrate innovative process control technologies

VISION 21 Projects
Gasification and Combustion

Clean Energy Systems
(Sacramento, CA)

"Rocket engine" steam generator to power an advanced turbine, generating electricity and emitting only water and a stream of CO_2 ready for sequestration

The *"Rocket Engine"* Steam Generator

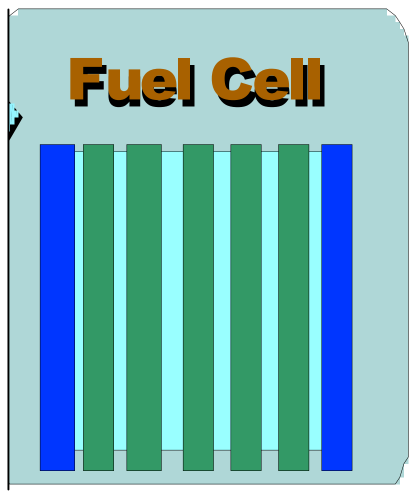


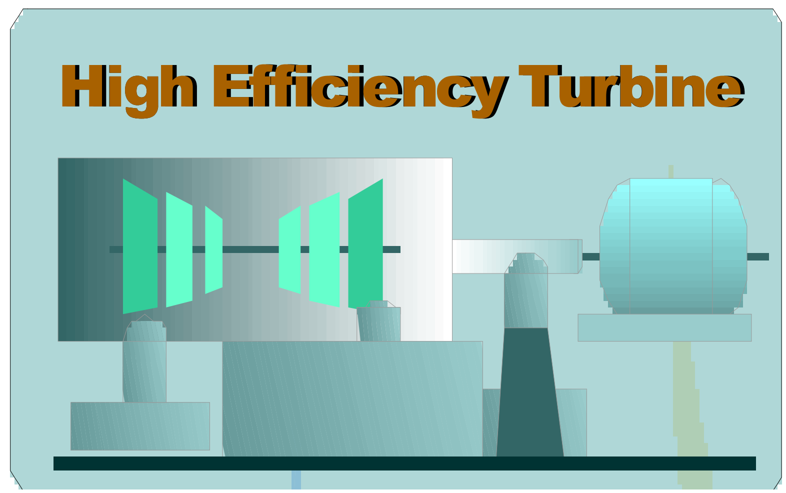
Clean Energy Systems

VISION 21 Projects
Turbines & Fuel Cells

Fuel Cell Energy *(Danbury, CT)*
Capstone Turbine (Woodland Hills, CA)

Fuel cell/gas turbine "hybrid" power system with 65-80% efficiency

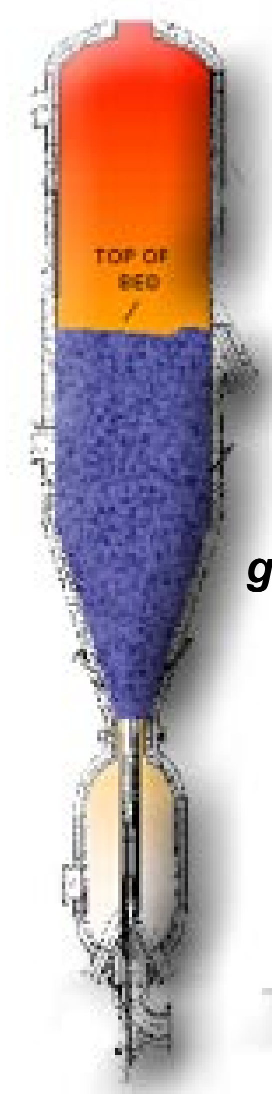




Gasification and Combustion

Foster Wheeler Development Corporation
(Livingston, NJ)
Nexant
(San Francisco, CA)
Praxair
(Danbury, CT)
REI
(Salt Lake City, UT)
Corning
(Elmira, NY)
ADA Technology
(Livermore, CA)

Pressurized circulating fluidized bed partial gasification module that produces gaseous and solid fuels for use in fuel-flexible high-efficiency plants



GE Energy & Environmental Research Corporation
(Irvine, CA)
Southern Illinois University
(Carbondale, IL)
California Energy Commission
(Sacramento, CA)

Advanced combustion/ gasification concept that produces hydrogen for fuel cells or combustion turbines and sequestration-ready CO_2

image courtesy of Foster Wheeler

Current Research and Future Needs in Power Generation

NETL Sensors and Controls Workshop

April 17 - 18 2001

Washington, D.C.

Robert Frank

EPRI I&C Center

865-717-2001 rfrank@tva.gov

EPRI I&C Center

Current Research and Future Needs in Power Generation

- Background
- Current Research
- Future Needs

Background

- Electric Power Research Institute (EPRI)
  - Headquartered in Palo Alto, CA
  - Research Arm of the Electric Power Industry
    - Various Research Initiatives in all phases of the industry
  - Several Technical Centers
    - I&C Center - near Knoxville, TN

EPRI I&C Center

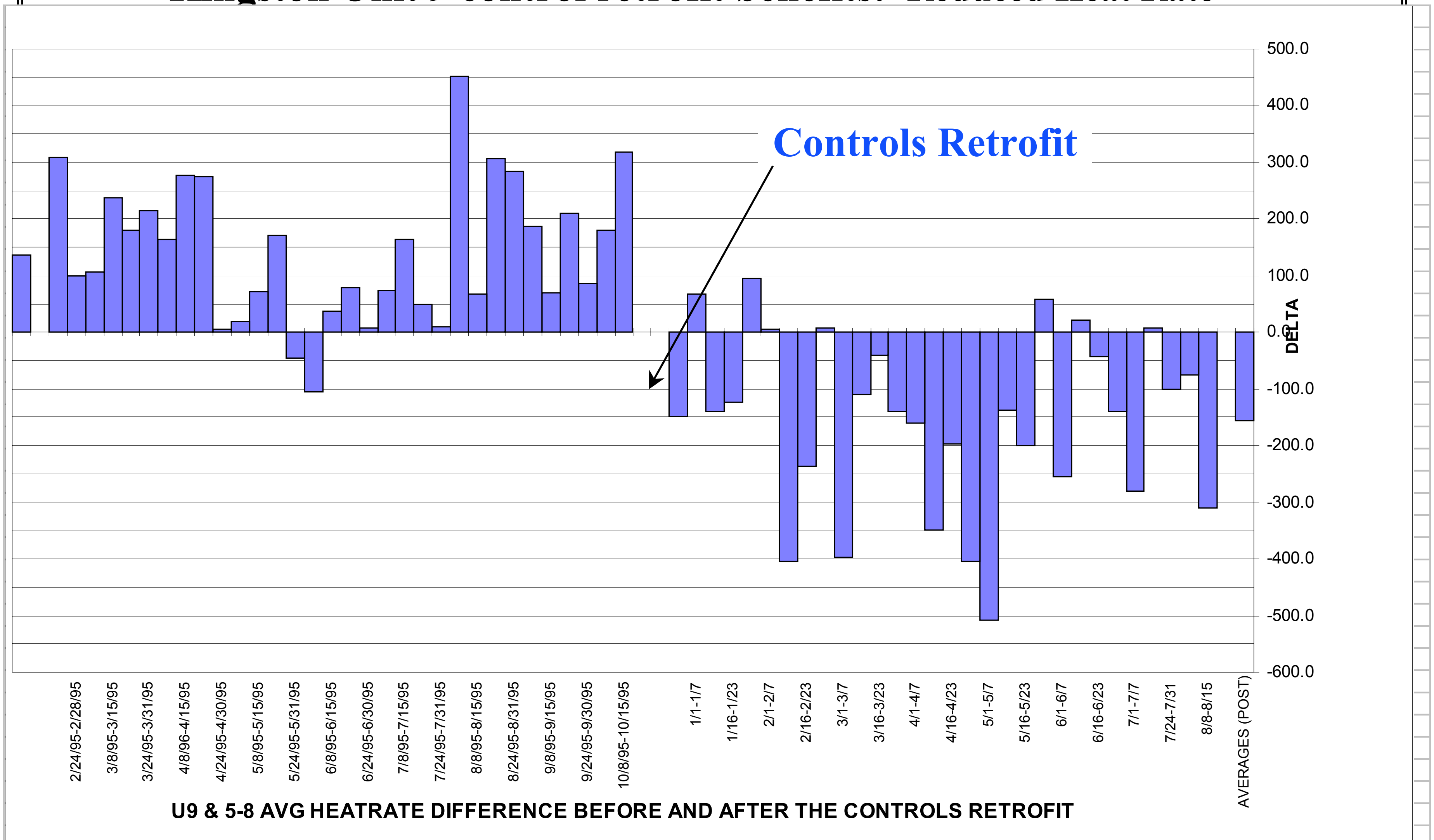
Kingston Fossil Plant

History of the I&C Center

- Unit 9 DCS Retrofit created the opportunity for the I&C Center.
- Mission: To provide advanced process control and instrumentation solutions that improve plant competitiveness and profitability
- Facility dedicated February 29, 1996

I&C Center Activities

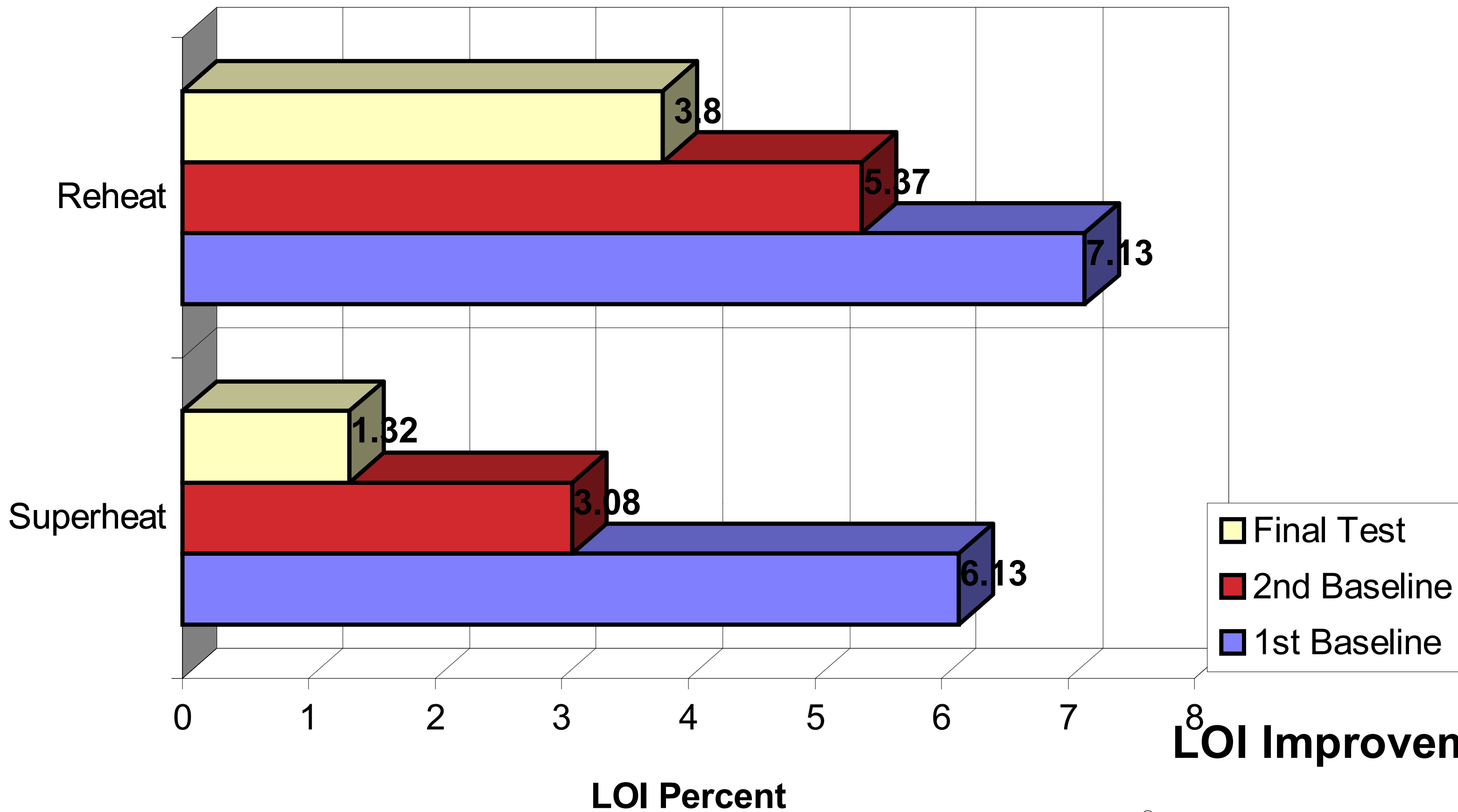
Kingston Unit 9 control retrofit benefits: Reduced Heat Rate



BUNKER PERIOD

EPRI I&C Center

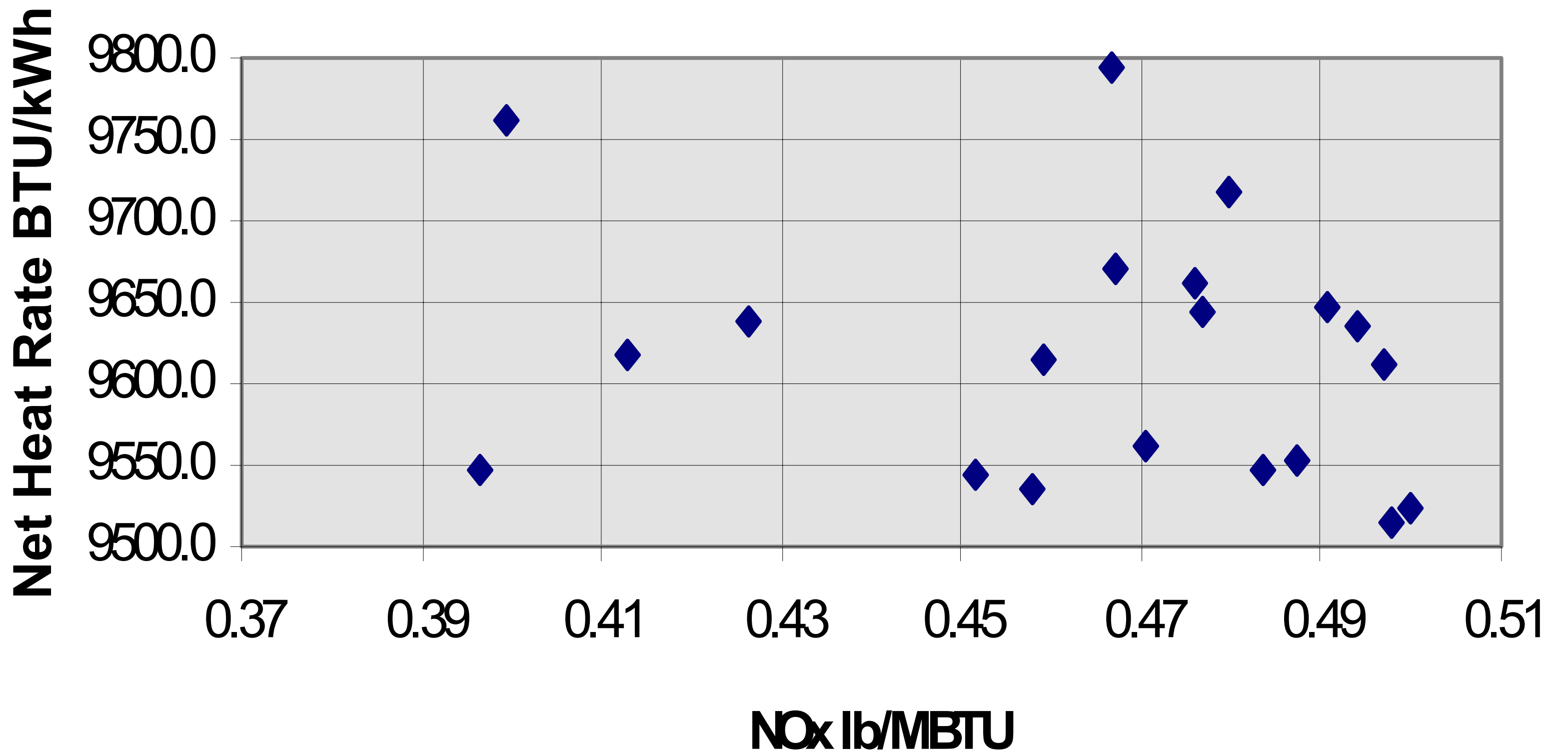
I&C Center Activities
Unit 9 LOI Improvement



LOI Improvement

NOx versus Net Heat Rate

Parametric Test Data



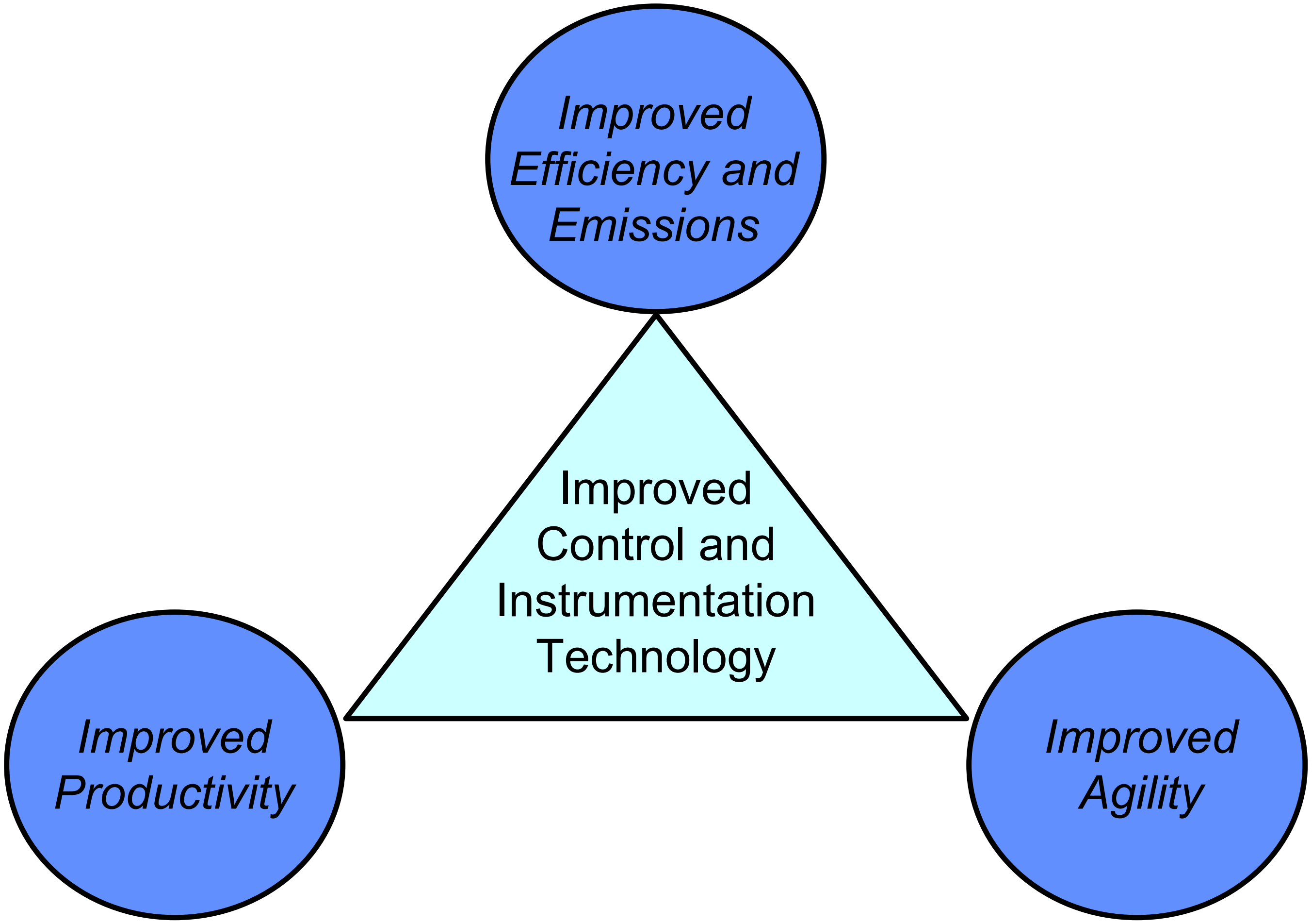
Baseline NOx before Controls Retrofit: .62 lbs./10e6 BTUs

NOx Data obtained by varying:

- **O2**
- **Fuel Bias**
- **Air Bias**
- **Burner Tilts**

EPRI I&C Center

I&C Issues and Opportunities



Improved Productivity

Improved productivity consists of better decisions due to better information available and more efficient use of staff. Examples of EPRI tools to enhance productivity include CMW and ICCP.

Improved Agility

Improved agility is the ability to respond to the new demands of dispatch as well as fuel quality. In the competitive world, the unit which can:

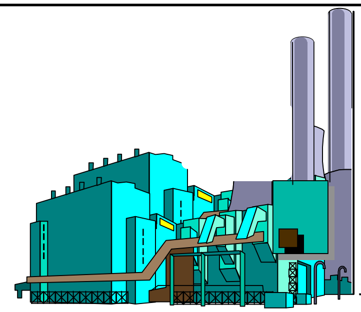
- reach target load faster and
- provide quality ancillary services such as
  - voltage regulation,
  - VARs, and
  - frequency control

is going to be much more profitable than one does not. Advanced I&C provides the platform and ability to provide this capability.

Improved Efficiency and Emissions

FUEL COSTS
$39,000,000/Year @ 9,500 BTU/kw-hr, $1.25/million BTU's

Non Fuel O&M COSTS
$5,850,000/Year
(10 - 20% of total costs)



Gaseous emissions

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

Solid wastes

Total Fuel + O&M Budget
$44,850,000 for "Avg. 500 Mw Unit"

- **A 1% improvement in EFFICIENCY yields $390,000 savings in fuel costs.**
- **For the entire installed fossil capacity, this yields $409,439,000.**
- **Additional benefits include 1% REDUCTION in greenhouse gases and solid wastes.**

- **A 1% increase in availability equals and additional 32,850,000 kw-hr/yr for the 500Mw plant($1,971,000 in additional sales @$60/1000kw-hr)**
- **At a retail price of $60/1000 kw-hr, this yields a $1,461,825 increase in gross profit for this plant at $15.5/Mw-hr production costs.**
- **This equals an additional 5,000 Mw of capacity for total installed fossil power plants**

Current I&C Center Projects

- Advanced Multivariable Boiler Control
- Combustion Optimization
  - GNOCIS Neural Network (KIF 5-9)
  - Forney OptiFlame (JFP 7)
  - MK Engineering LOI & CO Measurements (KIF 9)
- Improved Sootblowing
  - Intelligent Sootblowing
  - Heat Flux Sensors
  - Bergemann Water Cannon
- Heat Rate Monitoring
- Plant Monitoring Workstation Implementation & NT Conversion
- Heat Rate Monitoring Systems Assessment
- Cost of Generation Monitor Development

Current I&C Center Projects

Water Chemistry Expert System Implementation (KIF)

Assessment of On-line Coal Analyzers (PAF & CUF)

On-Line Pulverized Coal Flow Measurement (TVA BRF,)

Combustion Products Sensor Assessment (CO, NOx, etc.)

Advanced Pulverizer Control

Controls Maintenance Workstation Implementation

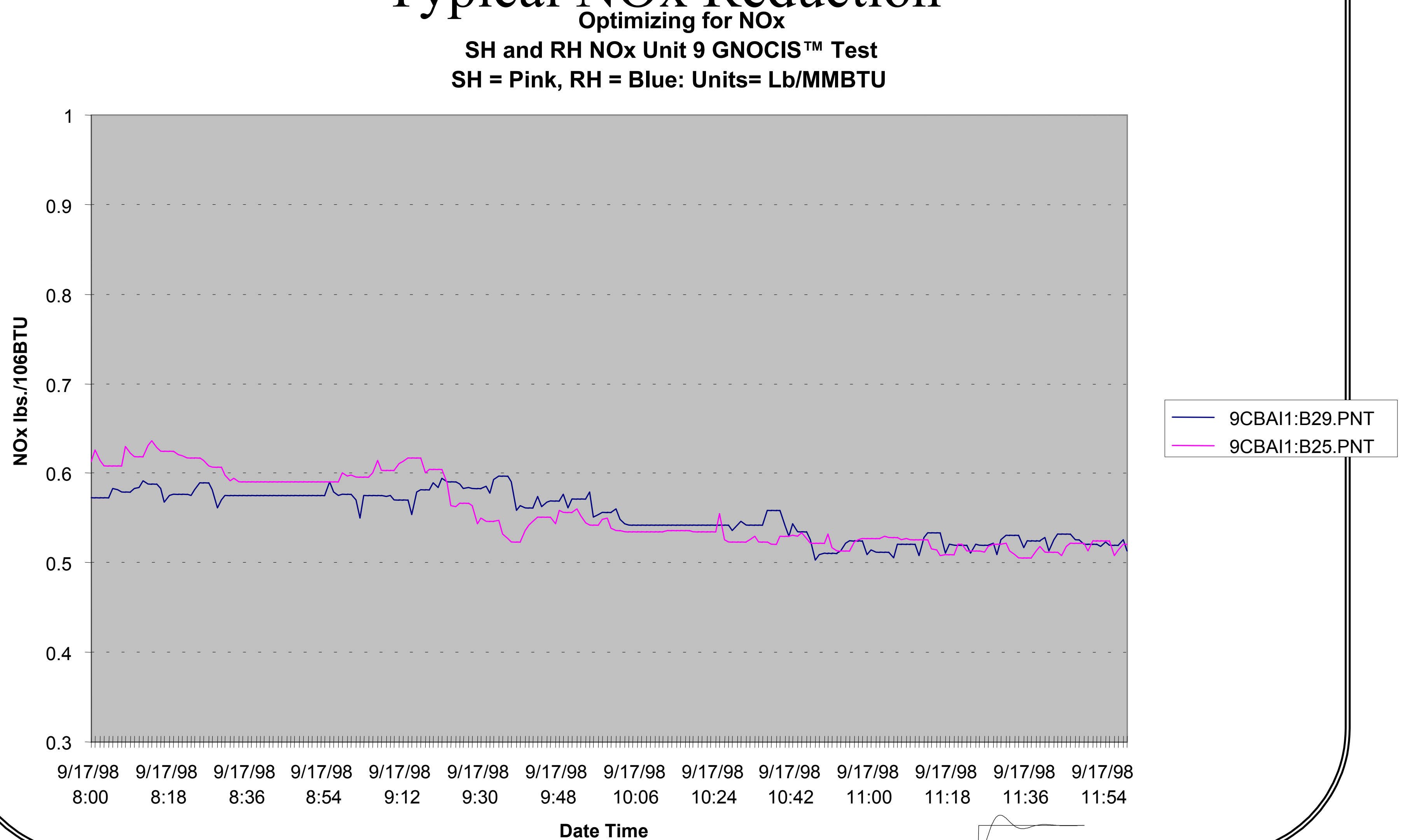
Ultrasonic Feedwater Flow Measurement

Boiler Inspection Robot Development

Sensor Validation

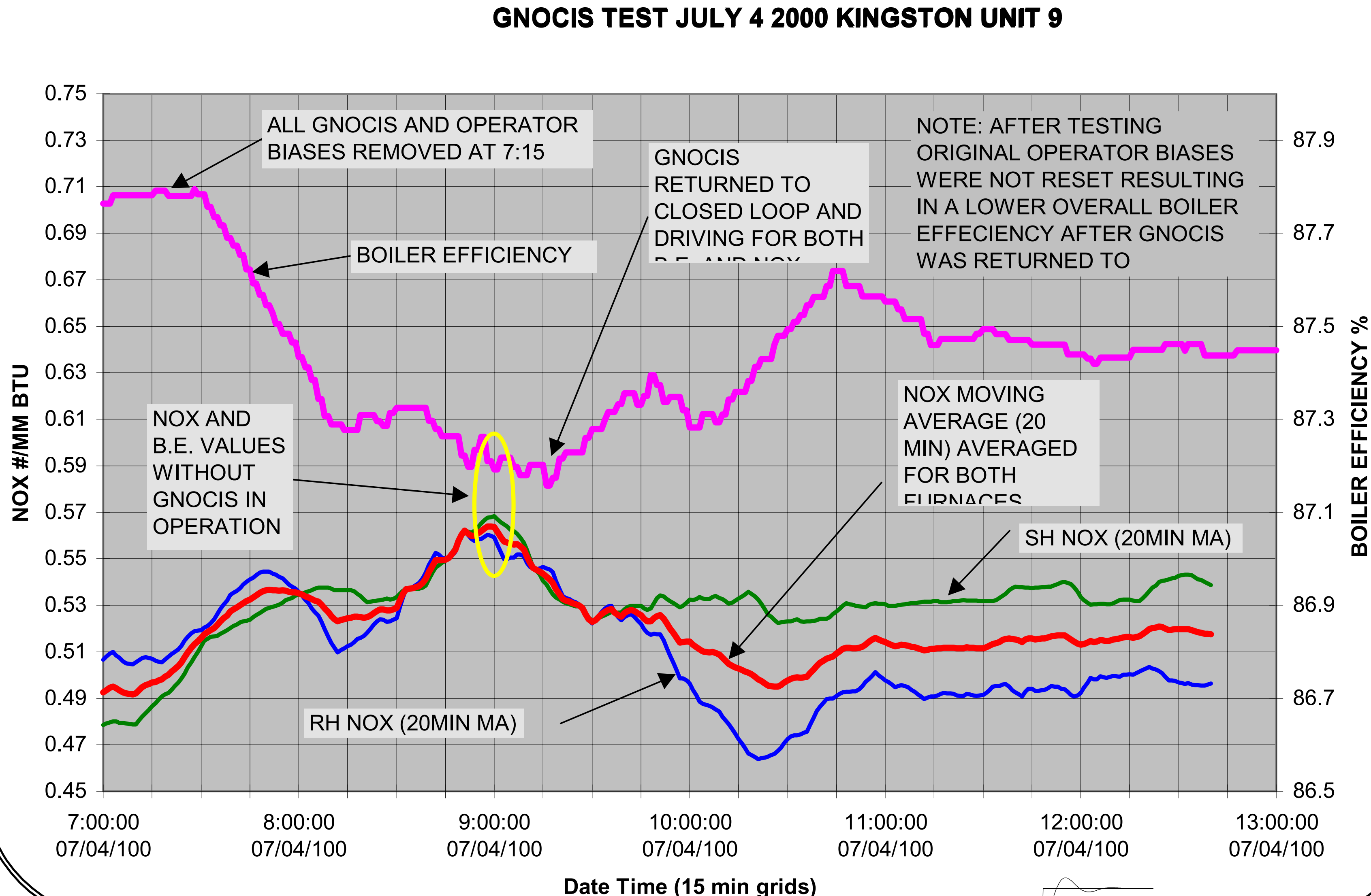
GNOCIS Neural Network

Typical NOx Reduction



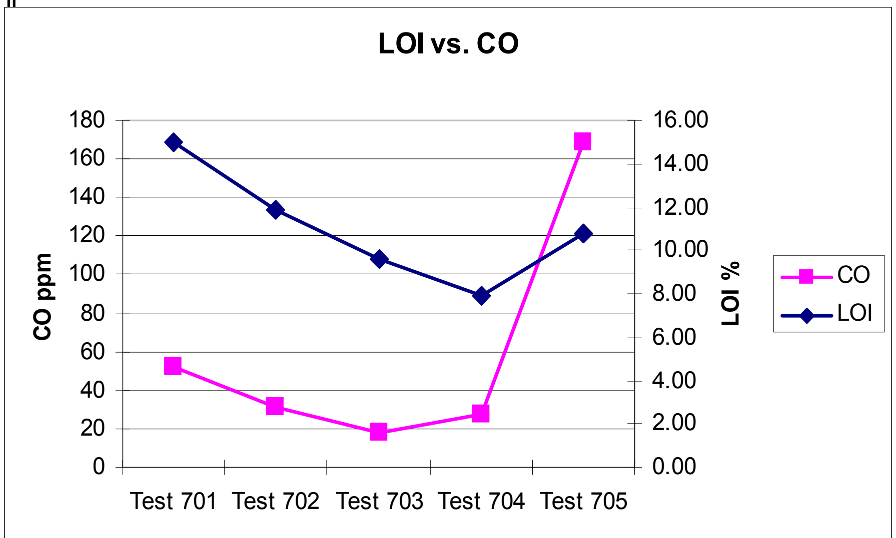
EPRI I&C Center

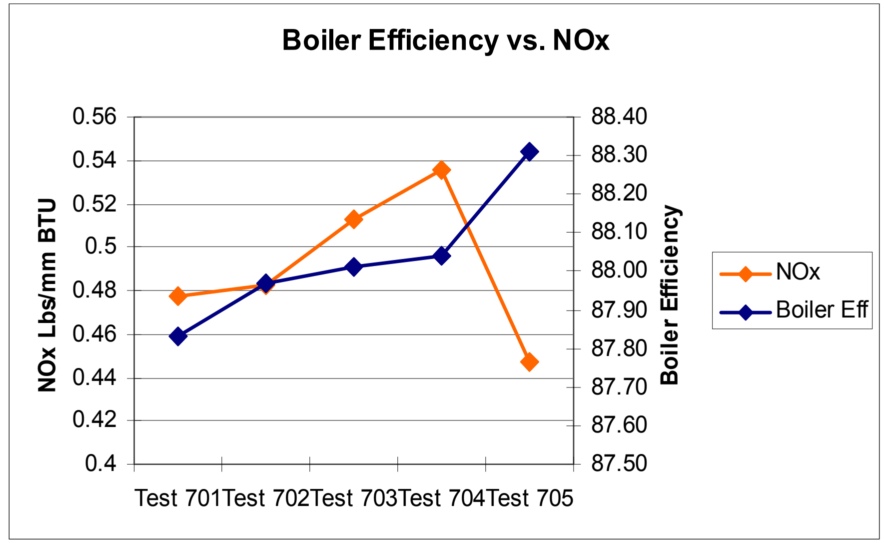
Typical NOx and Boiler Efficiency Results from GNOCIS

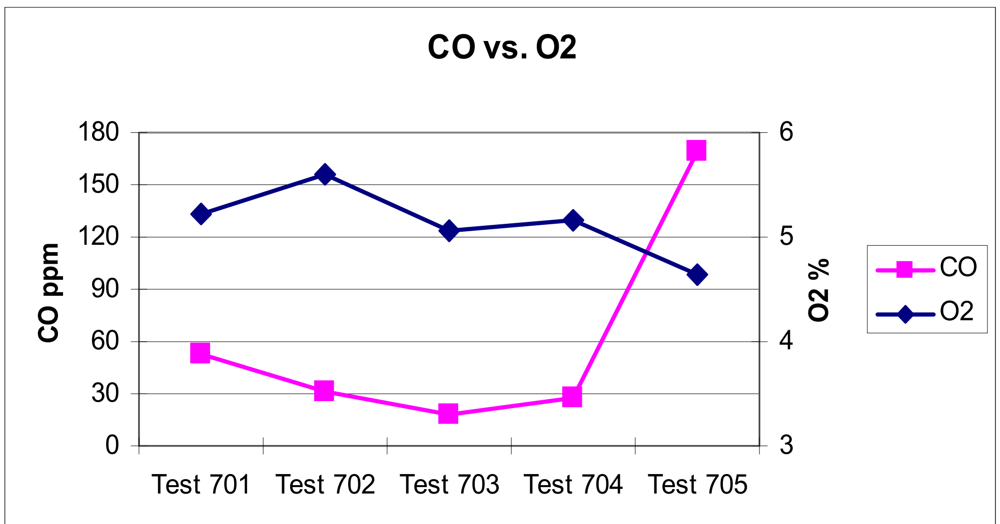


EPRI I&C Center

Johnsonville Optiflame Summary







EPRI I&C Center/TVA/TTU
Boiler Inspection Robot

Goal: Develop a low cost mobile platform for inspection of fireside boiler surfaces

Benefits: Reduced costs and time to inspect boiler tube surfaces

Long-term goal: Investigate the development of automated tube leak location, preparation, and repair.

Boiler Inspection Robot

- Dr. Steven Canfield (TTU) has developed such a platform and tested it at TVA Kingston
- It uses magnetic tracks to drive along water wall surfaces
- Current inspection device is a CCD camera
- Current project focuses on applying other NDE inspection methods onboard

Future Needs

- Individual burner tuning with active control
- Improved combustion measurements
  - NH_3, CO, NO_x, etc.
  - Flame quality
- Real time cost-of-generation linked with economic and environmental dispatch
- Improved plug and play software
- Adaptive control modes for changing market demands

Possible New Opportunities

- Generation Plant Challenges
  - Reduced staffing
  - Pressure to improve profitability
  - Push to reduce emissions
  - New emissions regulations
- R&D Opportunities/Challenges
  - Teaming to leverage funding
  - Short term goals
  - Long term vision

DELPHI
Automotive Systems

Automotive Sensors for
Improved On-Board Control and Diagnostics

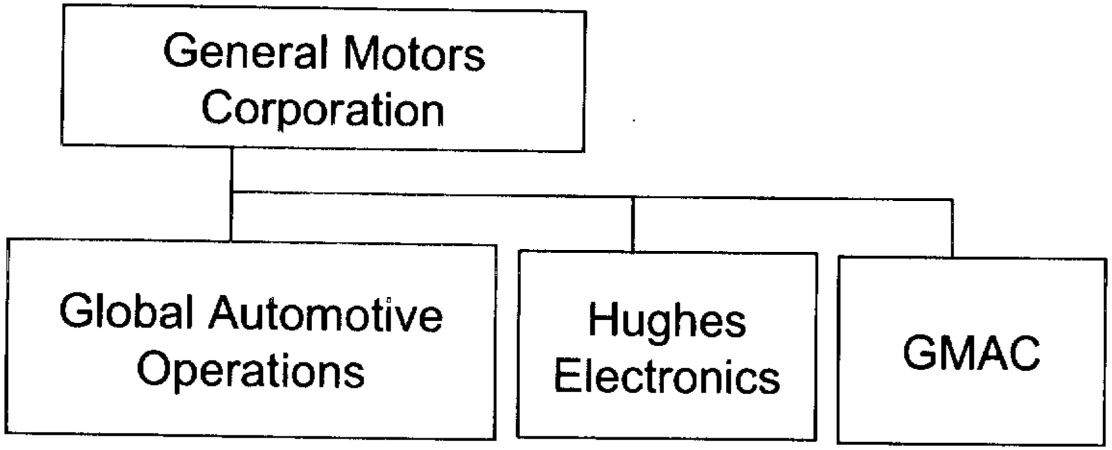
Galen B. Fisher

Delphi Research Labs
Delphi Automotive Systems

Sensors and Controls Workshop
Washington, DC
April 17, 2001

DELPHI
Automotive Systems

The Evolution of Delphi



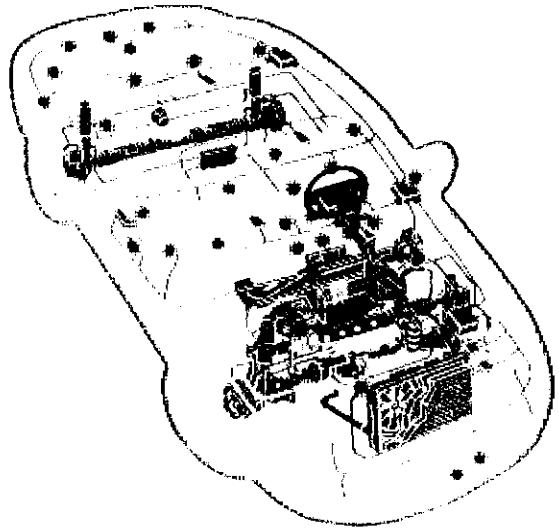
Spin-Off
May 28, 1999

DPH
Listed
NYSE
THE NEW YORK STOCK EXCHANGE

- 1988: ACG Worldwide Group structure created
- 1994: ACG Worldwide established as separate business sector
- 1995: ACG Worldwide became Delphi Automotive Systems
- 1998: Delphi incorporated as a subsidiary
- 1999: Delphi Initial Public Offering; "DPH" on NYSE
- 1999: Delphi becomes a totally independent company

DELPHI
Automotive Systems

Current Product Portfolio



Dynamics & Propulsion
Air/Fuel Systems
Ignition Systems
Exhaust Aftertreatment Systems
Fuel Handling & Evaporative Systems
Energy Storage & Conversion
Valve Train Products
Sensors & Solenoids
Chassis Systems & Modules
Intelligent Chassis Control Systems
Complete Brake Systems
Wheel Brake Components
Brake Apply Components
Gen III Wheel Bearing Modules
Suspension Dampers & Damper Modules
Vehicle Control Systems
- Electric Power Steering, Steering Columns, Power Steering Pumps & Hoses, Steering Gears, Driveline Systems, QUADRASTEER
- Half Shafts, CV Joints

Electronics & Mobile Communication
Sensors & Power Modules
Powertrain Controllers
Body & Chassis Electronics
Electronic Control Units
Supplemental Inflatable Restraint Electronics
FOREWARN Collision Warning Systems
Audio Systems
Communications Systems
Navigation Systems
Driver Information & Controls

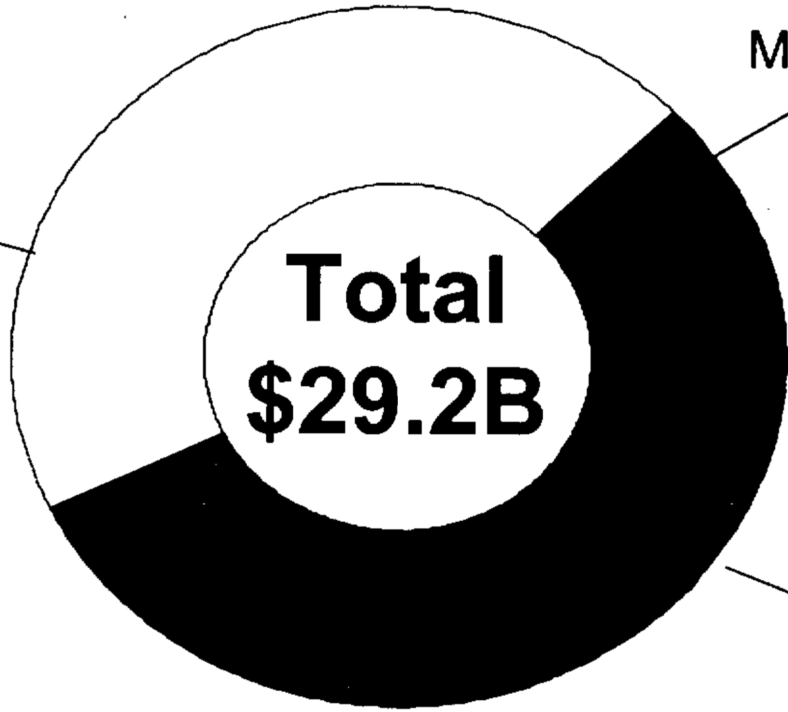
Safety, Thermal & Electrical Architecture
Instrument Panels
Airbag Systems
Steering Wheels
Power Products
Door Hardware & Trim Modules
Latching Systems
Modular Doors
Climate Control Systems
- HVAC Modules, Condensers, Compressors, Accumulator Dehydrators, Thermal Management Systems

Powertrain Cooling Systems
- Radiators, Oil Coolers, Engine Cooling Modules

Power & Signal Distribution Systems
Connection Systems
Switch Products
Sensors
Electronic Products
Fiber Optic Lighting/Data
Electrical/Electronic Centers
Ignition Wiring Systems
Modular Cockpits

DELPHI
Automotive Systems

1999 Consolidated Sales By Sector



Dynamics & Propulsion
$14.0B

- Delphi Saginaw Steering
- Delphi Energy & Chassis

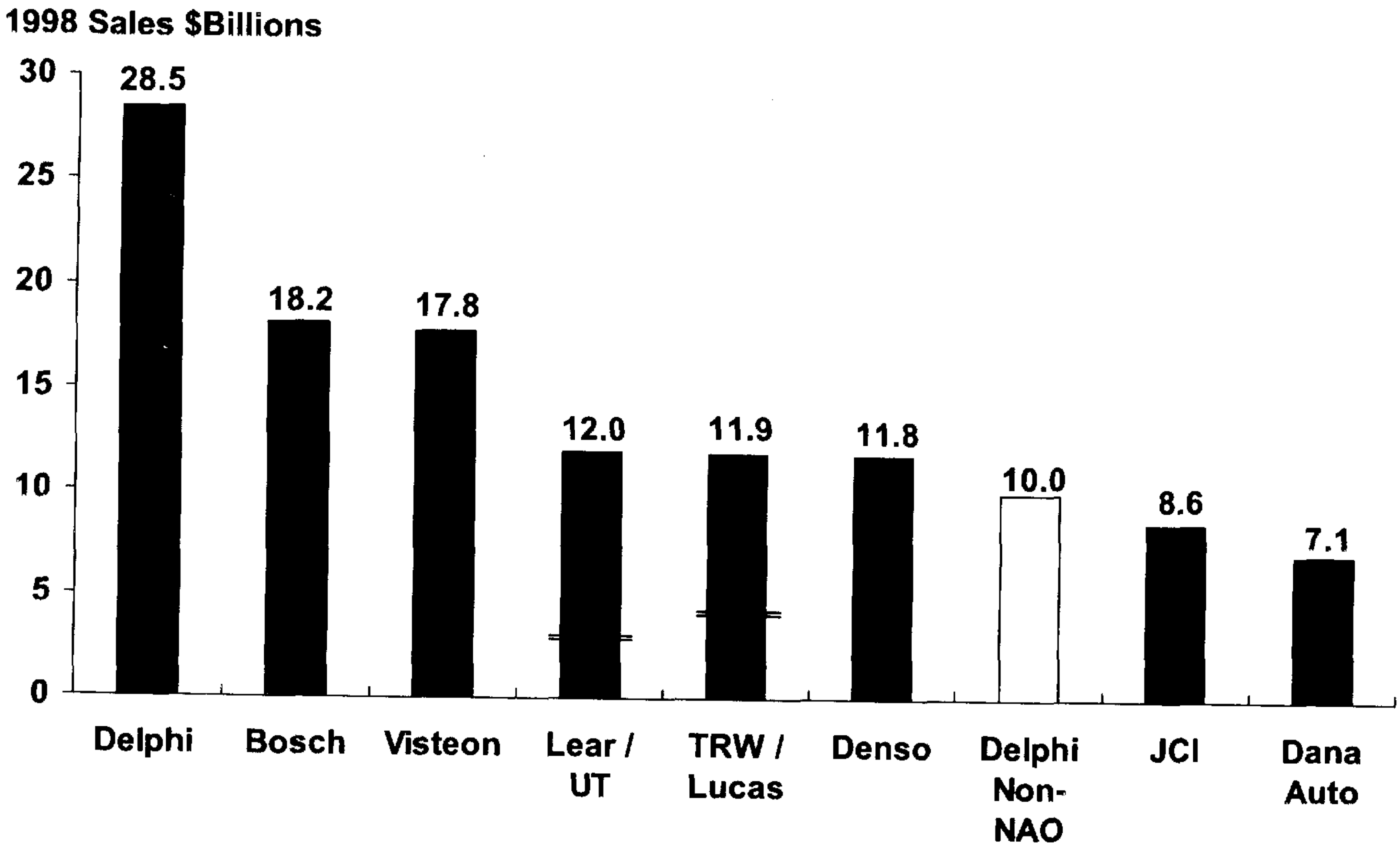
Electronics & Mobile Communications
$4.9B

- Delphi Delco Electronics

Safety, Thermal & Electrical Architecture
$10.3B

- Delphi Interior
- Delphi Harrison Thermal
- Delphi Packard Electric

Comparison To Major Competitors



Source: Automotive News '99 Market Data Book

DELPHI
Automotive Systems

Major Customers

BMW Group	Isuzu	Saab
DaimlerChrysler	Mazda	Suzuki
Daewoo	Mitsubishi	Toyota/NUMMI
Fiat	Nissan	VAZ
Ford	Opel	Vauxhall
GM	Peugeot Citroën (PSA)	Volvo
Honda	Proton	VW Group
Hyundai	Renault	

Global Presence -- Delphi Global Organization

DELPHI
Automotive Systems

- Delphi is a Global Organization Serving Major Automotive Compani es Around the World

Total Delphi

Manufacturing sites:	175
Employment:	213,500
Joint ventures:	41
Technical centers:	27

U.S. & Canada

Manufacturing sites:	44
Employment:	75,500
Joint ventures:	6
Technical centers:	14

Europe & Middle East

Manufacturing sites:	68
Employment:	46,700
Joint ventures:	8
Technical centers:	7

Mexico & South America

Manufacturing sites:	49
Employment:	85,300
Joint ventures:	7
Technical centers:	4

Asia Pacific

Manufacturing sites:	14
Employment:	6,000
Joint ventures:	20
Technical centers:	2

As of 1/27/00

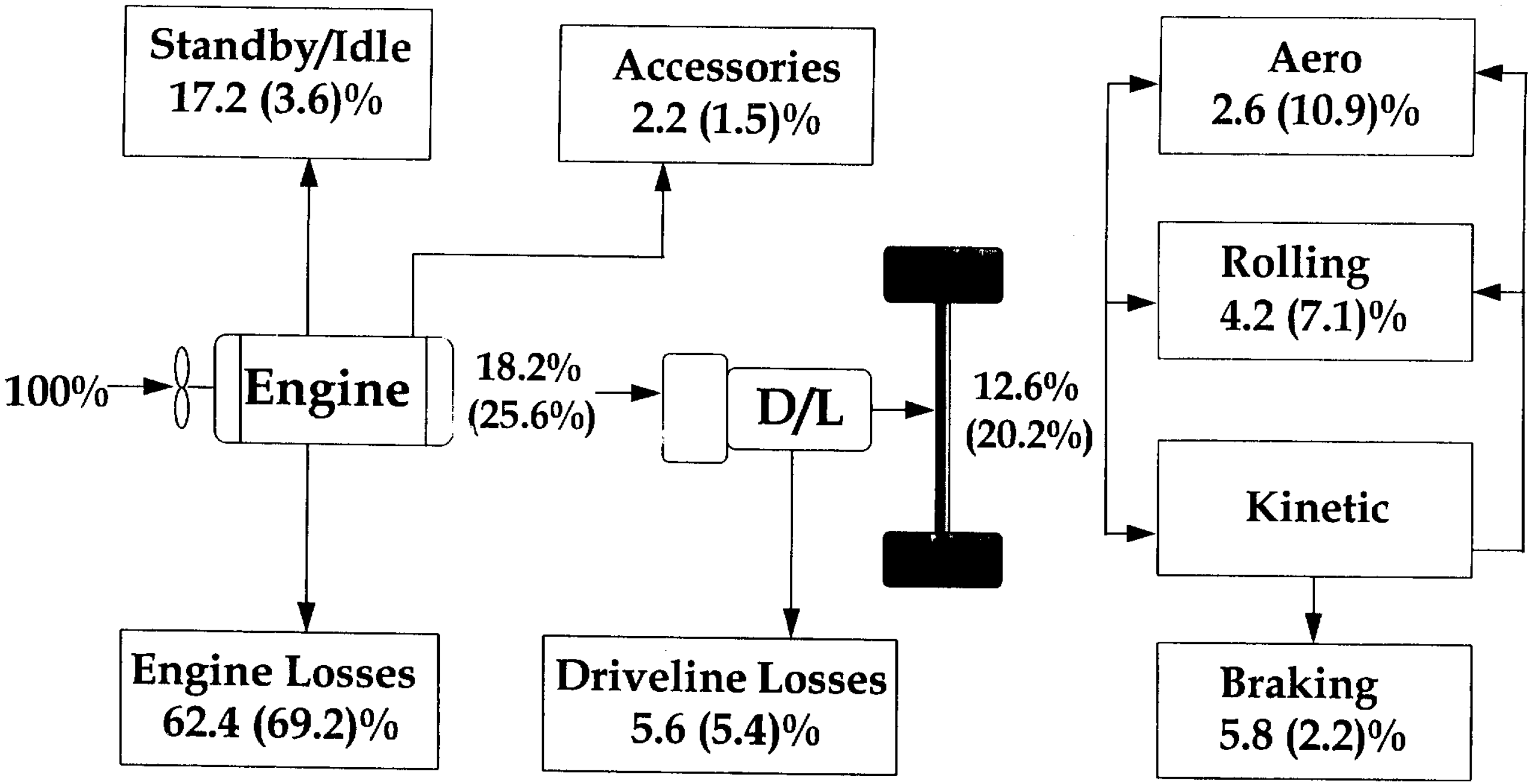
Over 16,000 engineers and over 5,000 patents

Sites, Employment and Technical Centers exclude Joint Ventures

PNGV

Energy Distribution

Typical Mid-Size Vehicle



5/5/95

Urban (Highway)

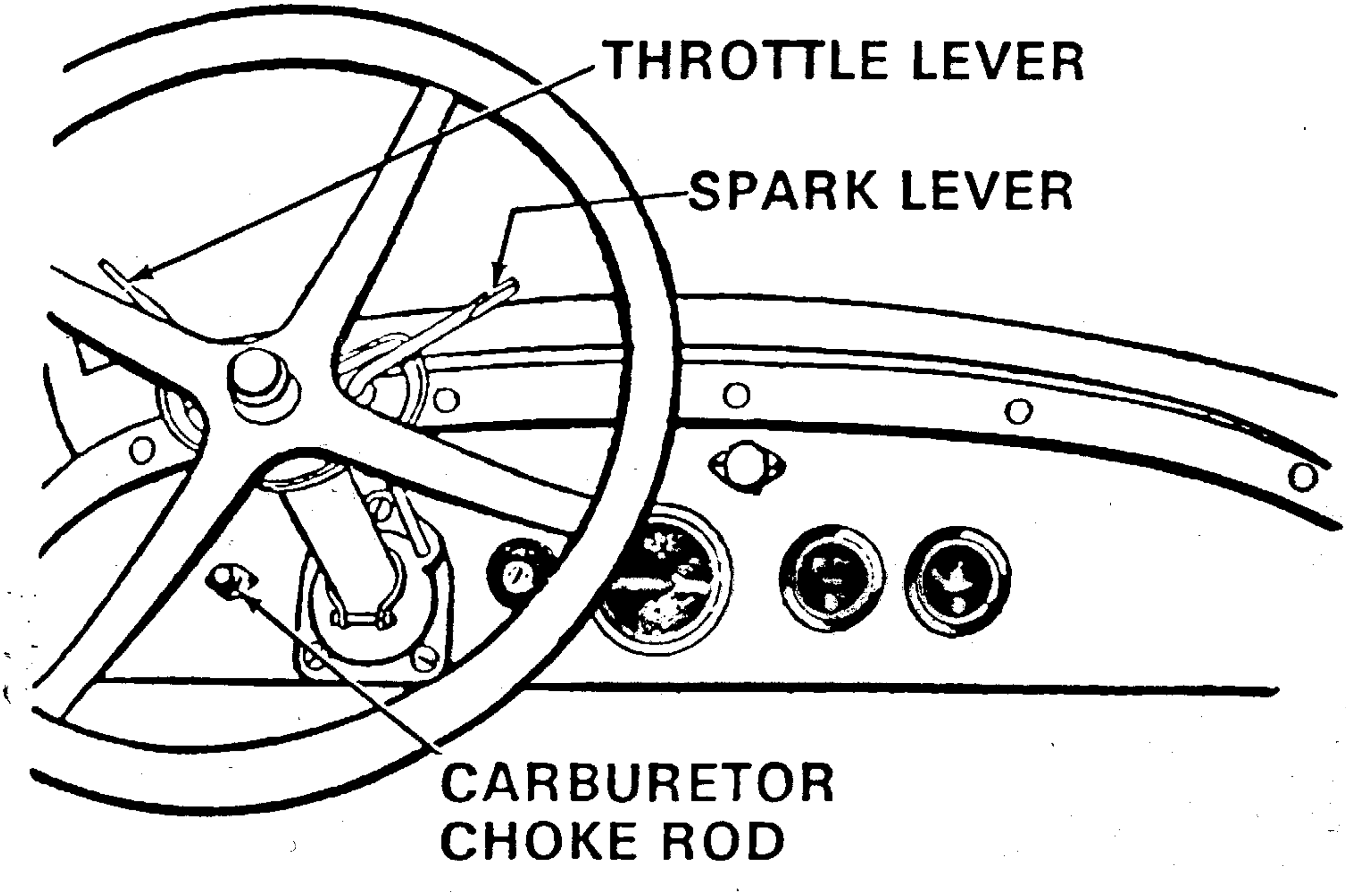
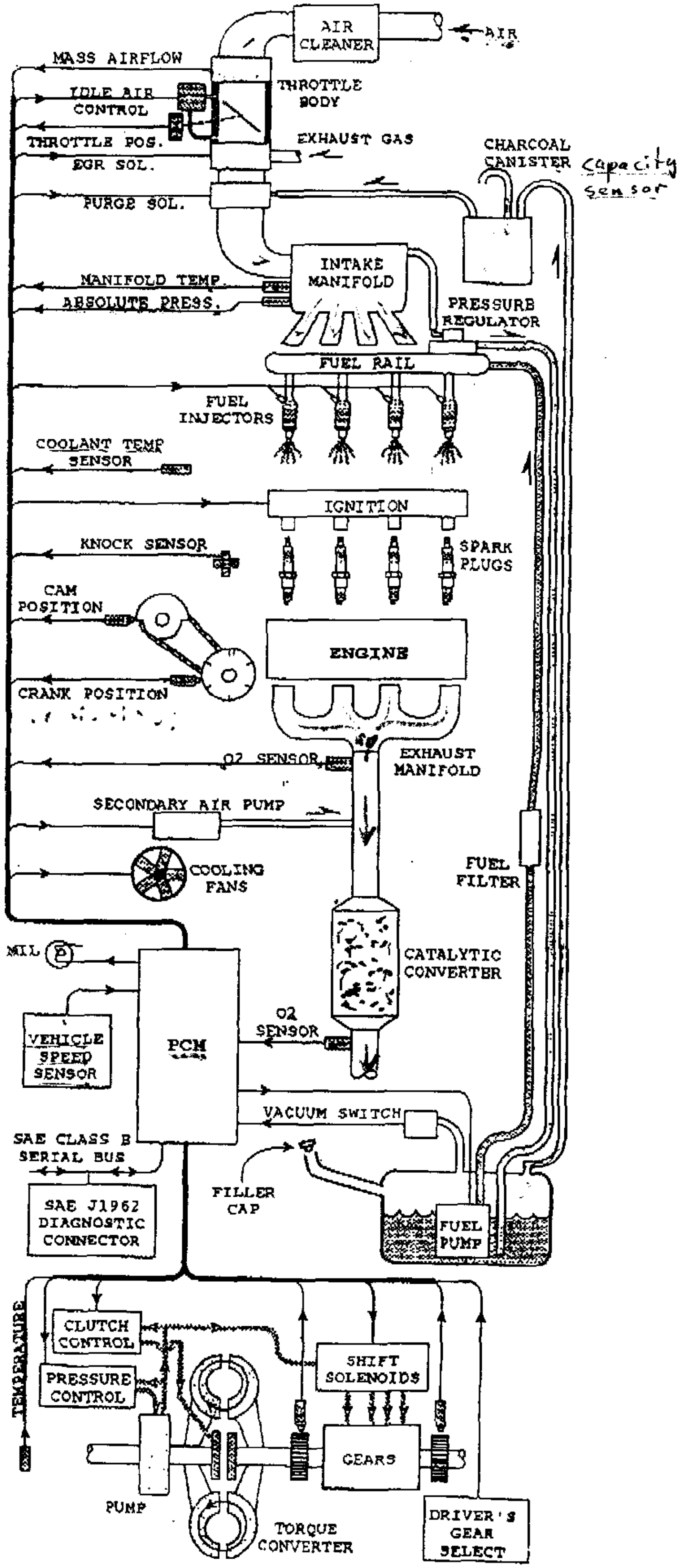


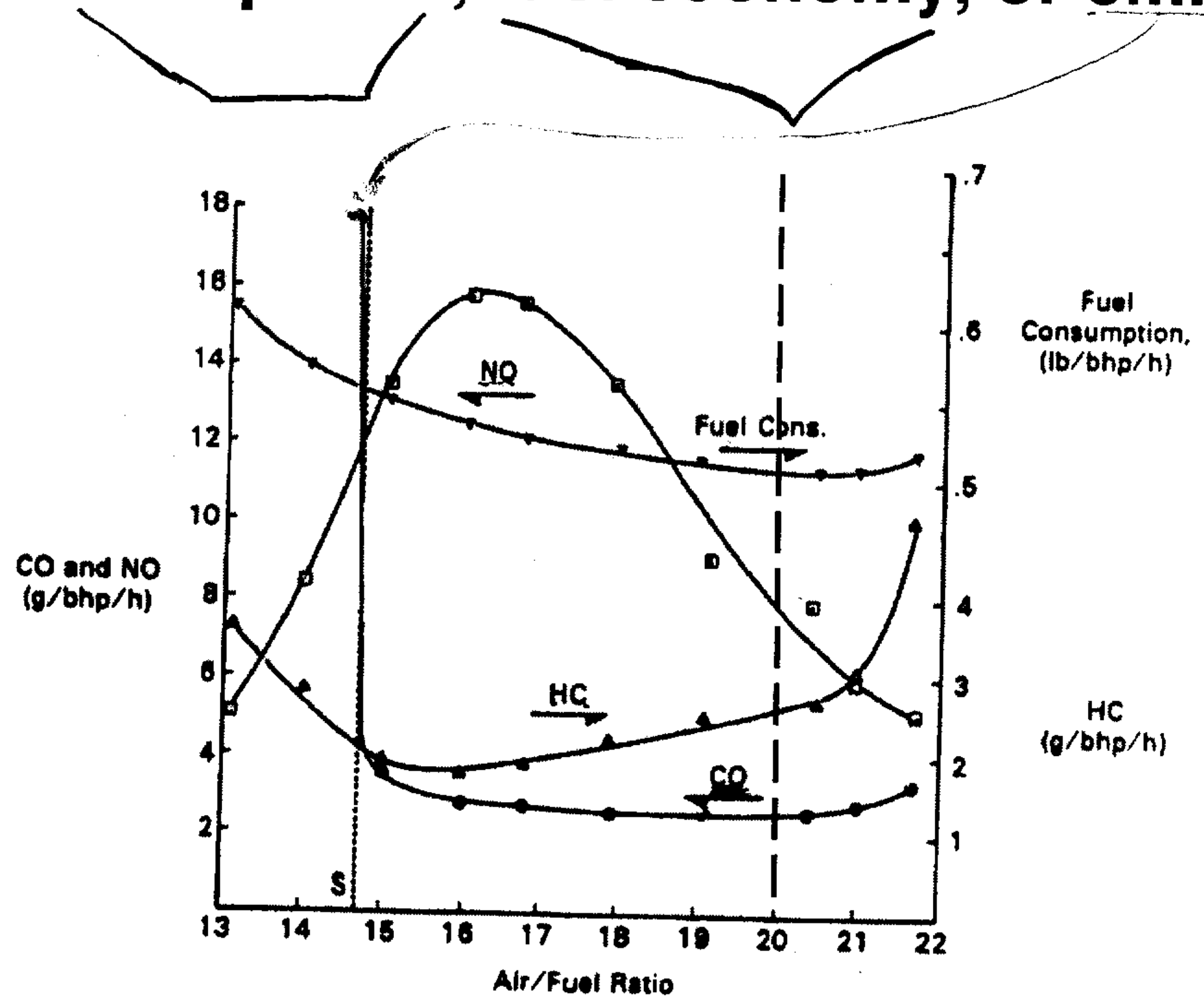
Illustration from instruction manual for 1924 Chevrolet



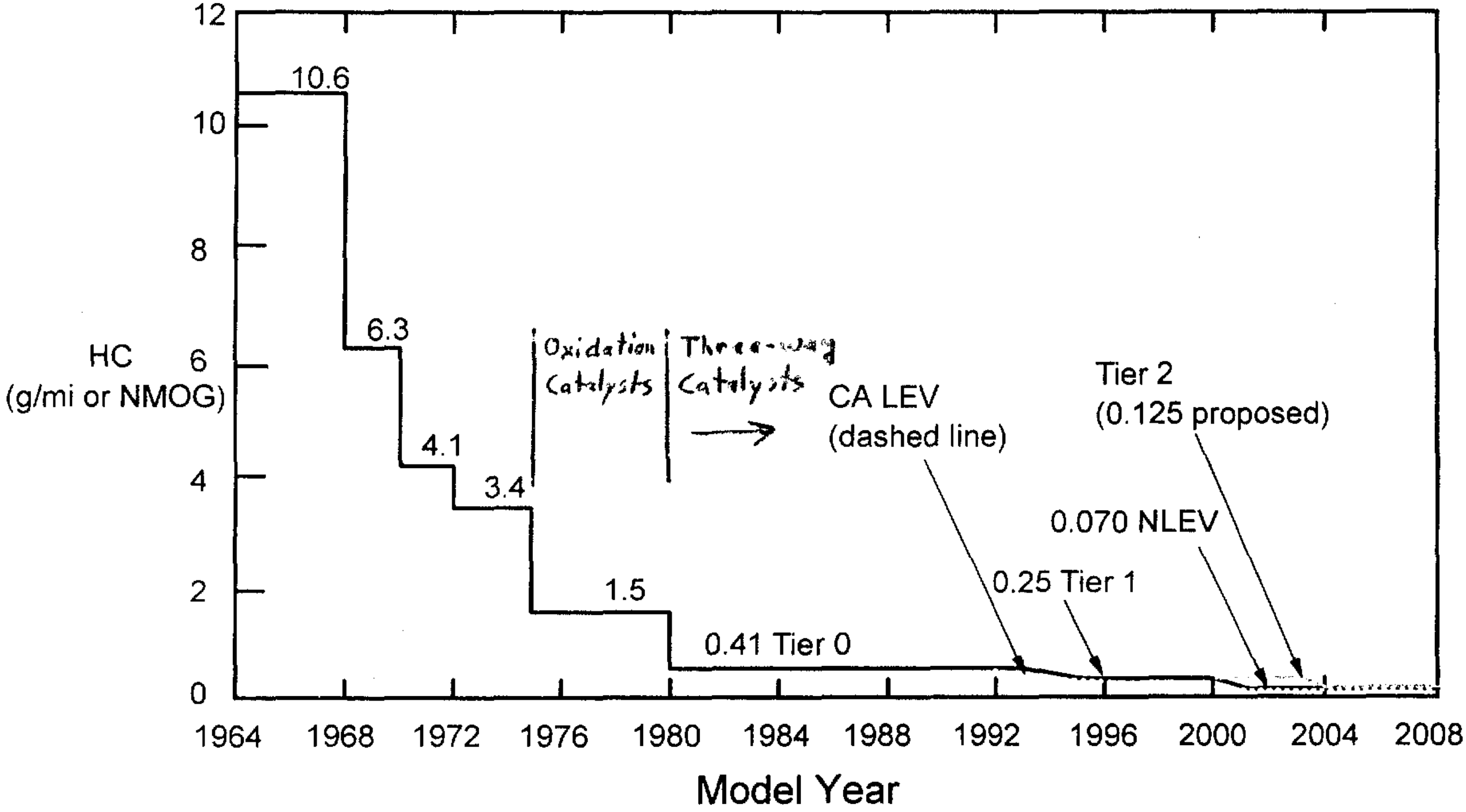
Major Powertrain Sensors

not including chasis systems (i.e., air bags, traction control, comfort + passenger compartment controls

What is the best engine A/F ratio?
--- For best power, fuel economy, or emissions?



Hydrocarbon Standards
U.S. - Fleet Average - Light Duty Vehicles



*CA, NY, MA, VT, ME have adopted California LEV standards.
Introduction years for each state varies. AZ may also adopt California LEV.

Three Generations of Exhaust Emission Control Catalyst Systems

<u>1975-1980</u> Oxidation catalysts (HC, CO)

$CO + O_2 \rightarrow CO_2$

$HC + O_2 \rightarrow CO_2 + H_2O$

<u>1981-1992</u> Three-way catalysts (HC, CO, NOx)

$CO + O_2 \rightarrow CO_2$

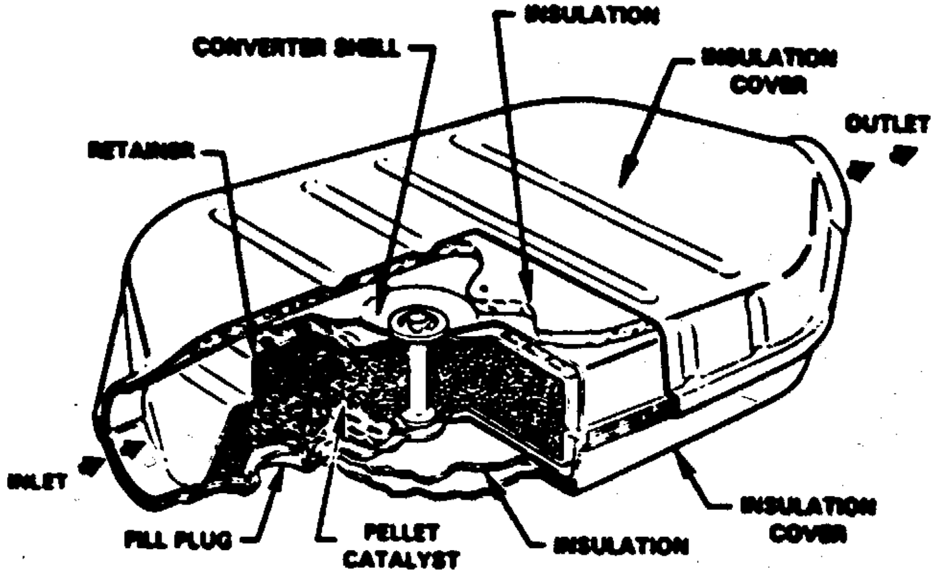
$HC + O_2 \rightarrow CO_2 + H_2O$

$NOx + H_2/CO \rightarrow N_2 + H_2O/CO_2$

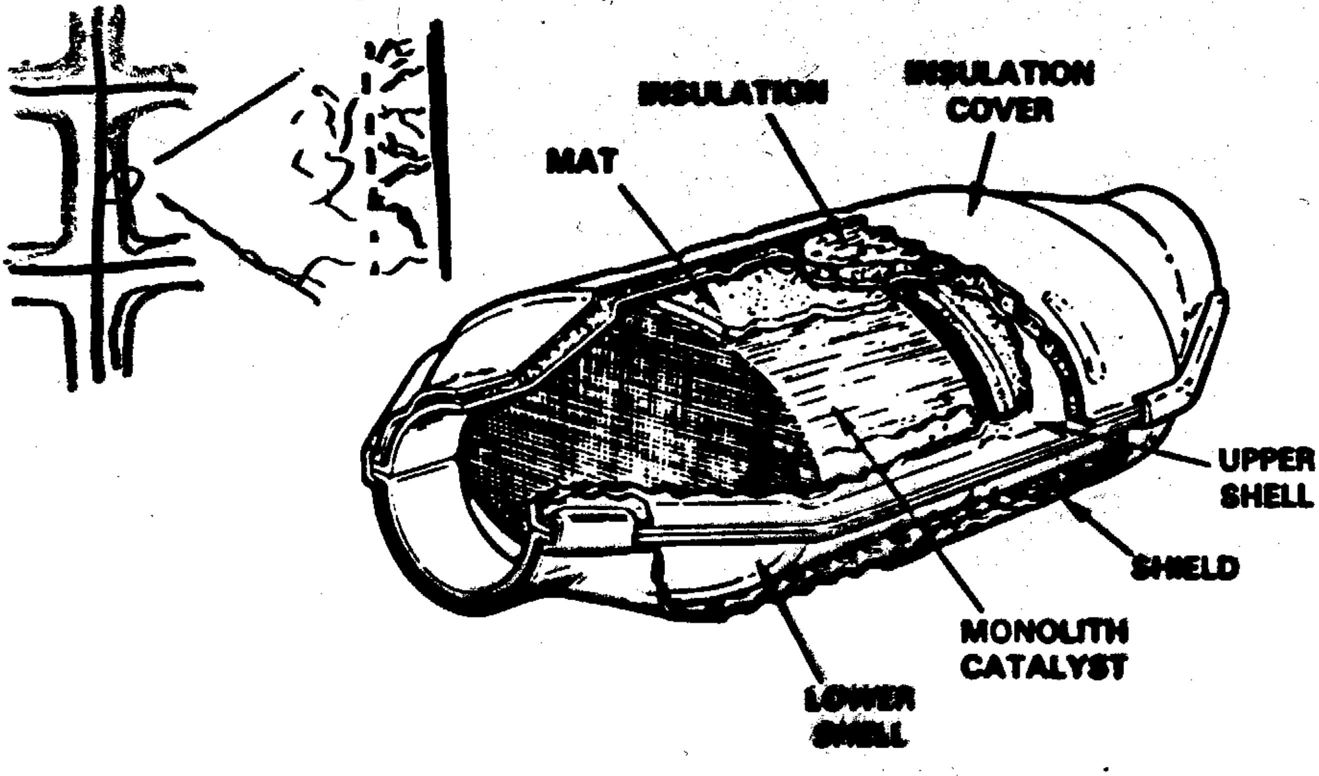
<u>1993 + later</u> In progress

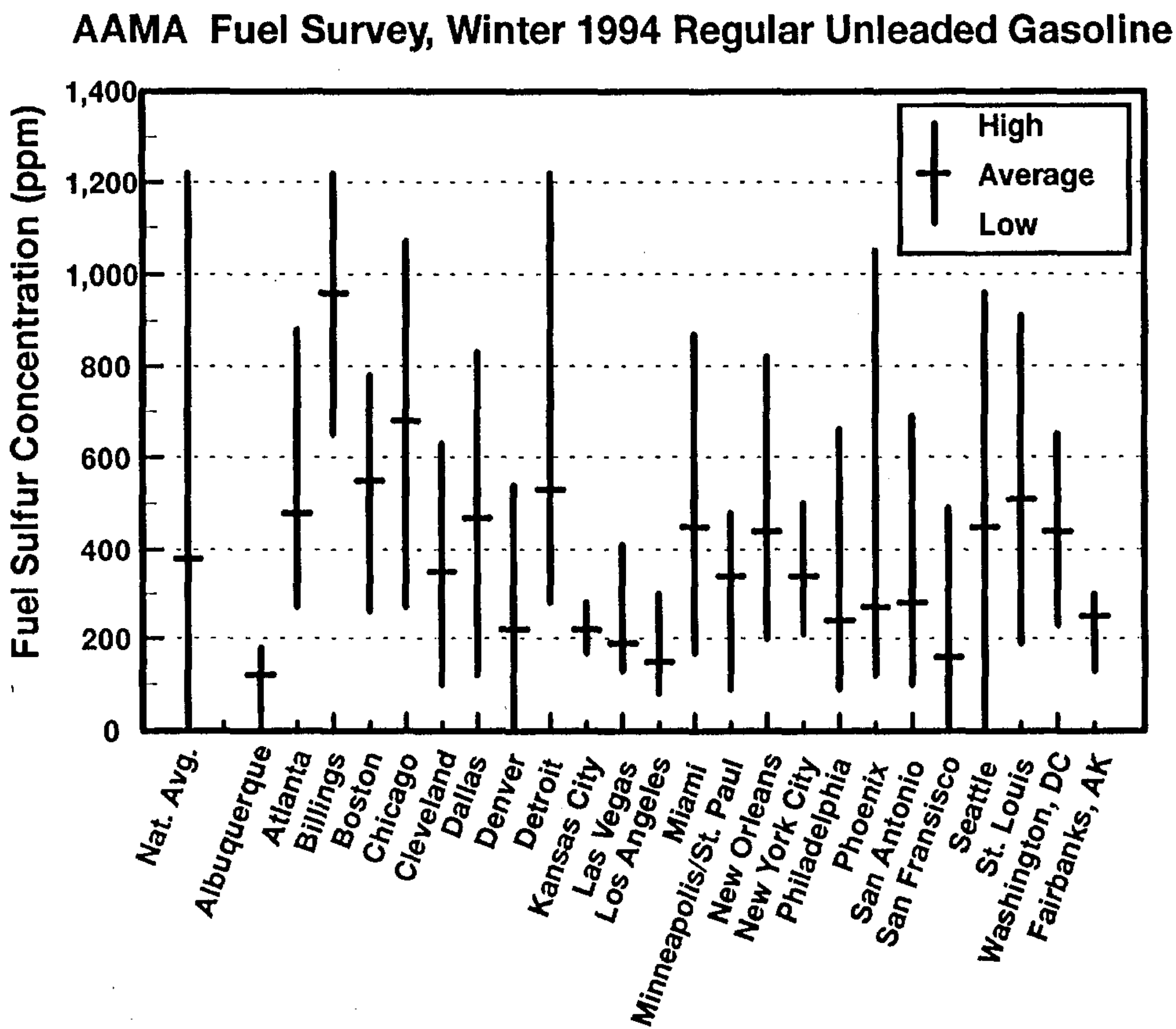
(3-way plus supplemental system)

PELLETIZED CATALYTIC CONVERTER

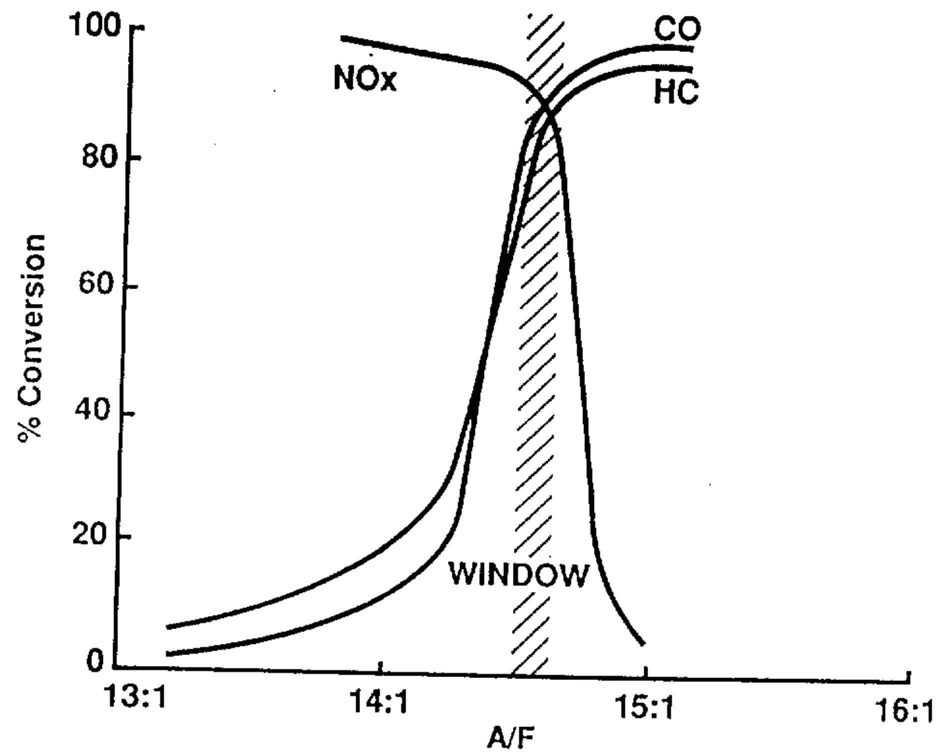


CERAMIC MONOLITH CATALYTIC CONVERTER

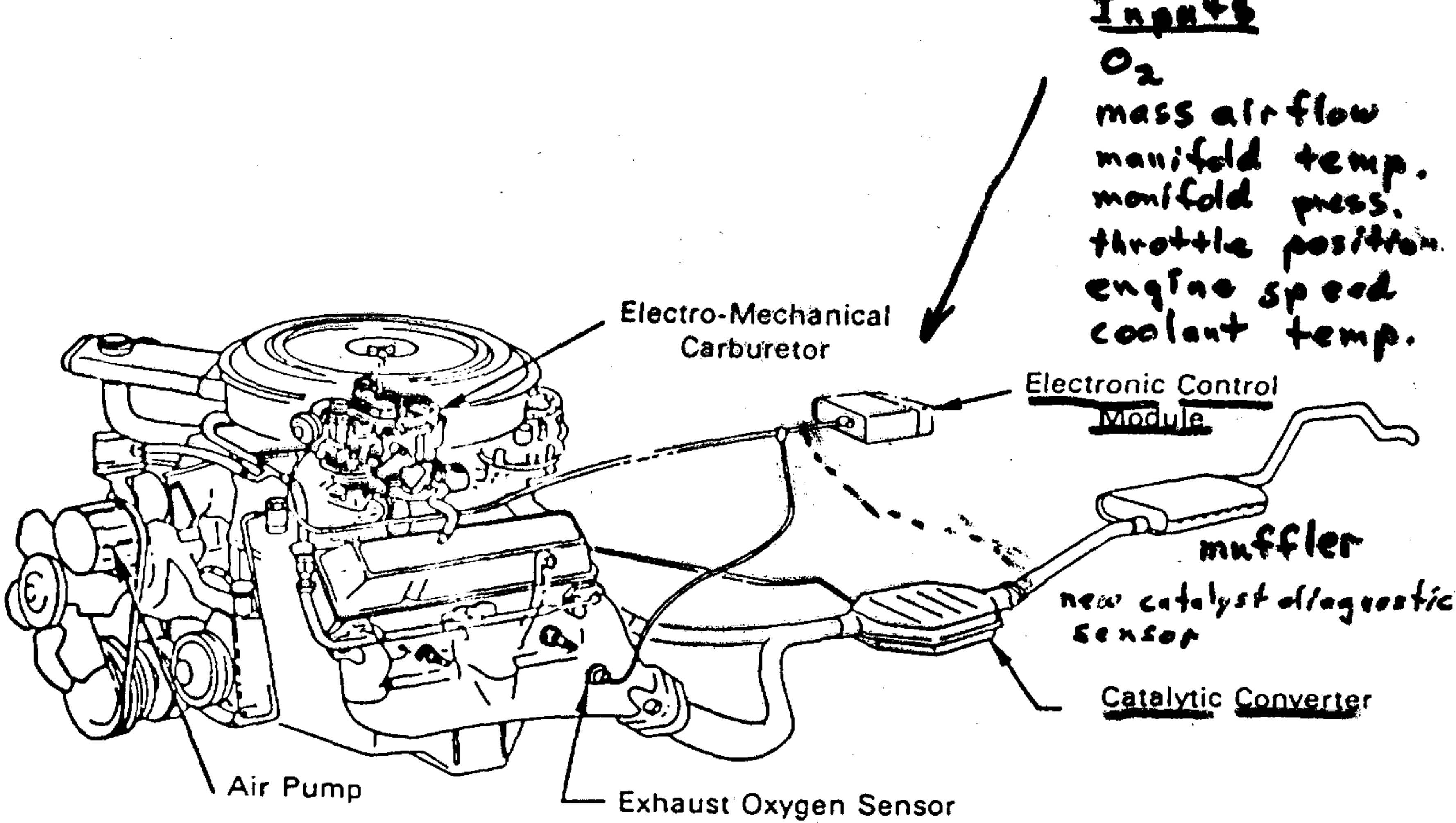



AAMA Fuel Survey, Winter 1994 Regular Unleaded Gasoline
Fuel Sulfur Concentration (ppm)
1,400
1,200
1,000
800
600
400
200
0
High
Average
Low
Nat. Avg.
Albuquerque
Atlanta
Billings
Boston
Chicago
Cleveland
Dallas
Denver
Detroit
Kansas City
Las Vegas
Los Angeles
Miami
Minneapolis/St. Paul
New Orleans
New York City
Philadelphia
Phoenix
San Antonio
San Fransisco
Seattle
St. Louis
Washington, DC
Fairbanks, AK

Catalyst Conversion Efficiencies vs. Air/Fuel Ratio - Three-Way Catalysis



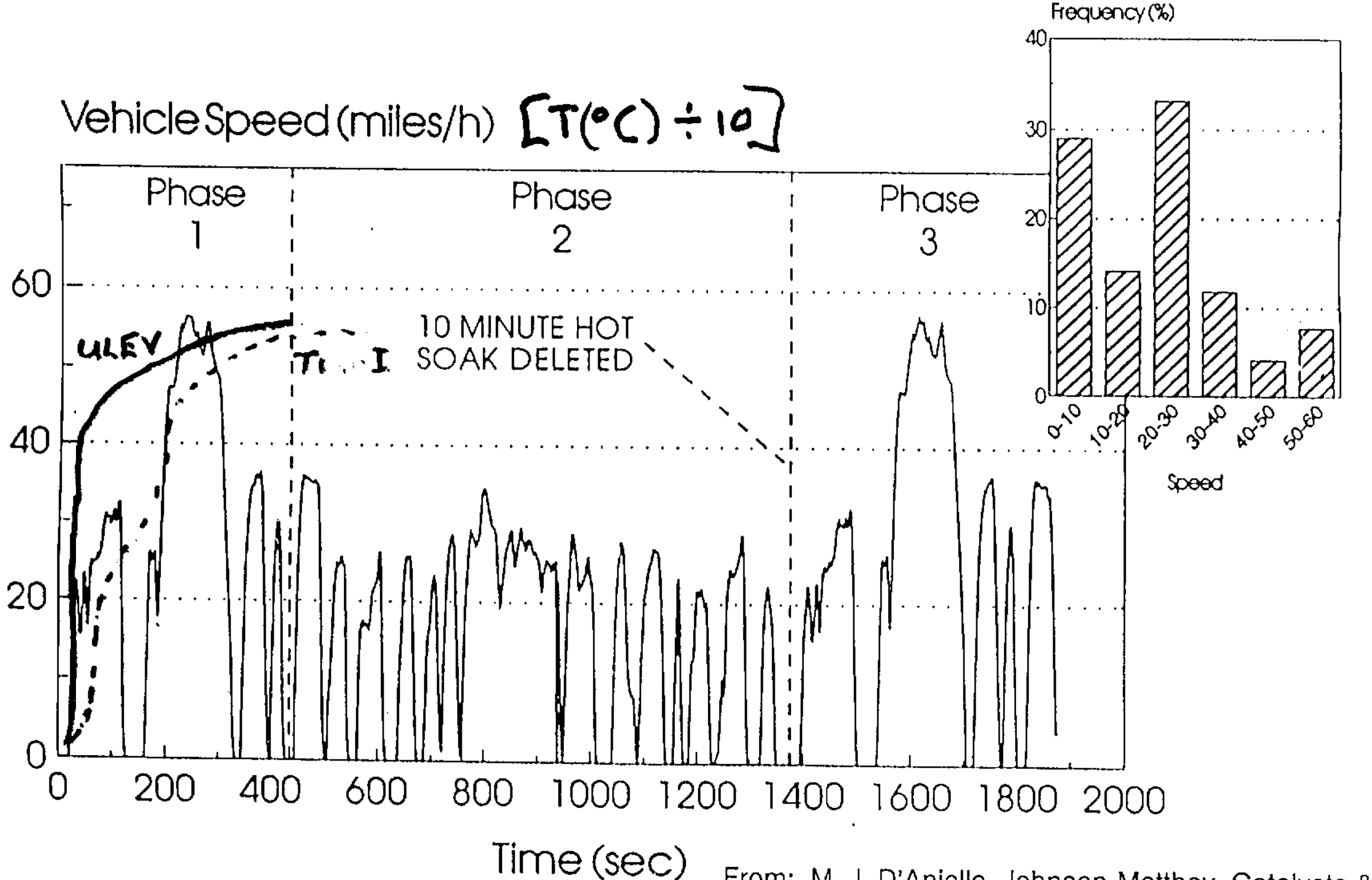
- Closed Loop A/F Control at Stoichiometry
- Simultaneous HC, CO, NOx conversion
- Using Ceria Under Cycled A/F Conditions Should Broaden the Window of High Conversion



Inputs
O_2
mass airflow
manifold temp.
manifold press.
throttle position
engine speed
coolant temp.
Electro-Mechanical Carburetor
Electronic Control Module
muffler
new catalyst diagnostic sensor
Catalytic Converter
Air Pump
Exhaust Oxygen Sensor

Federal Test Procedure (FTP)

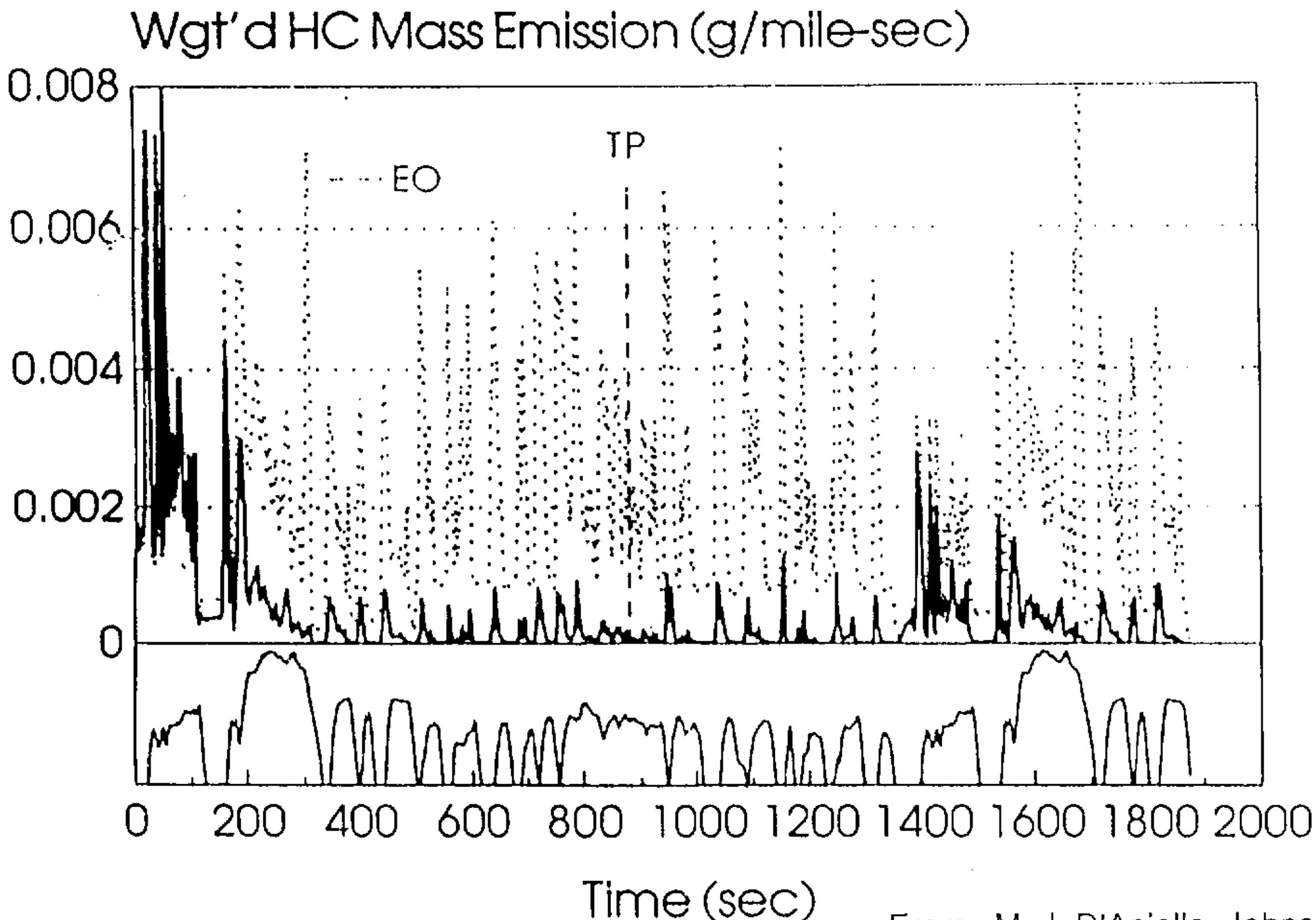
Vehicle speed



From: M. J. D'Aniello, Johnson-Matthey, Catalysts & Emission Control TOPTEC, Troy, MI, 9/20/94

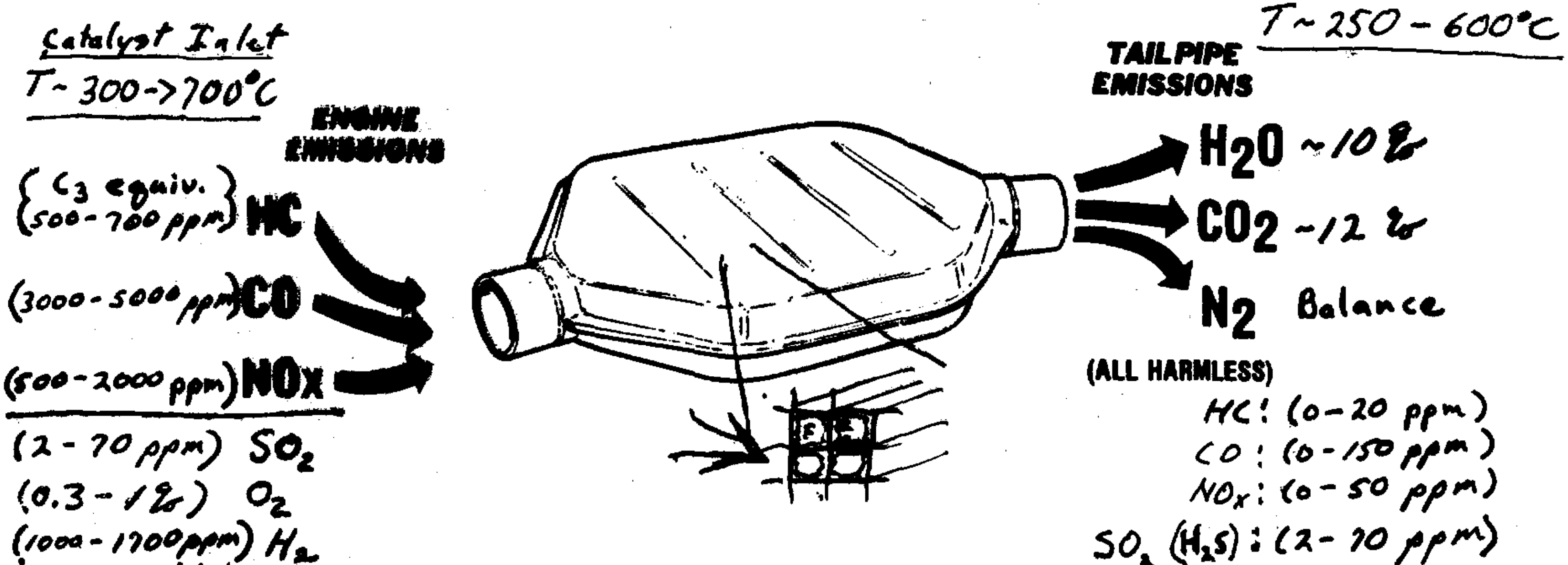
Vehicle Emissions

EO/TP Weighted HC Mass Emission



From: M. J. D'Aniello, Johnson-Matthey, Catalysts & Emission Control TOPTEC, Troy, MI, 9/20/94

THREE-WAY CATALYST



Major gases emitted by the engine are:

HYDROCARBONS	HC	WATER VAPOR	H_2O
CARBON MONOXIDE	CO	OXIDES of NITROGEN ...	NO_x
OXYGEN	O_2	HYDROGEN	H_2
NITROGEN	N_2	SULFUR DIOXIDE	SO_2

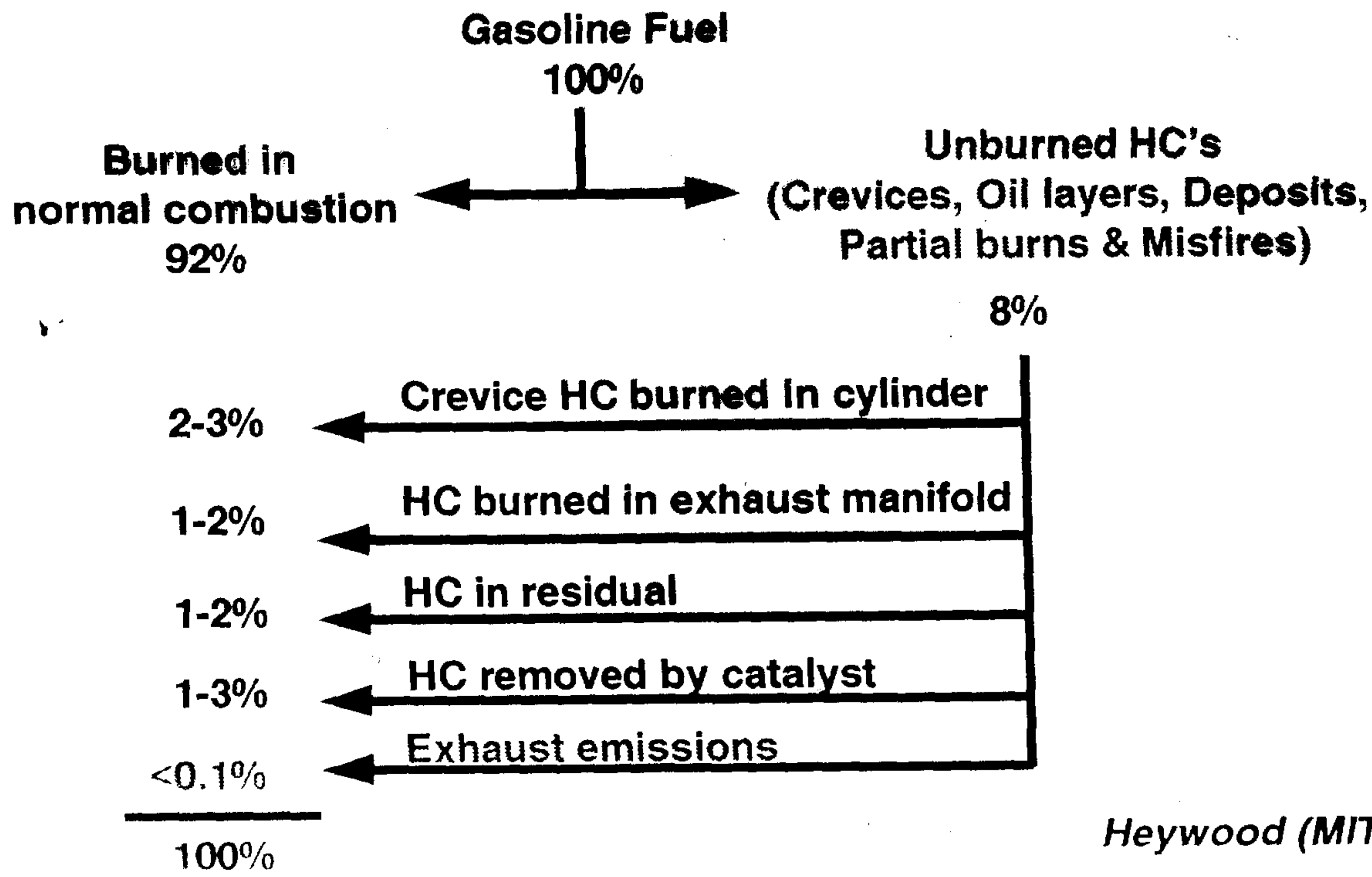
Environmentally regulated gases are hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x).

For V6 on FTP Test:
- HC ~ 1.5-2.0 g/mi
- CO ~ 9-11 g/mi
- NOx ~ 2.0 g/mi

To meet ULEV standards:

	standard	conv. eff.
HC	0.4 g/mi	~ 97%
CO	1.7 g/mi	~ 83%
NOx	0.4 g/mi	~ 90%

Fate of Fuel in Warmed-up Four - Stroke Engine

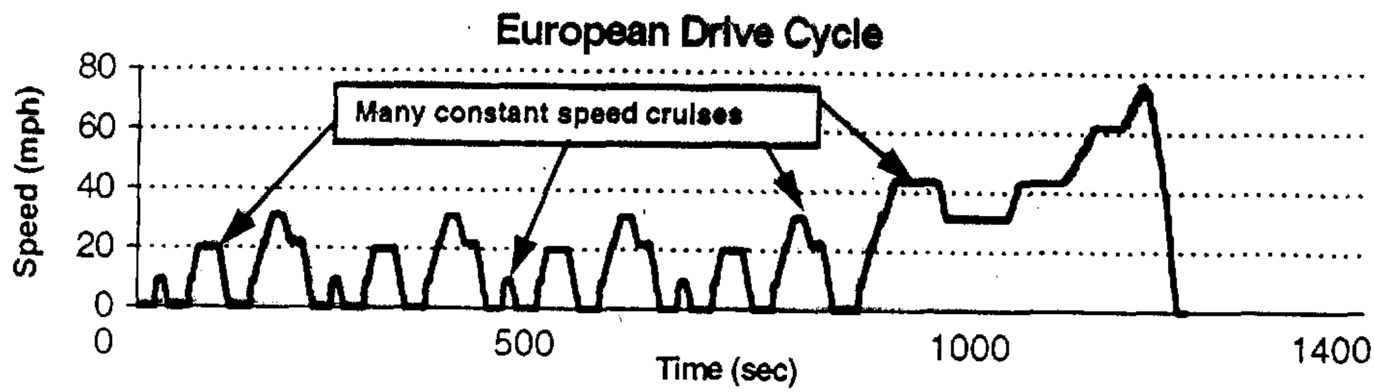


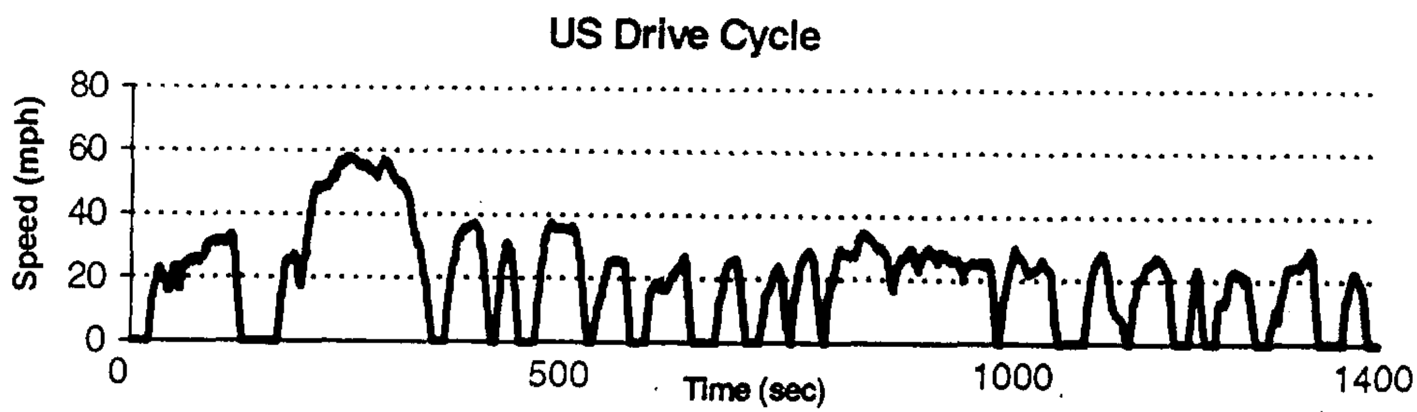
Heywood (MIT)

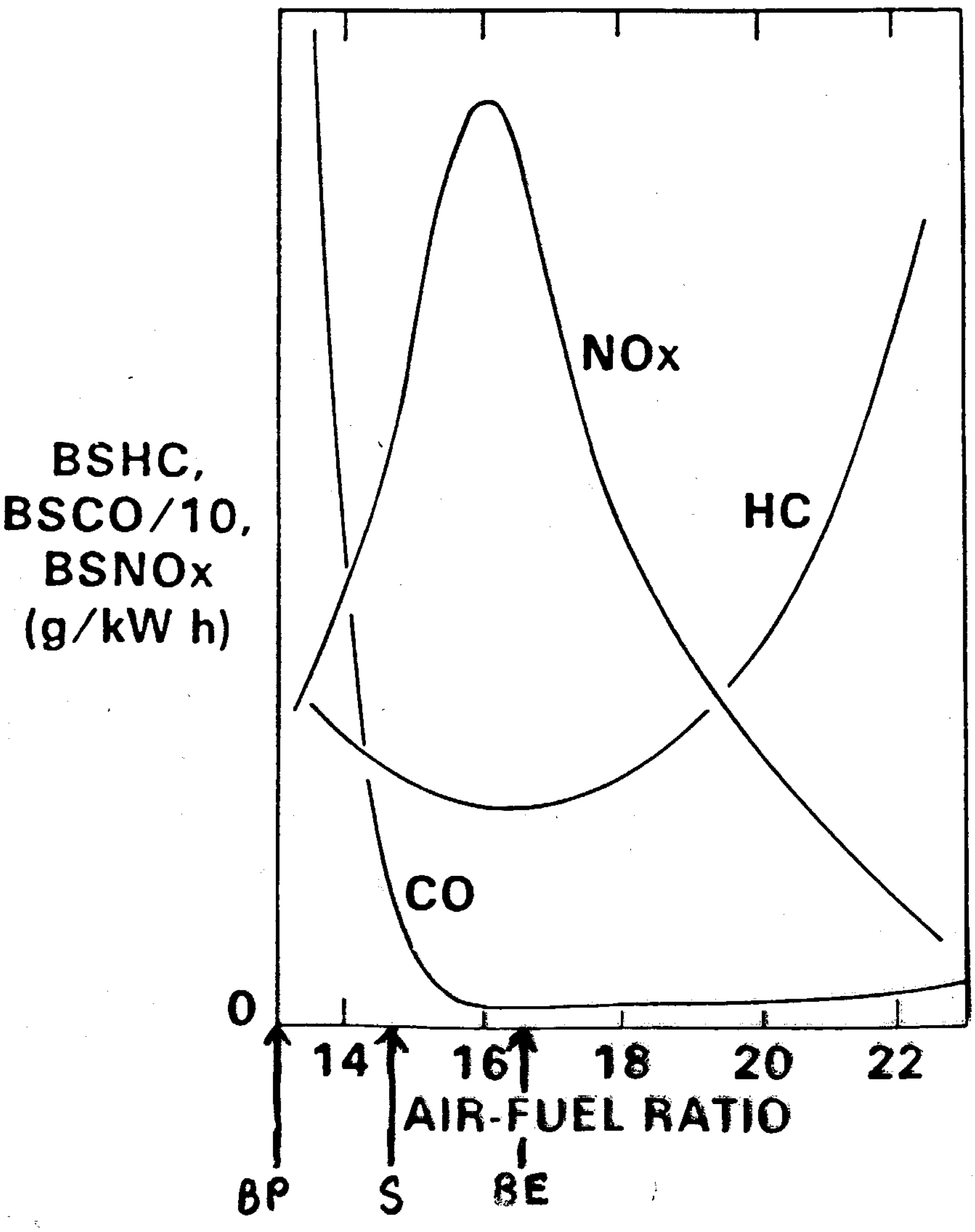
Exhaust Hydrocarbon Speciation Top Ten Engine-out and Tailpipe Hydrocarbons

Hydrocarbon	mg NMOG/mi		mg O_3/mi
	EO	TP	TP OFP
mg/mi:	961.62	108.53	392.6
	%	%	%
Propene	• 6.7	5.1	• 13.2
Ethene	• 10.7	• 6.3	• 12.7
m&p-Xylene	4.3	4.0	• 9.0
2M-Propene	4.9	5.1	7.4
Toluene	• 6.9	• 7.7	5.8
Formaldehyde	2.4	2.2	4.4
1,2,4-TM-Benzene	0.9	1.3	3.1
2M-Butane	2.7	• 7.8	3.0
o-Xylene	1.4	1.4	2.4
1,3-Butadiene	1.2	0.7	2.0

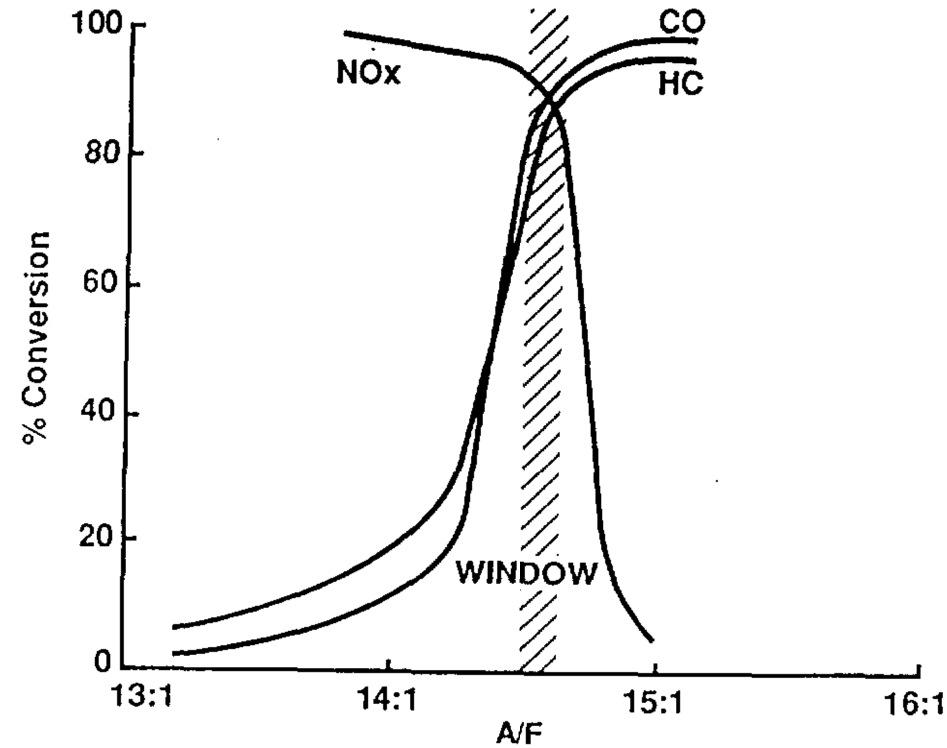
European and U.S. Drive Cycles






BSHC,
BSCO/10,
BSNOx
(g/kW h)
NOx
HC
CO
0
14
16
18
20
22
AIR-FUEL RATIO
BP
S
BE

Catalyst Conversion Efficiencies vs. Air/Fuel Ratio - Three-Way Catalysis



- Closed Loop A/F Control at Stoichiometry
- Simultaneous HC, CO, NOx conversion
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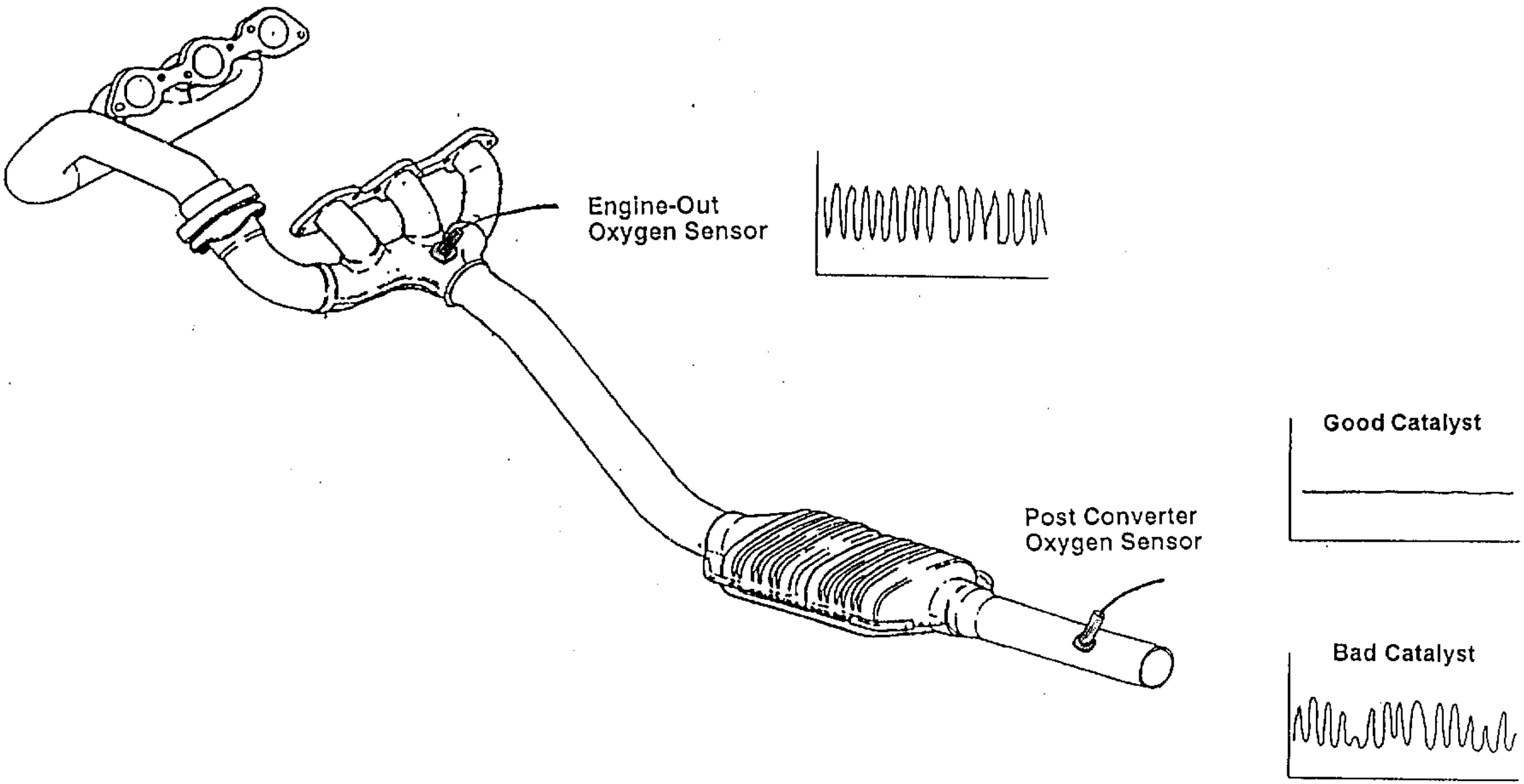
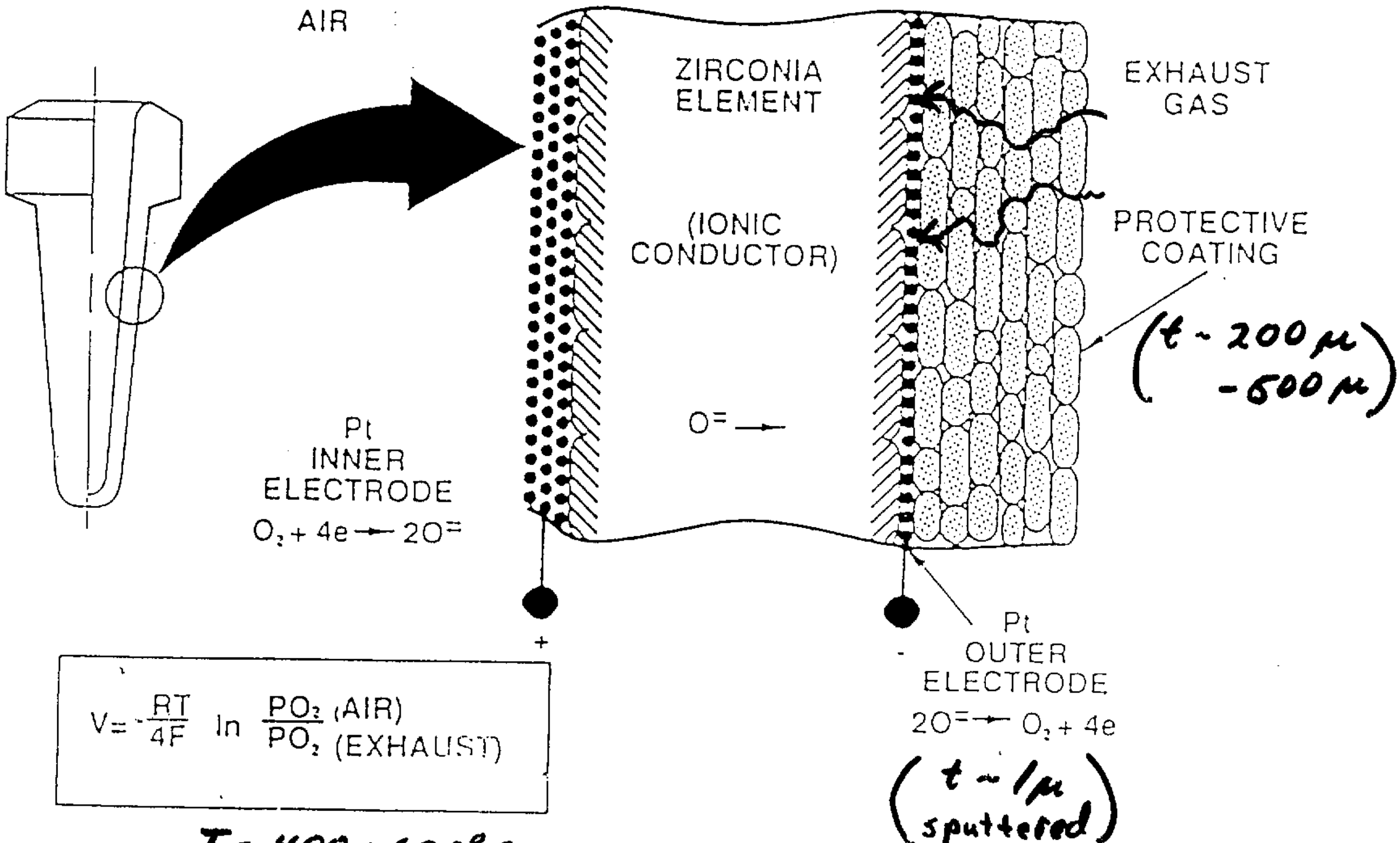
Dual O2 Sensor Method



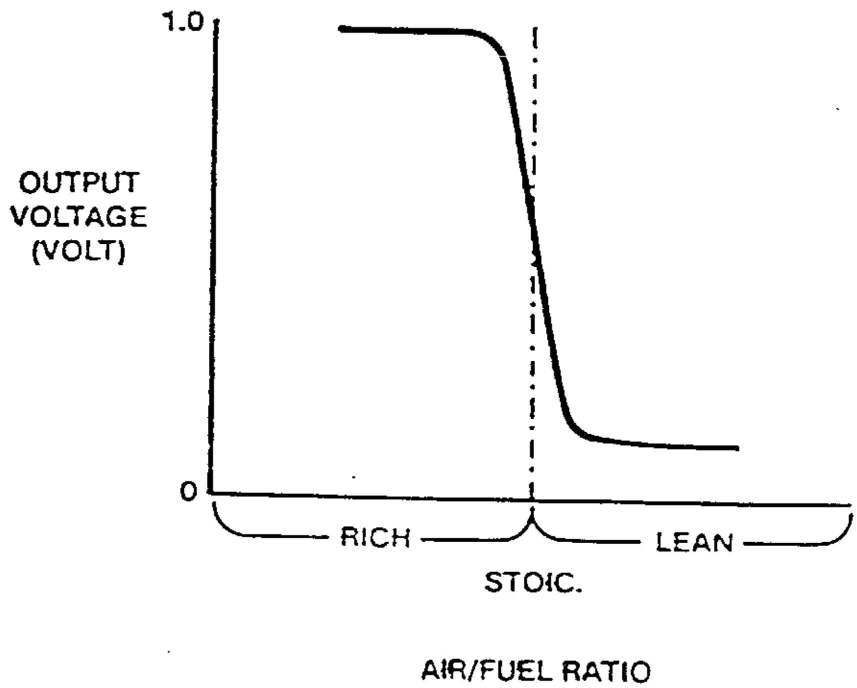
ZIRCONIA CELL



$$V = \frac{RT}{4F} \ln \frac{PO_2\,(AIR)}{PO_2\,(EXHAUST)}$$

T = 400 - 600°C

SENSOR VOLTAGE CURVE



Sensors for On-Board Catalyst Monitoring

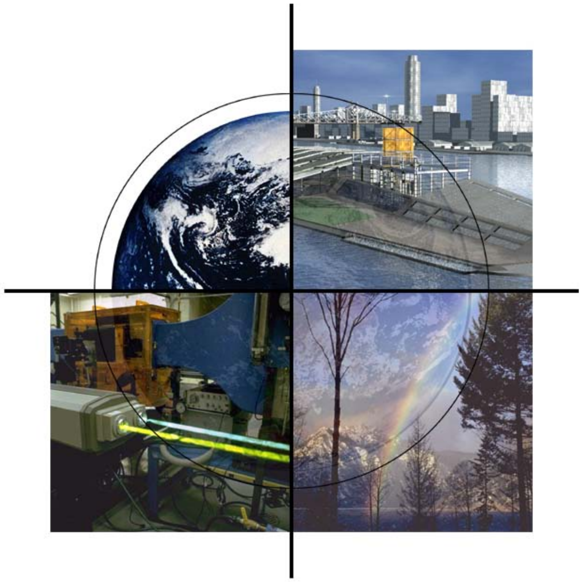
- Constituent Gas Sensors
  - » Exhaust gas sensors (O_2, CO, NO, HC, H_2)
    - – Electrochemical (EC) sensors dominant for O_2 (A/F ratio)
    - – Dual-element calorimetric sensor
    - – Resistive sensors (SnO_2, $SrTiO_3$, ...)
    - – Pt (Pd) MOSFET
  - » Fuel cell sensors (H_2, CO, ...)
    - – High and low concentration hydrogen
    - – low concentration CO

National Energy Technology Laboratory

Overview

and

Office of Coal and Environmental Programs



Carl O. Bauer, Associate Director

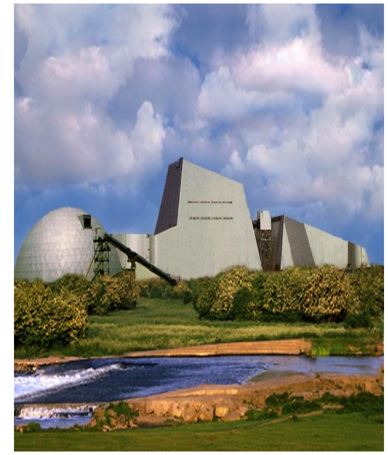
April 2001

National Energy Technology Laboratory

- **DOE's Only Fossil Energy National Laboratories**
- **Extensive extramural R&D with strong industry ties**
- **Focused on-site science and technology R&D**
- **Technical support for energy and environmental policy development**
- **Only Government-owned and -operated National Laboratory**

NETL

Our 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**

NETL

- **Director**
  - Chief Counsel
  - Strategic Center for Natural Gas
    - Gas Exploration, Production & Storage
    - Advanced Turbines & Engines
    - Fuel Cells
    - Infrastructure Reliability
  - Coal & Environmental Systems
    - Power Systems Advanced Research
    - Gasification Technologies
    - Combustion Technologies
    - Sequestration
    - Environmental & Water Resources
  - Fuels & Energy Efficiency
    - Natural Gas Processing
    - Transportation Fuels & Chemicals
    - Fuels Advanced Research
    - Energy Conservation Programs
  - Environmental Mgt. & Defense Programs
    - D&D Focus Area & Industry Programs
    - Nuclear & Strategic Processes
    - Center for Acquisition & Business Excellence
  - NPTO
  - Project Management
    - Gas Supply Projects
    - Gas Power Projects
    - Coal Power Projects
    - Environmental Projects
    - Environmental Management & Defense Projects
    - Center for Acquisition & Business Excellence
    - Fuels & Energy Efficiency Projects
  - Science & Technology
    - Combustion & Engine Dynamics
    - Clean Air Technology
    - Simulation & Multi-Phase Flow Analysis
    - Fuels & Process Chemistry
    - Separations & Gasification Engineering
    - Environmental Science & Technology
    - Engineering Applications & Operations
  - Business & Logistics
    - Acquisition & Assistance
    - Information Technology
    - Financial Management
    - Environmental, Safety & Health
    - Human Resources
    - Site Operations
  - Systems & Policy Support
    - Process Engineering
    - Evaluation & Planning
    - Communications & Public Affairs

Fossil Energy RD&D Activities Managed as Four Program Areas by NETL

Electric Power Using Coal
Mining to Light Switch

Energy Policy Support
A Key Issue in Use of Fossil Energy

Strategic Center for Natural Gas
Borehole to Burner Tip

Clean Fuels

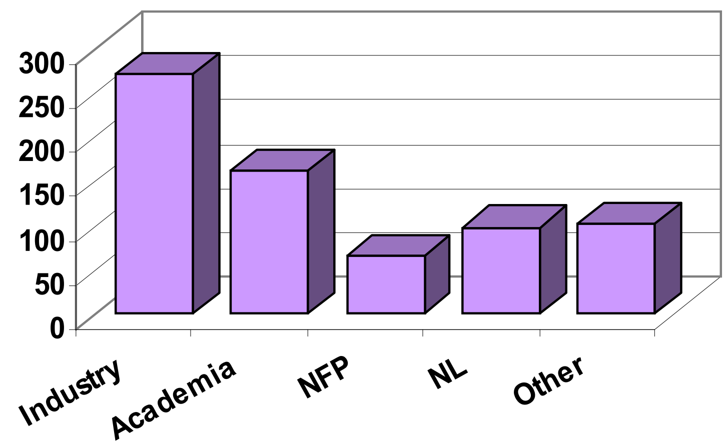
Oil Supply NPTO

Fuels from Coal and Gas
Supply and Delivery of Clean Fuels for Transportation/ Other End Use Sectors

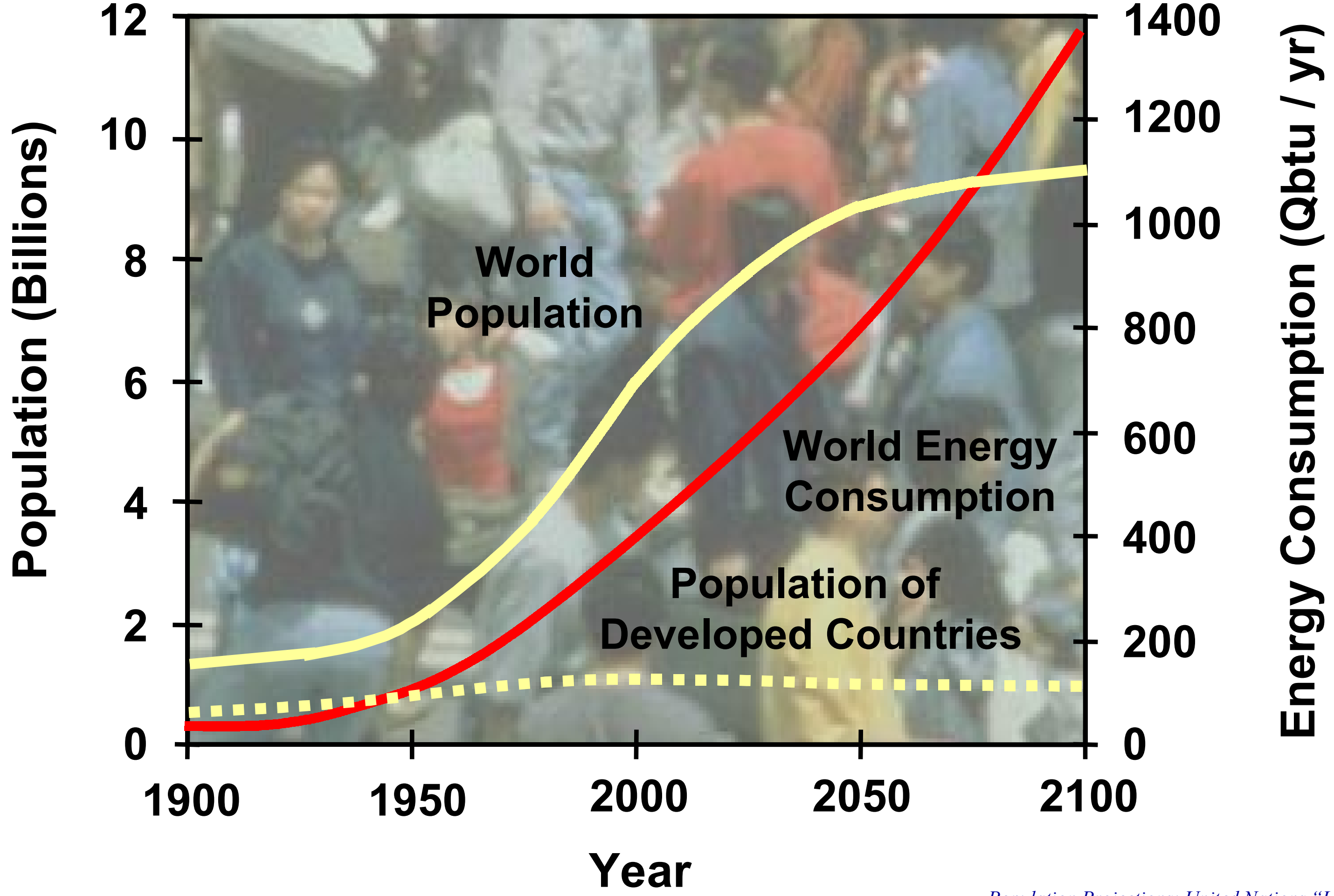
An Extensive Portfolio of Projects with External Organizations

- **Over 800 research activities in all 50 states and 16 countries**
- **Total award value of $7.3 billion**
- **Research performers include:**
  - Private industry
  - Universities/colleges
  - Not-for-profit labs
  - Other DOE national labs
  - Others
- **Private sector cost sharing of $3.9 billion**
  - Leverages DOE funding
  - Ensures relevance
  - Mission accomplishment only through commercialization
- **55 active MOU's and MOA's**

Projects by Partner Group



World Energy Use Is Growing Dramatically

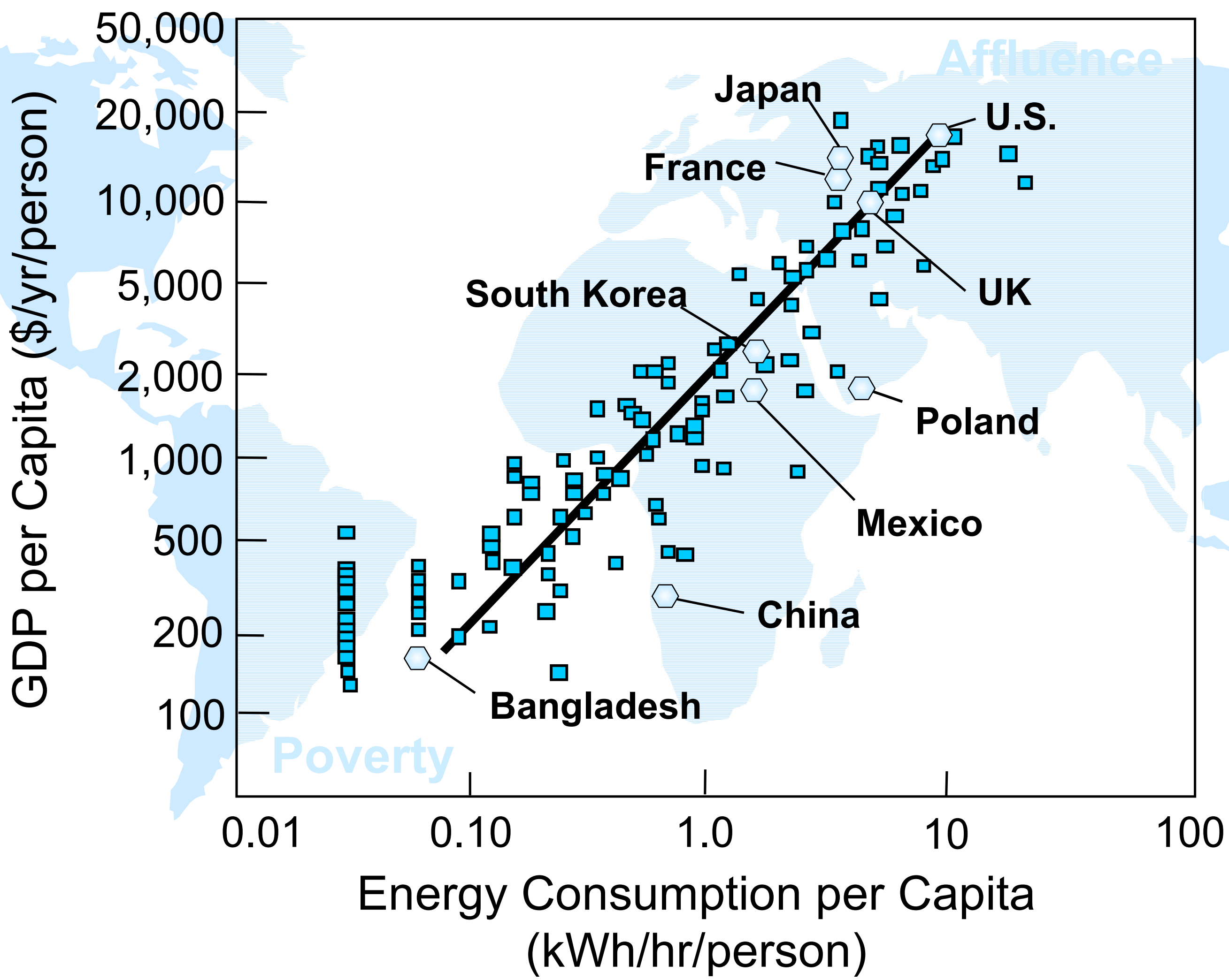


Population Projections: United Nations "Long-Range World Population Projections: Based on the 1998 Revision"

Energy Projections: "Global Energy Perspectives" ITASA / WEC

NETL

The World Needs Low-Cost Energy



NETL

Replacements for Fossil Energy?

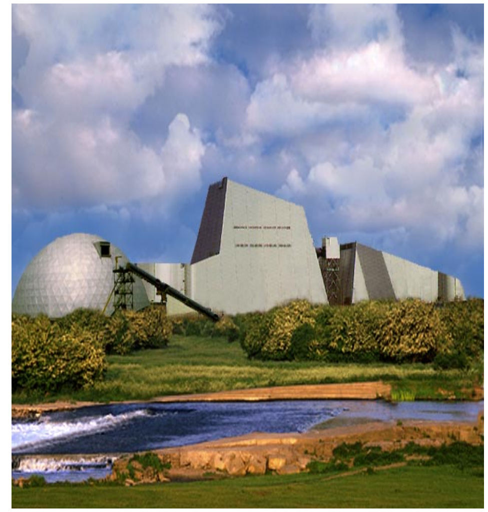
- **Wind/hydro/geothermal**
  - Not enough
- **Biomass**
  - Transportation, land use, expense
- **Solar**
  - Land use, capital cost, storage
- **Nuclear**
  - Expense, politically difficult, proliferation issue
- **Hydrogen**
  - Cost

Needed: An Affordable, Clean, and Abundant Energy Source

No Known Source Meets These Criteria

NETL

Electric Power Using Coal
Mining to Light Switch



Existing Fleet Technologies
- Emission control (NOx,SOx, PM2.5, mercury/air toxics)
- Efficiency improvements (Clean Coal Demonstrations)

Mid-Term Markets
- Improved environmental technology
- Efficiency improvements
- Repowering & retrofitting
- Power Plant Improvement Initiative

Vision 21-Future Energy Plants
- Near-zero emissions
- Technology innovation
- Market flexibility and competitive economics

Carbon Sequestration: An Important Option to Address Climate Change
- Low-cost capture
- Long-term storage

Mining/Water: Addressing Energy Supply Issues
- Mining "Industry of the Future"
- Watershed management

Coal and Environmental Systems Program

"A Strategic Center for Coal"

Associate Director Carl O. Bauer

Sr. Management & Technical Advisors Michael L. Eastman (Mining IOF) and Lawrence A. Ruth (Vision 21)

Products

Product Managers

Power Systems Adv. Res.
Robert R. Romanosky

Gasification Technologies
Gary J. Stiegel

Combustion Technologies
Nelson F. Rekos

Sequestration
Charles E. Schmidt

Environment and Water
Thomas J. Feeley

Policy Support and Analysis

- CES Analysts: Mildred B. Perry, Scott Klara, TBD
- Evaluation & Planning Division: Charles Drummond
- Process Engineering & Communications Divisions: Gil McGurl & Joe Culver

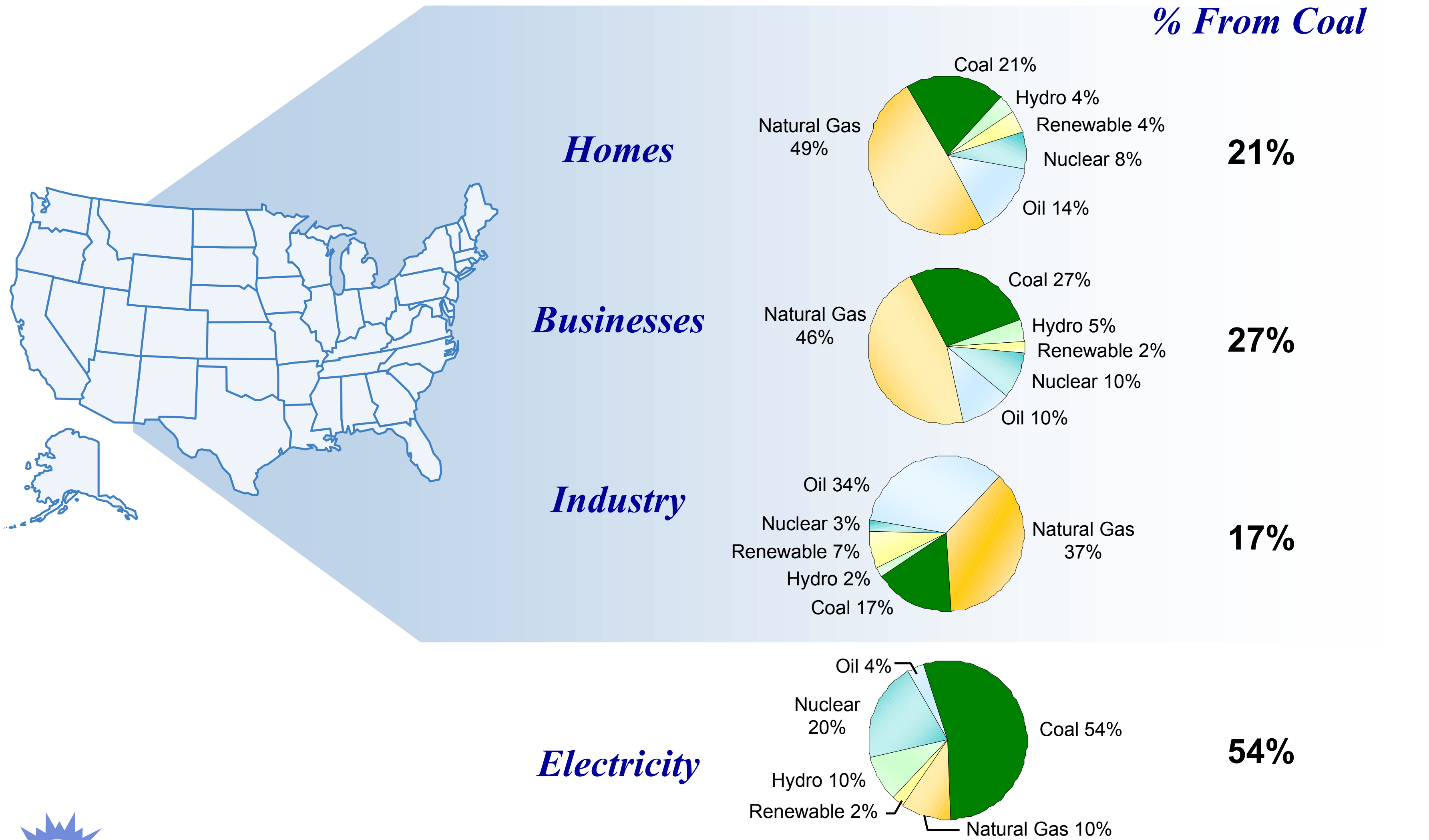
Projects

- Coal Power Projects Division: Rich Hucko (acting)
- Environmental Projects Division: Larry Carpenter (acting)
- Acquisition/ Assistance & Financial Mgt. Divisions: Randy Kesling & Jan Hogler

In-house R&D

- Sequestration Focus Area
- Computational Energy Science Focus Area
- Environmental R&D
- Vision 21 R&D (coal)

Coal Meets Much of Our Stationary Energy Needs

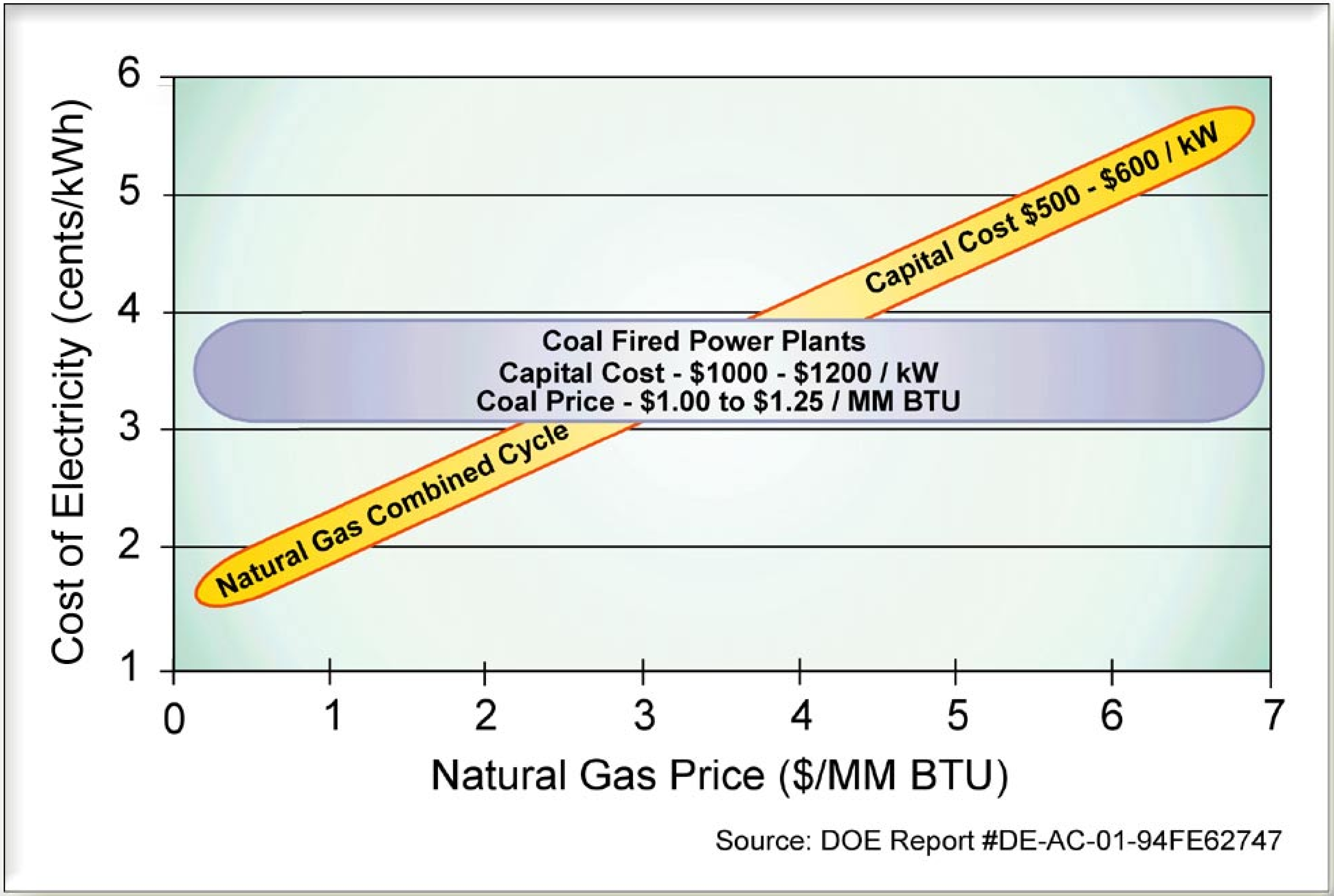


Source: EIA, Annual Energy Outlook, 2001

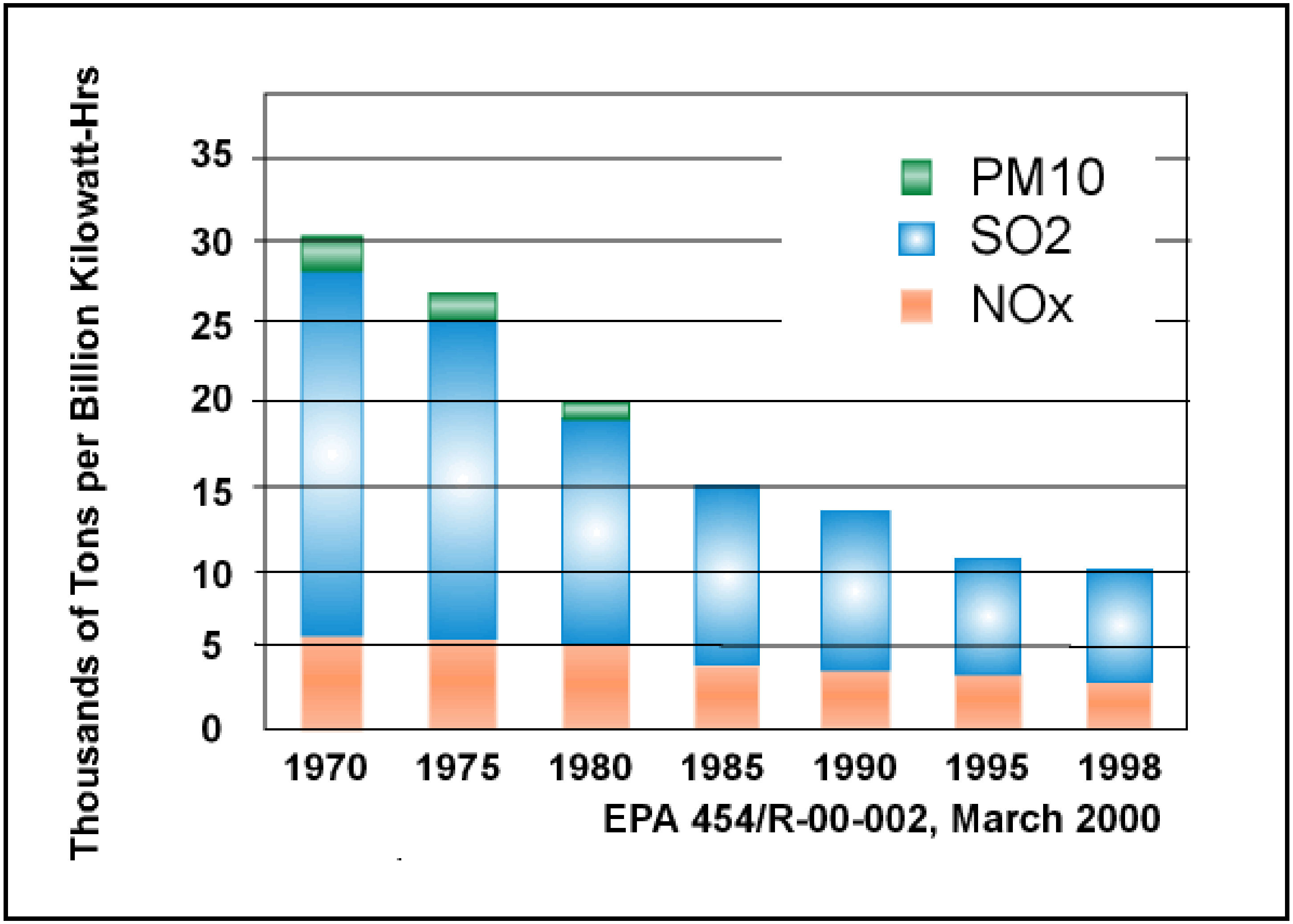
Benefits Legacy from CCT Program and Associated RD&D

- Life-Cycle Cost Savings to Industry and the Public for Near-Term Deployment
  - Lower capital and operating costs for advanced power plants and NOx and SO2 pollution control systems equate to $23 billion.
  - Lower compliance costs for air toxics and solid waste, through technology development, is estimated at $70 billion.
  - Market value of SO2 and NOx reduction is estimated at $10 billion.
  - Improved waste characterization and advances in waste recovery are estimated to result in a $25 billion cost benefit.

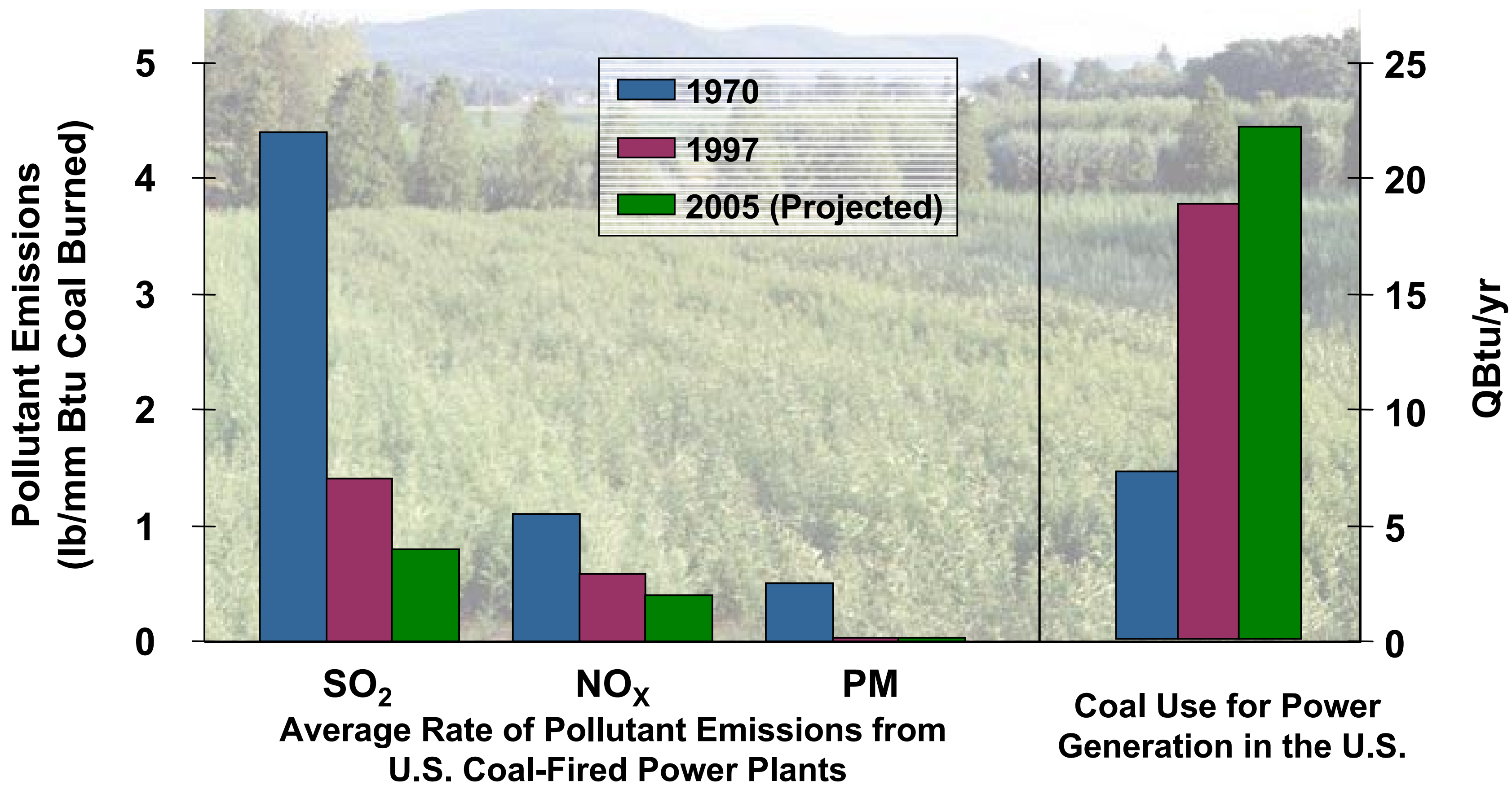
Coal Technologies Are Cost Competitive



Coal Technologies Keep Getting Cleaner



Improved Environmental Performance



Successes to date: pollutant emissions per unit of coal burned have decreased significantly

Comparison of Power Generation Technologies

	Average (1999)	State-of-the-Art (2000)			Future (2010)		
	PC	PC	IGCC	NGCC	PC	IGCC	NGCC
Nominal Efficiency HHV % (LHV%)	33	40	43	52 (57)	44	52	58 (63)
SO_2 Emissions $lb/10^6$ Btu (lb/MWh)	1.3 (13.8)	0.05 (0.5)	0.02 (0.15)	~ 0	0.025 (0.2)	0.017 (0.13)	~ 0
NO_x Emissions $lb/10^6$ Btu (lb/MWh)	0.5 (5.2)	0.15 (1.3)	0.04 (0.31)	0.028 (0.20)	0.03 (0.3)	0.024 (0.18)	0.028 (0.20)
Particulate Emissions $lb/10^6$ Btu (lb/MWh)	0.05 (0.5)	0.01 (0.08)	0.007 (0.053)	~ 0	0.01 (0.08)	0.002 (0.015)	~ 0
Fuel Type Cost - $\$/10^6$ Btu	Coal 1.2	Coal 1.2	Coal 1.2	Gas 3.5 - 7.5	Coal 1.1	Coal 1.1	Gas 4.0-7.0
Capital Cost 1999 $/kW	N/A	1000	1200	550	950	1000	500
Cost of Electricity 1999 ¢/kWh	4.0	3.5	3.7	4.0 - 6.8	3.4	3.1	3.5-6.0

Basis / Assumptions for Technology Comparisons

	Average (1999)	State-of-the-Art (2000)			Future (2010)		
	PC	PC	IGCC	NGCC	PC	IGCC	NGCC
Technology	Sub Critical	Super Critical	Texaco O_2 Blown	"H" Frame	Ultra Super Critical	Advances in Sub Components	Next Generation Turbine
SO_2 Control Technology	Low Sulfur Coal and/or FGD	Wet Limestone 96% - 98%	Amine & Claus or Hot Gas Clean-Up	Sulfur free natural gas	Wet Limestone > 99%	Hot Gas Clean-Up	Sulfur free natural gas
NO_x Control Technology	Combustion Mods such as Low NO_x Burners	Low NO_x Burner, and SNCR or SCR	Quench & Staged Combustion	Combustion Mods such as zoning / staging	Low NO_x Burner, and SCR	Quench & Staged Combustion	Combustion Mods, such as zoning / staging
Particulate Control Technology	Baghouse or ESP	Baghouse or ESP	Ceramic Candle Filter	Particulate free Natural gas	Baghouse or ESP	Ceramic Candle Filter	Particulate free Natural gas
Size (MW)	350	400	350	400	400	500	400

Notes: Assumes levelized costs
20 year book life
Nominal 70% plant capacity factor
Current maximum NSPS limits applicable to these plants

- SO_2 – 1.2 lbs/10^6 Btu and 90% reduction or 0.6 lbs/10^6 Btu and 70% reduction
- NO_x – 1.6 lbs/10^6 Btu for new construction
- PM – 0.03 lbs/10^6 Btu

Nomenclature: PC = Pulverized Coal
IGCC = Integrated Gasification Combined Cycle
NGCC = Natural Gas Combined Cycle

References: DOE Report #DE-AC01-94FE62747
EIA Annual Energy Outlook 2001
DOE NETL Program Goals / Extrapolations
Discussions with equipment vendors and contractors

Electric Power from New Plants Using Coal

(~15 GW New Capacity Proposed at $18 Billion Investment)

SPONSER	PROPOSED LOCATION	SIZE	TIMING	INVESTMENT	COAL TYPE
Tuscon Electric Power	Springerville Arizona	2 Units 380 MW each	Initiate - 2001 In Service - 2004, 2005	~ $ 500 Million	Sub-Bituminous
Tri-State Generation and Transmission	Las Animas Colorado	500 to 600 MW	Initiate - 2001 In Service - TBD	$ 1.2 Billion	TBD
Corn Belt Energy (DOE)	Elkhart Illinois	91 MW	Initiate - 2001 In Service - 2004	$ 137 Million	Waste Coal
Southern Illinois Power	Marion Illinois	120 MW	Initiate - 2000 In Service - 2002	$ 50 Million	Bituminuous Coal Fines
EnviroPower	Sullivan County Indiania	500 MW	Initiate - 2001 In Service - 2004	$ 600 Million	Waste Coal
EnviroPower	Pike County Indiania	500 MW	Initiate - 2001 In Service - 2004	$ 600 Million	Waste Coal
EnviroPower	Knott County Kentucky	525 MW	Initiate - 2001 In Service - 2005	$ 600 Million	Waste Coal
East Kentucky	Maysville Kentucky	250 MW	Initiate - 2001 In Service - TBD	~ $ 300 Million	TBD
Global Energy (DOE)	Clark County Kentucky	400 MW	Initiate - 1999 In Service - TBD	$ 432 Million	High Sulfur KY Bituminous
Peabody Group	Central City Kentucky	1500 to 2000 MW	Initiate - TBD In Service - TBD	TBD ~ $3 Billion	Western Kentucky high-sulfur coal
AES Corporation	Cumberland Maryland	180 MW	Initiate - 1996 In Service - 2001	~ $ 200 Million	Maryland Coal
Tractebel Power	Choctaw County Mississippi	440 MW	Initiate - 1997 In Service - 2001	~ $ 400 Million	Lignite

Electric Power from New Plants Using Coal

(~15 GW New Capacity Proposed at $18 Billion Investment)

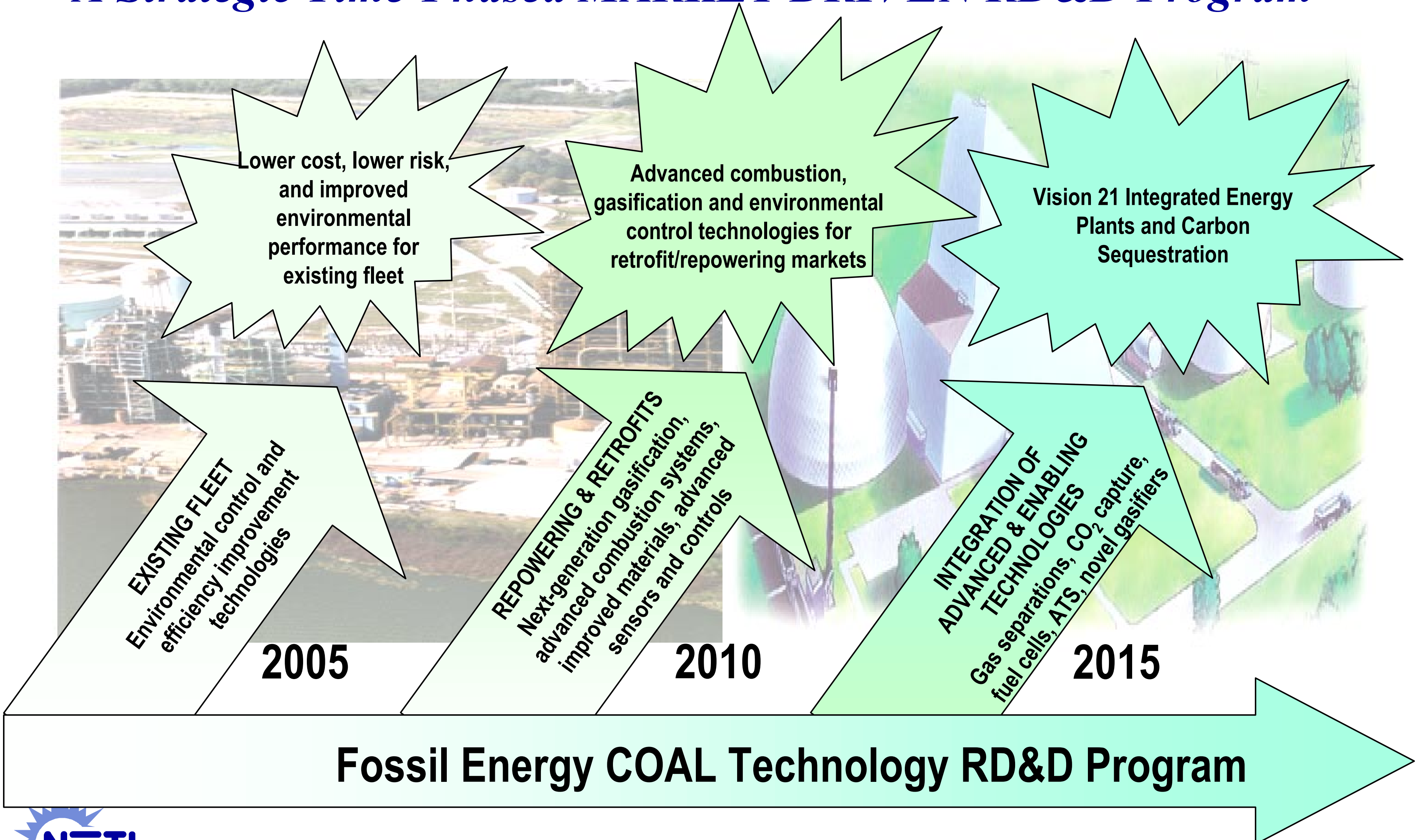
SPONSER	PROPOSED LOCATION	SIZE	TIMING	INVESTMENT	COAL TYPE
LS Power Services	Osceola Mississippi	1200 to 1600 MW	Initiate - 2001 In Service - 2005	$ 1 Billion	TBD
Composite Power	Bear Creek Montana	4 Plants 500 MW each	Initiate - 2001 In Service - 2006	$ 1.5 Billion	Montana Coal Deposits
Great River Energy or Westmoreland Coal or Montana Dakota Utility	North Dakota	500 MW	Initiate - 2001 In Service - 2008	$ 800 Million	North Dakota Lignite
Reliant Energy	Indiana Pennsylvania	520 MW	Initiate - 2001 In Service - 2004	$ 800 Million	Waste Coal
U.S. Electric Power	Whatcom County Washington	249 MW	Initiate - 2001 In Service - 2004	~ $ 300 Million	Low Sulfur Coal Vancouver
Wisconsin Energy & Madison Gas	Oak Creek Wisconsin	3 Plants 600 MW each	Initiate - 2002 In Service - 2007, 2009, 2011	$ 2.5 Billion	Powder River Basin Sub-Bituminous
Alliant Energy	Wisconsin	500 MW	Initiate - 2001 In Service - 2006	~ $ 600 Million	TBD
Black Hills Corp.	Gillette Wyoming	80 MW	Initiate - 1998 In Service - 2003	$ 100 Million	Powder River Basin Sub-Bituminous
Black Hills Corp.	Gillette Wyoming	500 MW	Initiate - 2001 In Service - 2005	~ $ 600 Million	Powder River Basin Sub-Bituminous
Intermountain Power	Southwest Utah	500 to 800 MW	Initiate - TBD In Service - 2006	$ 800 Million	West Ridge Mine
Utah Governor Mike Leavitt (R)	Delta Utah	3 Plants 500 MW each	Initiate - TBD In Service - TBD	TBD ~ 2.5 Billion	TBD

Coal-Based Power Production Issues and Opportunities

- **Electric power reliability**
  - Multi-pollutant control
  - Fine particulates ($PM_{2.5}$) and Hg
  - Improved efficiency
  - Global climate change

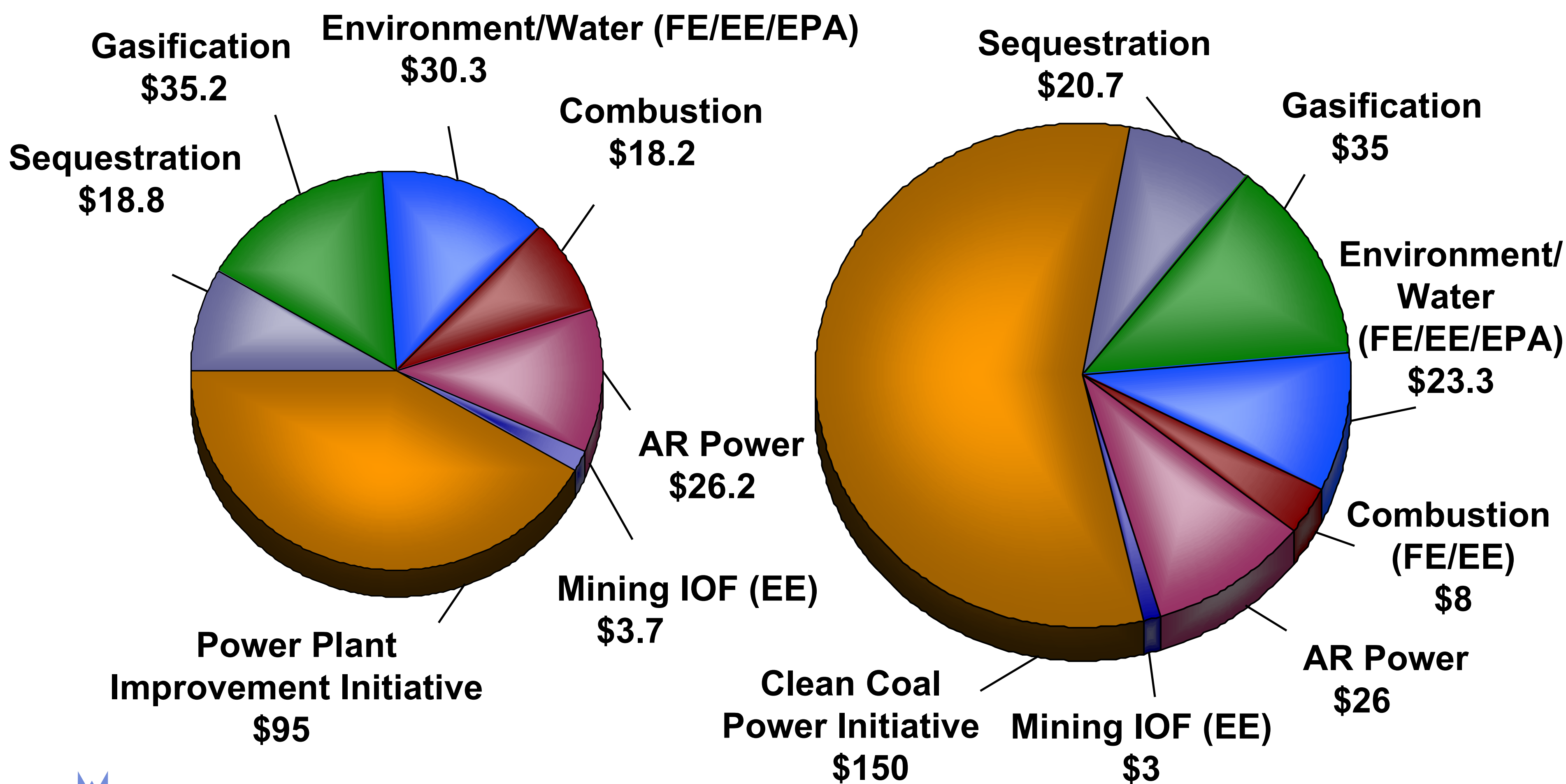
Coal-Based Power Technologies

A Strategic Time-Phased MARKET DRIVEN RD&D Program



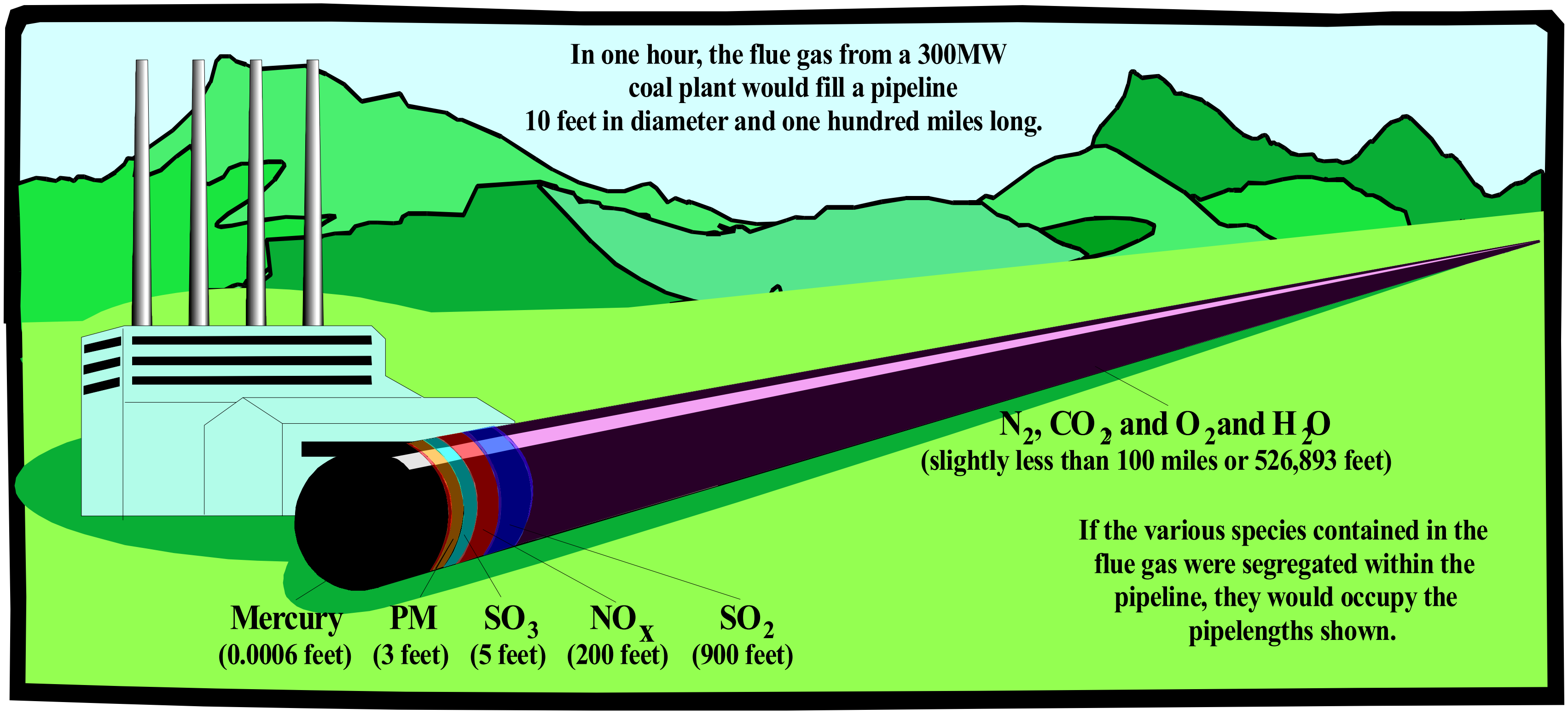
Coal and Environmental Systems*
FY 2001/FY 2002 Budget Comparisons
(all sponsors)

FY 2001 $227.4M | **FY 2002 $273M** (DOE request)



*excluding CCT

Traditional Pollutants



Vision 21

Ultra-Clean Energy Plant of the Future

Energy Plants for Post-2015

- **Use available feeds:**
  - Coal, gas, biomass, waste
- **Electricity is a primary product**
  - Can co-produce fuels, chemicals, steam, heat

Goal:

Absolutely Minimize Environmental Implications of Fossil Energy Use!

Approach:

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

Vision 21 Program Objectives

Capital & Operating Costs/RAM

- Vision 21 must be competitive with other energy systems with comparable environmental performance

Emissions

- < 0.01 lb/10^6 Btu SO_2 and NO_x
- < 0.005 lb/10^6 Btu PM
- <1/2 organic compounds in *Utility HAPS Report*
- <1 lb/10^9 Btu Hg

Schedule of Benefits

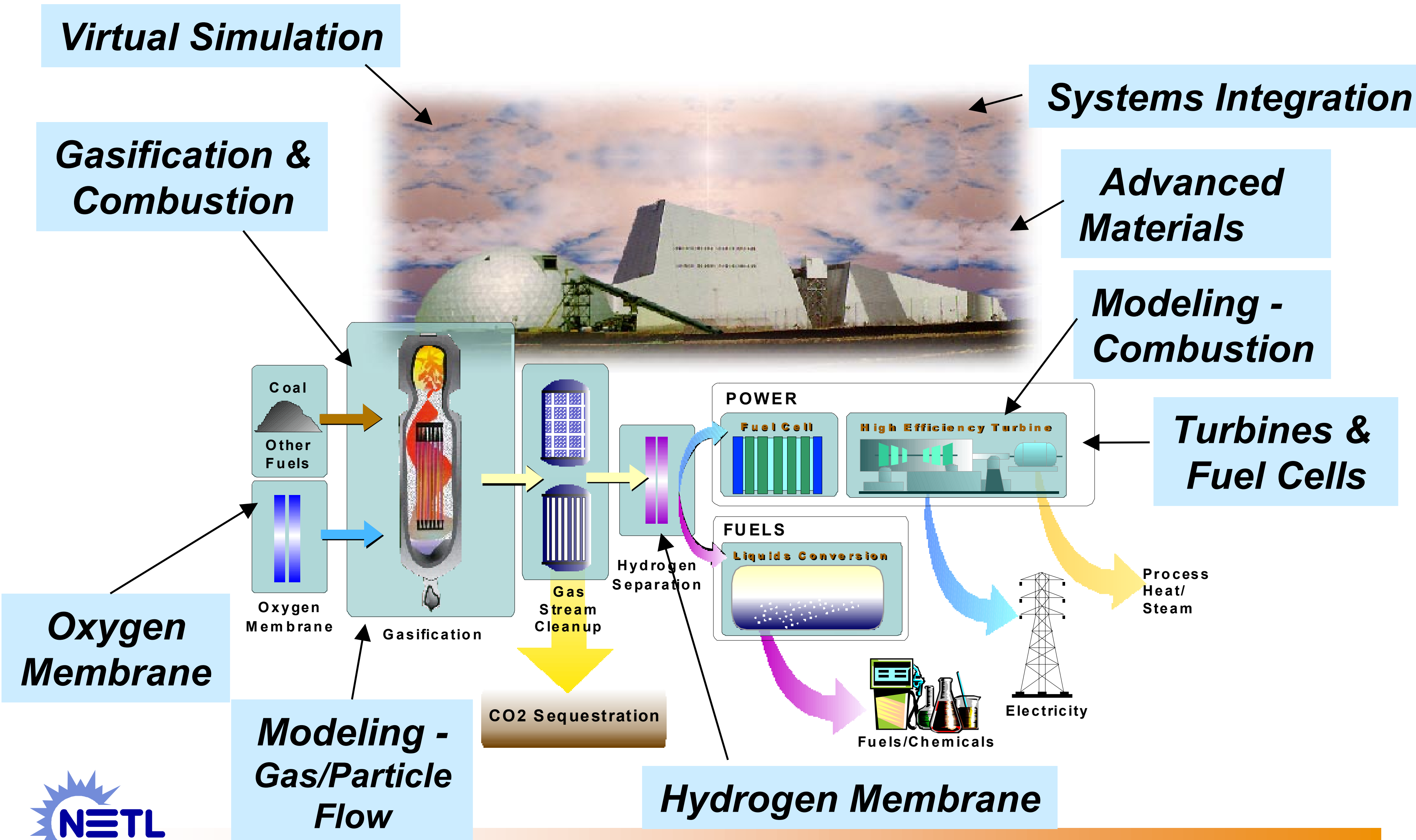
- Technology spinoffs by 2005
- Designs for modules by 2012
- Commercial plant designs by 2015

Efficiency

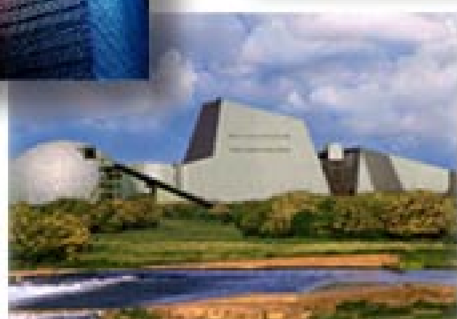
- Electricity generation
  - coal based 60% (HHV)
  - gas based 75% (LHV)
- Fuels only plants 75% (LHV)

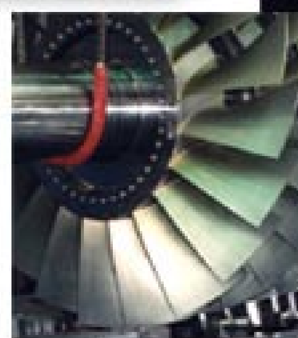
Vision 21 Program

New Projects Contribute to the Ultra-Clean Energy Plant



Advanced Technologies Will Play a Crucial Role in Addressing Climate Change





Appendix C. Workshop Discussion Topics With Questions

Combustion: Areas Where Sensors and Controls May Be Needed or Improved

- Feedstock characterization and mixing
  - Speciation
  - Contaminants (Hg, metals)
  - Btu
  - Size
  - Moisture
- Fuel ratio / balancing
  - Solids flow sensor
  - Air flow (primary, secondary) control
  - Temperature sensor
  - Flame stability control
    - On-line flame characterization sensor
- Gas separation performance
- Maintenance and diagnostics
  - Component integrity and degradation
- Ash formation, handling
  - Soot blowing control
  - Carbon content of ash
  - Ash deposition
  - Metals
- NO_X, SO_X, NH_3 sensors
- SCR catalyst fouling
- NO_X and ammonia slip control
- Cycle water/steam control/automation
- Reliable measuring techniques for Hg – on-line or off-line
- Database on co-firing performance for control or optimized performance
- Advanced controls integrating emission control, combustion efficiency, steam and electricity generation

Gasification: Areas Where Sensors and Controls May Be Needed or Improved

- Temperature (high temperature, high pressure)
- Feedstock characterization and mixing
    - Speciation
    - Contaminants (Hg, metals)
    - Btu
    - Size
    - Moisture
    - Alkali (Na K)
- Solids flow
- Slag formation
- Sulfur and tar production/control
- Particulate detection
    - Gas separation performance
    - Filter performance/fouling
    - Flue gas cleanup
    - NO_X, SO_X
- Reliable measuring techniques for Hg – on-line or off-line
- Database on co-firing performance for control or optimized performance
- Advanced controls integrating emission control, combustion efficiency, steam and electricity generation
- Component integrity and degradation

Advanced Turbines and Engines: Areas Where Sensors andControls May Be Needed or Improved

Sensors

- Feedstock contaminants and Btu value
- Fuel / feedstock particulates
- Feedstock mixing fuel ratio, balancing individual fuel nozzle and air inlet flows
- Thermal barrier coating failure
- Fast pressure and differential pressure (response time)
- Fast sensors coupled with actuators and control algorithm for combustion instabilities
- Torque Measurement
- Signal transmission out of the engine

Sensors in the hot gas path for:

- Combustion pressure pulsation
- Turbine circumfrential inlet temperature distribution
- Turbine blade surface temperature
- Turbine blade vibration
- Turbine blade tip deflection and clearance
- stator vane bowing

Embedded Sensors for use in hot gas section

Direct measurement of the combustion process – optically based technique

Maintenance and diagnostic sensors

- On-line monitoring of component life/component degradation through component operating conditions and component physical properties
- Sensors that map the blades and vanes for integrity
- Hot gas leakage, coolant leakage
- Paticulates in oil
- Off-line non destructive techniques to monitor is component replacement is required before scheduled maintenance including
    - component physical condition referenced to a baseline,
    - component cyclic fatigue, and component coating wear and integrity status

Controls/Communication

- Software to collect and interpret data
- Software for predictive maintenance and predictive control
    - reduce nuisance shutdowns and failures
    - optimize engine operation
    - continuous real-time maintenance scheduling

Neural Nets for information management and adaptive control

Control system for engine thermal performance and equipment failure

Fuel Cells: Areas Where Sensors and Controls May Be Needed or Improved

Feedstock characterization (contaminants, particulates)
Micro/miniaturized sensors and non-intrusive sensors
- Gas flow
- Hydrogen and oxygen sensors
- Membrane integrity
- Catalyst fouling / performance
- Temperature
- Differential pressure

Reliable models and predictive controls
Open architecture for modular control systems
Integrate systems with a standard communication protocol
Proven control techniques for large scale highly integrated systems with respect to load scale

Applications for Sensors and Controls Technology Development

Physical Properties
- Temperature, pressure, flow

Chemical and Emission Detection and Speciation
- Oxygen, hydrogen, water/moisture, methane
- Hydrocarbons low molecular weight - high molecular weight
- Other Organics / VOCs
- Chlorine and other halogens
- HCl, NO_X, NH_3, H_2S, SO_X, CO_2, CO

Trace Element Detection
- Hg (Speciation)
- Arsenic, cadmium, lead
- Other TCLP metals

Particulate and Carbon Detection
- Particulates (quantity, size)
- Carbon in ash, feedstocks
- Particulate / ash desposition

Diagnostics for RM and PM
- Leaks
- Corrosion
- Fouling
- Coating degradation
- Component fatigue

Control and Communication
- Control scheme for plant / equipment design
- Supporting numerical methods, algorithms, or models
- System integration—interfacing/reporting
- Matrix/database management
- Wireless data transmission

Sensors, Controls, and Instrumentation Development and Implementation Goals

Cost
Low cost justifies routine replacement and affords the use of many sensors to support advanced control
Moderate to high purchase costs must be balanced with life-cycle and installation costs
Response time
- Fast, real time responses are needed to apply advanced control

Repeatable/verifiable accuracy for emission monitoring
- Accurate data can be used for direct reporting and control
- Difficult to justify cost and maintenance w/o high degree of accuracy
- Used in an integrated control scheme

Robustness (corrosion, temperature, vibration)
- Without robustness, the sensors will not be used for control because the data will be masked
- High maintenance costs may preclude the use

Non-intrusive/non-contact where applicable
Large, applicable, accurate database to support advanced controls
Simple maintenance or support tools for simple maintenance including sensors with self-diagnostic capabilities

Facilitation Discussion Subjects and Questions

A. Vision 21

1. What kinds of sensors and control technologies would be required to achieve the goals of Vision 21?
2. What is the current status of development for these types of sensors?
3. What are the barriers for these types of sensors?
4. What are the most promising technologies for use in the Vision 21 timeframe?
5. What planning or recommendations do you have for this technology with respect to Vision 21 goals and timeline?

B. Controls

1. What are the limitations of current control technologies for power generation facilities or technologies? (e.g., slow valve response time, inadequate measurement points, instabilities in control modes)
2. What are the major improvement areas? (e.g., need more input information [sensors] for measuring temperature distributions, fuel distributions, and chemical specifies such as CO, NO_X)
3. What are the barriers for using advanced control technologies?
   - For existing power plants?
   - For new facilities or major overhauls?
4. What are the most promising control technologies or approaches for new facilities in (a) 0-5 years, (b) 5-10 years, (c) 10-20 years?
5. If the individual needs of the various sensor and controls are developed successfully, what approach should be taken to insure that a variety systems can communicate and integrate successfully to achieve advanced system control?
6. What are your recommendations to DOE for developing control technologies?

C. Sensors

1. Is the list of sensors and controls needs complete? (refer to individual lists)
2. Can you prioritize the list of needs or identify key measurement needed for this application?
3. Are currently available sensors adequate or appropriate?
4. What are the largest or most detrimental maintenance problems that could be prevented or addressed by the proper sensor?
5. What are the technical/ performance requirements, such as range, sensitivity, accessibility for new or future sensors?
6. What are the promising approaches to making these measurements?
7. What are the emerging technologies applicable to these measurements ?(e.g., MEM, Laser acoustic, SAW, Metal Oxides, Sensor arrays, Integrated fiber optic)
8. Which merging or novel technologies should be emphasized for development and use in (a) 0-5 years, (b) 5-10 years, or (c) 10-20 years?
9. What are some recommendations to DOE for supporting sensor development