Stakeholder Workshop
Advanced Process Control for Next Generation Power Plants

Summary Report

June 2007

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Contents

Executive Summary

On June 13-14, 2007, the U. S. Department of Energy's National Energy Technology Laboratory (NETL) sponsored a workshop entitled "Advanced Process Control for Next Generation Power Plants". The workshop was held in Pittsburgh, PA and in conjunction with the 50^{th} Annual Instrument Society of America (ISA) Power Industry Division (POWID) Symposium and the 17th Annual Joint POWID/EPRI on Controls and Instrumentation Conference in Pittsburgh, PA held June 10-15, 2007.

The goal of the workshop was to identify research and development opportunities for advanced process control to ensure that key technologies will be available to meet the needs of future near-zero emission power systems.

NETL is using the information gathered during this workshop and from other sources as input for the Sensors and Process Control program which; in turn, will guide future R&D solicitations and programmatic efforts. Representatives from process control, advanced power plant technology development, the electric utility industry, system integration, and research communities were invited to participate in the workshop.

The general sense expressed by the workshop participants is that the state of the art system for new power plants today is a digital control system (DCS) with flexibility to interface with a variety of vendor-supplied equipment control systems by means of a variety of network protocols. While some participants believe it desirable to control the entire plant with an integrated system, many feel this is impractical at present because vendors insist on installing their own system due to concern with warranties and liability.

Many of the participants expressed a view that the advanced process control system of the future would have most of the following attributes or characteristics:

- Allows asset management (economic control), planning, and scheduling.
- Allows integration of decision making levels for total plant control.
- Has a secure/configurable/self-evolving cyberstructure.
- Allows the operator to address different issues for baseload versus dispatched operation.
- Allows the opportunity to quickly respond to future grid demands, or process coal for conversion to other products (i.e. gasification, chemical looping).
- Would permit on-line fuel quality measurements for coal being fed to a plant (difficult, but very desirable).
- Would have additional sensor needs that are not satisfied (e.g. sensors in slagging flows, sensors for hydrogen membranes, fuel cell stacks, turbine inlets, etc.).
- Would build robust models as needed to operate plant at peak performance.
- Would allow adaptation of systems used in chemical plants and consideration for application on advanced energy plants (e.g. those using AspenTech control systems).

When challenged to address the effects of future plants exceeding their emissions limits, some observations were made that systems need to accommodate changing fuels (e.g., the addition of biomass, which could have a 20% step change in fuel), wireless systems, coal flow control, reconfiguration, etc. The attendees thought that one primary area of emphasis for advanced process control systems should be the ability to incorporate scientifically accurate real-time models of the processes into the control system. These models could include 3-dimensional models, partial differential equations, steady-state, and/or dynamic versions.

For integrated gasification combined cycle (IGCC), chemical looping, and oxy-fueled systems distributed computing needs to be considered. Dynamic process models running in real time can provide design and optimization, and allow control theory development. Distributed control can be adapted from today's chemical plants, with black boxes inside controllers for distributed sensing, actuation, and control. These systems need to consider operators, communication, safety, and security. There is a new methodology of how systems are designed/tested starting with dynamic simulation.

Based on a straw poll results for the industry attendees, the highest priority R&D categories for the advanced process control (APC) program are as follows (highest priority first):

- Diagnostics/validation- The main topics of interest here include sensor networking, sensor validation/data quality, soft or virtual sensors, diagnostics/prognostics, excitation of systems, and condition monitoring.
- Sensors- Interest focused on sensors to measure state variables (temperature, pressure, etc), solids flow, solids state or composition, wear/corrosion/lifetime, and gas composition.
- Computational intelligence- This highly significant area includes control algorithms, adaptive methods, controls intelligence, complexity management, and decision systems.
- Model-based control- Key topics in this area were interface issues with mathematical models, models designed for use in control systems, and standard models.

Draft recommendations can be drawn from the workshop, including the briefings, group discussions, exercises, response to presentations, and informal discussions. A brief list of recommendations for potential consideration is presented below:

- Consider results of the straw poll in developing plans for future program activities.
- Initiate a systems study on the potential payback benefits of advanced control systems. If benefits are significant, this could help "sell" the R&D program.
- Initiate a review or white paper on on-line coal quality measurement systems and state of art of solids flow and composition measurements.
- Assess state of art of supervisory control systems for chemical plants and application to advanced fossil energy (FE) technologies such as IGCC.
- Conduct a study or white paper on the interfacing of models with control systems, and the potential needs for standards in this area.
- Assess possible approaches to identify APC R&D activities at FutureGen.
- Conduct a study to identify one or two "best" commercial systems that can serve as baseline for advanced work.

MEETING REPORT

Stakeholder Workshop
Advanced Process Control for
Next Generation Power Plants
June 13 & 14, 2007

1.0 INTRODUCTION/OVERVIEW

Advanced process control for next generation power plants is an enabling technology that is critical to achieving the targets of high efficiency, low/no emissions, high reliability, and competitive cost of electricity. To expand upon this identified need for utilizing advanced technology, the U. S. Department of Energy's National Energy Technology Laboratory (NETL) sponsored a workshop entitled "Advanced Process Control for Next Generation Power Plants" on June 13-14, 2007. This workshop was held in conjunction with the 50th Annual Instrument Society of America (ISA) Power Industry Division (POWID) Symposium and the 17th Annual Joint POWID/EPRI on Controls and Instrumentation Conference in Pittsburgh, PA held June 10-15, 2007. The ISA POWID Symposia and EPRI Conference brought together industry leaders in the instrument, sensors, and control technology area that are focused on power plant applications. The expertise represented at this symposium was an excellent resource for DOE NETL to solicit input and this report summarizes the input received from 35 participants from both industry and academia.

The goal of the NETL workshop was to identify research and development opportunities in advanced process control to ensure that key technologies will be available to meet the needs of future near-zero emission power systems.

The workshop was organized around a series of briefings followed by facilitated roundtable discussions. The workshop agenda is provided in Appendix A. Representatives from process control, advanced power plant technology development, the electric utility industry, system integration, and research communities participated in the workshop. A listing of all attendees is provided in Appendix B. The three briefings given at the workshop are included in Appendix C and provided overviews of the DOE NETL Advanced Research Program in Sensors and Controls, current status of the FutureGen Project and a 10-15 year outlook at sensor and control technology.

NETL is using the information gathered during this workshop and from other sources as input for the Advanced Research Sensor and Control Program, road mapping efforts, and programmatic goal of utilizing advanced process control technology and methodology to achieve seamless, integrated, automated, optimized, intelligent power and fuel production facilities.

2.0 SUMMARY OF 2006 WORKSHOP RESULTS

The first workshop dedicated to outlining technology for advanced control of coal fired power plants was held in March, 2006. Proceedings from this workshop have been posted at http://www.netl.doe.gov/publications/proceedings/pro_toc.html. Many of the attendees from the 2006 workshop also participated in this workshop to build upon prior discussions and efforts in outlining appropriate research in advanced process control for near zero emission power plants.

The following insights regarding current technology issues and trends were developed at the 2006 workshop and used as a basis to begin discussions at this workshop:

- External drivers needed to promote adoption of new technology
- Industry is risk-averse and cost-sensitive
- End users provide external drivers, but technology developers and federal government serve as catalysts to remove barriers or reduce risks associated with advanced technology
- Base load requirements differ from those for peak load systems and need to be considered in developing and applying advanced control technology.
- Opportunities for advanced process control (APC) exist in designing for variations in load and operation modes
- APC is important when varying generation outputs such as power and fuels
- An adaptive APC framework is important to incorporate new sensor and computational technologies and performance levels of a plant
- Utilize APC to perform coal fired power plant optimization at system and subsystem levels

3.0 PURPOSE AND OBJECTIVES OF 2007 WORKSHOP

The goal of the workshop was to identify research and development opportunities for advanced process control to ensure that key technologies will be available to meet the needs of future near zero emission power systems. The intent is to develop seamless, integrated, automated, optimized, intelligent power and fuel production facilities.

Workshop objectives include the following:

- Assess and refine understanding of current state-of-art of process control applications in energy plants
- Respond to a vision of advanced process control systems of the future
- Refine the view developed at the 2006 workshop of process control issues, emerging trends and needs for the next 15 years
- Develop specific requirements/attributes for advanced process control systems for a range of potential near- zero-emissions fossil fuel based energy plants
- Refine opportunities identified at the 2006 workshop for process control research and development
- Develop specific requirements/attributes for an advanced process control system test bed at DOE's FutureGen facility

4.0 SUMMARY OF PRESENTATIONS

Three presentations were made at the beginning of the workshop and provided an overview of DOE NETL’s Sensor and Control Program and progress since last workshop in March 2006. Robert Romanosky, Technology Manager for the Advanced Research Program also described NETL's role in supporting R&D of process control to ensure key technologies will be available to meet the needs of future advanced power systems. Thomas Sarkus, Director of Advanced Energy Initiatives Division, provided an updated overview of DOE Fossil Energy’s FutureGen Project. The final presentation was made by Dr. Mark Bryden, Program Director for Simulation Modeling and Decision Science. This presentation offered a conceptual view of a long range vision for future sensors and controls networks for advanced energy systems. Copies of these presentations are provided in Appendix D.

5.0 SUMMARY OF DISCUSSIONS

Following the presentations, the remainder of the workshop consisted of roundtable discussions focused on the workshop objectives.

5.1 Current State of Art of Process Control

The general sense expressed by the workshop participants is that the state of the art system for new power plants today is a digital control system (DCS) with flexibility to interface with a variety of vendor-supplied equipment control systems by means of a variety of network protocols. While it is desirable to control the entire plant with integrated systems, a high degree of integration may be impractical (or increase cost) because a number of plant components are controlled with vendor supplied systems due to concern with warranties and liability.

While there are differences between goals and approach to design and control of chemical plants versus the envisioned power and fuel production facilities such as a FutureGen type facility, chemical facilities appear to adopt advanced control approaches more readily and have derived benefit from this technology. Some participants suggested that control systems used in chemical plants are more advanced than those used in today’s power plants; in some cases allowing economics to be used as an objective function to drive plant operation.

The following were offered to characterize advanced commercial or near-commercial control systems:

- Major vendors (e.g. Emerson, Honeywell, Invensys, ABB, etc) offer state-of-art commercial systems. These systems are generally characterized as Distributed Control Systems with proportional-integral-derivative (PID) controllers. Vendors offer many features and incorporate some aspects of non-PID advanced control. For traditional coal fired power plants, it was stated that PID is sufficient for most systems/components within the plant.
- It has been demonstrated that 3 or 4 operating facilities are tied together in a networked system, including some coal-fired pulverized combustion plants. This system uses agent-based control and some problems in hybridization have been encountered.

- A robust hybrid control based on the H-infinity approach has been developed and tested. The issue of hopping among controllers was solved. A simplified model was used based on a quadratic controller.
- A variety of plants have used game theory in controls. There are advantages to using this. The shell allows redesign. Unconstrained linear control is possible.
- Predictive control methods can be model-based using a variety of models. There are two key issues- robustness and reconfigurability. Incorporating dynamic nonlinearities in the models can result in an optimized solution for real time predictive control. Examples of this approach exist but may not be prevalent throughout the power industry.
- The state-of-art system can incorporate feed-forward and a library with PID, is stable, and is advanced in the bulk of the pulverized coal fleet.
- Fuzzy logic has been used for the development of a steam turbine controller. However, commercial success using this approach has not been demonstrated.
- Some aspects of commercial control systems allow and adopt a “plug and play approach” (i.e. can new sensors and/or models be plugged into the control system and be instantly recognized) but more development is needed.

5.2 Vision of Advanced Process Control Systems

Many of the participants expressed a view that the advanced process control system of the future should/would have most of the following attributes or characteristics:

- Asset management (economic control), planning, and scheduling, e.g. optimization based on CO2, emission credits, cash, product management, assets & liabilities, resource utilization (power, fuel, etc).
- Integrated decision making levels for total plant control, but could allow higher level controls based on local execution. Everything would be done at the lowest appropriate level. It would have a decentralized (multi-agent) structure.
- Have a secure/configurable/self-evolving cyberstructure.
- Allow the operator to address different issues for baseload versus dispatched operation.
- Merging of the physical process with communications and data storage/computation.
- Broadened definition of “plant” to include all inputs and outputs (e.g. CO_2, feed, fleet management, grid)
- Enable opportunities to respond to future grid demands (e.g. for energy storage downstream via a multi-product platform), and would apply to coal conversion systems (e.g. gasification, chemical looping).
- Incorporate measurement and data for only what is needed with appropriate accuracy.

When challenged to identify the “dream control systems” of the future, a major issue was identified under the heading of complexity management. The issues with complexity management are as follows:

- Thousands or millions of data points
- Data output too complex to manage
- Human-machine interface (major issue)

5.3 Advanced Process Control Systems for Zero-Emission Fossil Fuel Based Energy Plants

The attendees identified the following major issues and opportunities with advanced process control systems for near-zero emission fossil fuel based energy plants:

- On-line coal quality measurements for coal being fed to a plant are still difficult to achieve, but would be very desirable. While on-line measurement systems for coal heating value, sulfur content, and ash content have been in development for many years, the systems are still not providing the information needed for operators to control the process, and accuracies of sampling and statistical variations are not sufficient.
- There are additional sensor needs that are not satisfied, e.g. sensors in slagging flows, sensors for hydrogen membranes, fuel cell stacks, turbine inlets, etc.
- Validated robust models are needed.
- Additional work is needed on methods to identify, monitor, and improve plant performance.
- Assessments are needed to evaluate potential performance of sensors and controls with oxy-fueled systems such as those Alstom is working on.
- Modern communication systems need to be incorporated, with attention paid to security.
- Adaptation of systems used in chemical plants need to be assessed and considered for advanced energy plants, e.g. those using AspenTech control systems.

When challenged to address the effects of future plants exceeding their emissions limits, some observations were made:

- Systems need to accommodate changing fuels (addition of biomass, 20% step change in fuel), wireless systems, coal flow control, reconfiguration, etc.
- These will be accommodated by means of:
    - Advanced sensors, e.g. for on-line coal quality
    - Smart systems
    - Knobs for coal flow control

Additional observations for advanced systems included:

- Systems should consider model-free adaptation controls similar to those licensed for oil drilling. These are being evaluated for supercritical power plants under DOE funding.
- Multivariable systems are being used in Chinese CFB boilers with varying coals. Multivariable control can be used/imbedded in equipment for control using fuzzy logic controllers and has been applied in other industries.

For IGCC and chemical looping systems, as well as oxy-fueled systems, distributed computing needs to be considered. Dynamic process models running in real time can provide design and optimization, and allow control theory development. Distributed control can be adapted from today’s chemical plants, with black boxes inside controllers for distributed sensing, actuation, and control. These systems need to consider operators, communication, safety, and security. There is a new methodology of how systems are designed/tested starting with dynamic simulation. Some other characteristics include:

- Feed forward capability
- Wireless in 20% to 40% of the plant for favorable economics
- Model Predictive Control (MPC) for core processes
- Emission control integrated by overall integration of systems component

5.4 Process Control Issues, Emerging Trends, and Needs

Some over-arching issues, trends, and questions were identified with development and implementation of advanced power and control systems.

A concern was expressed that the availability of large amounts of data to the plant operators is not always as valuable as it might be (e.g. condition monitoring, preventative maintenance) since the data may not be used most effectively due to either useful data management and analysis tools or lack of skilled resources and time.

A related issue is that the plant operator's responsibility is to make the plant operate safely. The operator must take 100,000 data points, consider them, and make real-time decisions about plant operation. The design of an APC must consider output, and provide the correct information in a reasonable format specific to a variety of different operators. There are mechanical design limits on what can be done. The control systems may not be the limiting factor. One cannot use the control system to change the plant characteristics.

One of the broadest and most far-reaching questions was whether advanced control systems can provide an economic payback. The attendees by and large believe that advanced systems can provide a positive payback by improving operational efficiency and performance, and reducing unplanned maintenance. However, convincing and publicly available information on the value of advanced process control to a company's bottom line is lacking. Future research and development efforts need to consider potential payback from advanced controllers.

APC developers must keep in mind that the objective of APC is to enable or improve plant operations by integrating the control system with the process.

While sensors and control systems will be more capable in the future, involving control personnel early on in the design process remains a challenge to positively affect the design process. A reactive approach to designing controls for a given plant design is the current practice which inhibits the ability to work collaboratively towards a plant design and process controls that are well integrated and incorporate advanced techniques that could have positive impacts. This problem is expected to continue.

5.5 Advanced Process Control at FutureGen

Discussions regarding process control for FutureGen were based on the update provided by Thomas Sarkus as well as a representative from the A&E firm selected for FutureGen, The Washington Group.

For the "backbone" portion of the FutureGen Plant, the sense of the attendees was that the process control system(s) will consist of a relatively conventional system based on the current state-of-art. The process control system, in whole, will be the best available state-of-the-art and commercially available at the time that the project solicits for and selects this portion of the design. Further, it is anticipated that a digital control system (DCS) with most control loops based on traditional PID will be used and have the capability to incorporate advanced control and communication.

The group thought it desirable that the system have the built-in flexibility and capability to allow add-ons such are wireless systems. Additional comments are as follow:

- The system may have one or bus type communications networks, and will need to accommodate pre-fabricated package control for subsystems such as the air separation plant and the gas turbine.
- It would be desirable that the overall platform be defined to enable coordinated control with a unification layer.
- The system should have the capability to test advanced sensors for coal quality, gas quality, temperature, etc.
- Some attendees suggested that the system should be standardized for ease of use and operator training.

The attendees also support the concept of testing advanced process control system concepts and components, e.g. advanced sensors, at R&D portion of the FutureGen Plant.

5.6 Future R&D Opportunities

A related issue is that the plant operator's responsibility is to make the plant operate safely. The control system may be handling up to 100,000 input/output and must allow the operator to make real-time decisions about plant operation. The design of an APC must consider output and provide the correct information in a reasonable format specific to an operator or teams of operators. The human machine interface, alarm management, embedded intelligence needs to be carefully considered to allow the operators to focus on the right problems/issues within the right time frame. As an aside, it must further be recognized that even with vast amounts of computing and control capability, the physical and mechanical limits of the system must be understood and respected from both safety and mechanical integrity view points and incorporated in the control system. There have been instances where the designs of the plant and/or subsequent changes to plant render it very difficult to control regardless of type of control system that is used. This point refers to back to prior comments that controls should be considered early on the design stages of new plants.

The discussion focused on R&D needs for advanced process control systems to enable operation and optimization of advanced near-zero emissions fossil fueled power plants based on IGCC, oxy-fuel combustion, or chemical looping systems. These recommendations are grouped into categories of models, sensors, and the control system.

Models and Interfaces - The attendees thought that one primary area of emphasis for advanced process control systems should be the ability to incorporate scientifically accurate real-time models of the processes into the control system. These models could include 3-dimensional models, partial differential equations, steady-state, and/or dynamic versions. Additional efforts are needed to define the levels of fidelity needed for models and efforts to validate, update, and adapt models as the process matures or is modified during operation.

Sensors - R&D needs to address advanced sensor development as well as sensor optimization. Additional areas of emphasis should address:

- Critical measurement needs for the gasifier.
- Various types of sampling and/or impacts of observation ports and locations
- Fuel quality, gas measurements, temperature at extreme conditions
- Real and virtual sensors
- Expanded research, development, testing, and evaluation of new and innovative sensors

Process Control System - Advanced process control system research needs to address the following issues:

- What type of enterprise system is needed to unify the competing standards?
- How can the system incorporate interchangeable architecture?
- How do the systems interface with advanced models as described above?
- What kinds of standards are needed for interfaces; what "hooks" are needed in software and hardware so that future systems can be "plug and play" in terms of models, advanced sensors, and entire subsystem controls.
- What kind of flexibility needs to be included to readily accommodate new computational hardware, new communication standards, etc?
- Should vendor sources be standardized?
    - To allow ease of use and to minimize operator training requirements.

Results of Prioritization Exercise - Budget Allocation Straw Poll

An exercise was conducted with the workshop participants to identify R&D topics that the participants believed are significant to the future development of advanced process control systems for power plants of the future.   A total of 25 project funding topics were identified and each attendee participated in a "straw poll" to identify R&D topics that should receive high priority in research funding. The topics were grouped into seven budget areas for emphasis on research value and are listed below.

- Sensors- This category included sensors to measure state variables (temperature, pressure, etc), solids flow, solids state or composition, wear/corrosion/lifetime, and gas composition.

- Diagnostics/validation- This category included sensor networking, sensor validation/data quality, soft or virtual sensors, diagnostics/prognostics, excitation of systems, and condition monitoring.
- Model-based control- This includes interface issues with mathematical models, models designed for use in control systems, and standard models.
- Computational intelligence- Includes control algorithms, adaptive methods, controls intelligence, complexity management, and decision systems.
- Control framework- Included lower level control systems, communication systems, and system architecture and integration.
- Plant control and communications- This includes supervisory control systems as well as security and communications at the system level.
- Actuation- This includes flow control and response systems as well as actuators.\

The results of the straw poll survey are summarized in the table below, with the priority research categories ranked from highest to lowest. The total dollars represents the cumulative funds allocated to each budget area by the attendees participating in the survey. To insure that a unique count was observed, no participant was counted more than once when multiple allocations were made to the same budget area. This resulted in a more normalized weighted average calculation (unit dollars allocated per budget area) and the priority rankings less skewed for any group participating in the survey. The straw poll survey provided meaningful results on what priorities were significant to the group and insight on allocating funds in the most cost-effective manner to help meet the goals and objectives of the workshop.

S&C 2007 Workshop - Priority Rank by Budget Area				
Budget Area	Total Dollars	Unique Vendors	Weighted Average	Survey Rank
Diagnostics/Validation	$618	24	$25.75	1
Sensors	$515	23	$22.39	2
Computational Intelligience	$443	21	$21.10	3
Model Based Control	$309	20	$15.43	4
Control Framework	$260	18	$14.42	5
Plant Control & Communications	$221	17	$13.00	6
Acutation Control	$104	11	$9.45	7

6.0 CONCLUSIONS AND RECOMMENDATIONS

Utilizing advanced process control technology and methodology to achieve a seamless, integrated, automated, optimized, intelligent power and fuel production has been the goal of NETL's Advanced Research Sensor and Control Program. Through workshops like this, the industry, academia, and government can come together to discuss the current state of APC and define the areas that require additional R&D efforts.

The following recommendations can be drawn from the workshop, including the briefings, group discussions, exercises, response to presentations, and informal discussions. The following are the conclusions and recommendations of this workshop:

- Expand research on:
  - Sensor networking
  - Sensor validation/data quality
  - Soft or virtual sensors
  - Diagnostics/prognostics
  - Excitation or systems
  - Condition monitoring

- Continued development of advanced and innovative sensors to measure state variables (temperature, pressure, etc.), solids flow, solids state or composition, wear/corrosion/lifetime of components, and gas composition is needed.

- Resolve the interface issues with mathematical models, models designed for control system use, and standard models.

- Initiate a system study on payback benefits of advanced control systems.

- Develop white papers on:
  - On-line coal quality measurement systems
  - State-of-the-art of solids flow and composition measurements
  - Interfacing of models with control systems
  - Standardizing of interfacing models and control systems

- Assessment of the current state-of-the-art of supervisory control systems for chemical plants and application to advanced fossil energy power systems is needed.

- Identify advanced process control activities at FutureGen.

- Conduct a study to recommend a few “best” APC commercial systems to serve as a baseline.

- Consider results of the straw poll in developing plans for future program activities.

- Initiate a systems study on the potential payback benefits of advanced control systems. If benefits are significant, this could help "sell" the R&D program.

- The next APC workshop is tentatively planned for early summer 2008.

LIST OF APPENDICES

APPENDIX A

Workshop Agenda

U.S. Department of Energy - Office of Fossil Energy - National Energy Technology Laboratory

Stakeholder Workshop
Advanced Process Control for Next Generation Power Plants

Sponsored by the Department of Energy
National Energy Technology Laboratory
in Conjuction With the

17th ISA POWID/EPRI Controls & Instrumentation Conference
50th Annual ISA POWID Symposium

AGENDA

WEDNESDAY, JUNE 13, 2007 - BRIGHTON IV

12:00 p.m.	**Registration - Brighton IV Foyer**
1:00 p.m.	**Welcome**
	Overview of DOE NETL's Sensor and Control Program *Robert Romanosky*, Technology Manager, Advanced Research Office of Coal and Power R&D U.S. Department of Energy, National Energy Technology Laboratory
1:30 p.m.	**Overview of the FutureGen Initiative** *Thomas Sarkus,* Director of the Advanced Energy Initiatives Division U.S. Department of Energy, National Energy Technology Laboratory
2:00 p.m.	**Looking Ahead: Sensor Nets, Modeling, and Decision Science** *Dr. Mark Bryden*, Interim Chair and Associate Professor Iowa State University, Program Director for Simulation Modeling and Decision Science
2:20 p.m.	**Break** *(Beverages and snack)*
2:30 p.m.	**Roundtable Discussion** *All Participants,* Discussion, Q&A - Power Plant Control Issues and Trends - Research & Development Opportunities and DOE's Role
4:30 p.m.	**Adjourn**

THURSDAY, JUNE 14, 2007 - BRIGHTON IV

7:30 a.m.	**Registration** *(Continental Breakfast)* **- Brighton IV Foyer**
8:00 a.m.	**Welcome / Review of Control Challenges and Opportunities** *Susan M. Maley,* Project Manager for Gasification and Fuels Division U.S. Department of Energy, National Energy Technology Laboratory
8:30 a.m.	**Roundtable Discussion** *All Participants,* Discussion, Q&A **10:15 - 10:30 a.m. - Break** - Current Research in Control Technology and Data Management - Control Technology R&D for Power Plant Control
11:35 a.m.	**Conclusion**
12:00 p.m.	**Adjourn**

APPENDIX B

Registration List

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APPENDIX C

Acknowledgements

Our thanks go out to Instrument Systems and Automation Society (ISA) and Electric Power Research Institute (EPRI) for allowing us to participate in their 17th Annual Joint POWID/EPRI on Controls and Instrumentation Conference in Pittsburgh, PA. The response and participation in our workshop was very successful and provided us with information to help guide our control program in future development.

Technology & Management Services (TMS) was again outstanding in helping us facilitate the workshop. Larry Headley did an outstanding job in keeping everything on track and moving us forward.

The NETL Event Management staff has successfully pulled off another workshop for us without a hitch. Karen Lockhart, Susan Clemons, Dann Burton, Norm Smith, and Linda Forney of Performance Results Corporation (PRC) were instrumental in getting the attendees lined up, scheduling the facilities and handling the little things that popped up in a professional manner. Their can do attitude made it easy for us to have another successful workshop in the short time we had.

And finally, the workshop attendees were great in providing information critical to help us develop research topics for the next generation of power plant control and operations.

We look forward in working with you.

Robert R. Romanosky and Susan Maley
U. S. Department of Energy
National Energy Technology Laboratory

APPENDIX D

Presentations

- **Presentation: Overview of DOE's NETL's Sensor and Control Program**
  Bob Romanosky, Technology Manager, Advanced Research Office of Coal and Power R&D

- **Presentation: Overview of the FutureGen Initiative**
  Tom Sarkus, Director of the Advanced Energy Initiatives Division
  U.S. Department of Energy, National Energy Technology Laboratory

- **Presentation: Looking Ahead: Sensor Nets, Modeling, and Decision Science**
  Dr. Mark Bryden, Interim Chair and Associate Professor Iowa State University, Program Director for Simulation Modeling and Decision Science

Overview of DOE's NETL's Sensor and Control Program

Bob Romanosky, Technology Manager,
Advanced Research Office of Coal and Power R&D

Stakeholder Workshop Advanced Process Control for Next Generation Power Plants

Welcome

Wednesday, June 13, 2007

Sponsored by the
Advanced Research Program
National Energy Technology Laboratory

Workshop Agenda

Wednesday, June 13th

12:00 pm	**Registration**
1:00 pm	**Welcome**
	Overview of DOE NETL's Sensor and Control Program
	Robert R. Romanosky, Technology Manager for Advanced Research
	U.S. Department of Energy, National Energy Technology Laboratory
1:30 pm	**Overview of the FutureGen Initiative**
	Thomas Sarkus, Director of the Advanced Energy Initiatives Division
	U.S. Department of Energy, National Energy Technology Laboratory
2:00 pm	**Looking Ahead: Sensor Nets, Modeling, and Decision Science**
	Dr. Mark Bryden, Interim Chair and Associate Professor Iowa State University, Program Director for Simulation Modeling and Decision Science
2:20 pm	**Break** ***(Beverages and snack)***
2:30 pm	**Roundtable Discussion**
	All Participants, Discussion, Q&A
	- Power Plant Control Issues and Trends
	- Research & Development Opportunities and DOE's role
4:30	**Adjourn**

Workshop Agenda

Thursday, June 14th

7:30 am	**Registration** *(Continental Breakfast)*
8:00 am	**Welcome / Review of Control Challenges and Opportunities**
	Susan M. Maley, Project Manager
	U.S. Department of Energy, National Energy Technology Laboratory
8:30 am	**Roundtable Discussion**
	All Participants, Discussion, Q&A
	10:15-10:30 pm – Break
	- Current Research in Control Technology and Data Management
	- Control Technology R&D for Power Plant Control
11:30 pm	**Conclusion**
12:00 pm	**Adjourn**

Acknowledgements

- **ISA and EPRI**
- **NETL Site Support Contractors**
  - TMS & RDS
- **NETL Event Management**
- **Sheraton Station Square**
- **Workshop Participants**

National Energy Technology Laboratory

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

Alaska

Oklahoma

Oregon

Pennsylvania

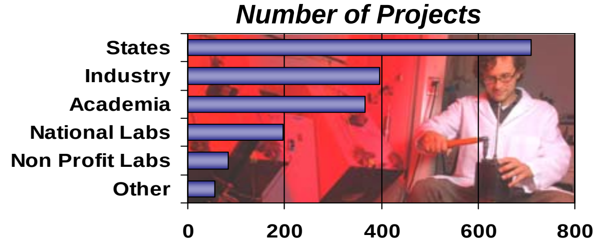
West Virginia

NETL

NETL Implements and Manages Extramural RD&D

- **Over 1,800 research and deployment activities in U.S. and more than 40 foreign countries**
- **Total award value over $9 billion**
- **Private sector cost-sharing over $5 billion**
  - Leverages DOE funding
  - Ensures relevance
  - Accomplishes mission through commercialization

Number of Projects



Updated 11/13/2006

NETL

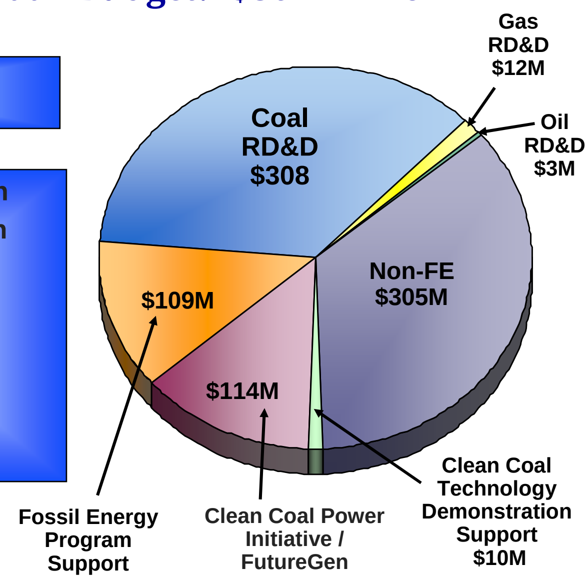
NETL FY 2007 Budget: $861 Million

Coal RD&D

Advanced Research
Total - $25.5 Million

Technology Areas

- Computational $6.8
- Material $7.5
- Sensors/Control $6.8
- Other $4.4



Summary of 2006 Workshop Results

- **Insights regarding current technology issues and trends**
  - End users provide external drivers, but technology developers and federal government serve as catalysts to remove barriers to advanced technology
  - Industry is risk-averse and cost-sensitive
  - Base load requirements differ from those for peak load systems
  - External drivers needed to promote adoption
- **Opportunities for advanced process control**
  - Designing for variations in load and operation modes
  - Variation of generation outputs such as power and fuels
  - Framework adaptive to new sensor and computational technologies and performance levels
  - Optimization at system and subsystem levels
- **Value of workshop**
  - Guidance for NETL's Advanced Research Program
  - Identification of R&D thrusts for advanced process control
  - Input from cross section of interested parties

Goal of 2007 Workshop

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

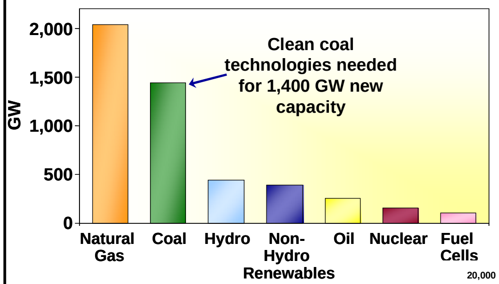
Seamless, integrated, automated, optimized, intelligent power and fuel production facilities

Workshop Objectives- Discussion/Interactions

- Assess and refine understanding of current state-of-art of process control applications in energy plants
- Respond to a vision of advanced process control systems of the future
- Refine the view developed at the 2006 workshop of process control issues, emerging trends and needs for the next 15 years
- Develop specific requirements/attributes for advanced process control systems for a range of potential near- zero-emissions fossil fuel based energy plants
- Refine opportunities identified at the 2006 workshop for process control research and development
- Develop specific requirements/attributes for an advanced process control system test bed at DOE’s FutureGen facility

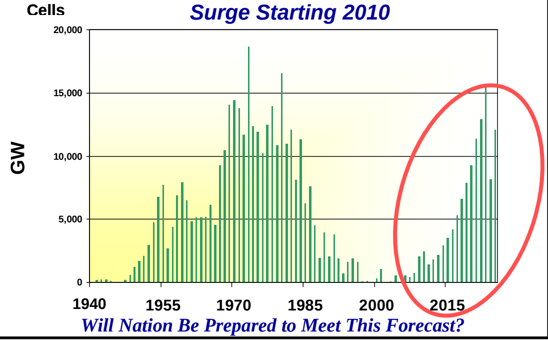
World Power Generation Capacity Additions

2000 – 2030



Process Controls Technology has the potential to greatly impact the power generation capacity and plant availability.

Coal Capacity History and Forecast
Surge Starting 2010



Will Nation Be Prepared to Meet This Forecast?

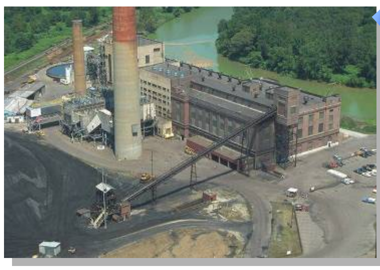
So What?

- **Putting megawatts on grid at required rates means—**
  - Getting absolute most from existing fleet
    - process optimization will play big time!
  - Getting reliable operation from new (more complex) plants
    - process control will play big time!
- **Realizing a reliable power grid is highly dependent on reliability of individual plants**

Technology Challenges

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

Near/Zero Emission Advanced Power Generation System



Mid 20th Century Plants

- Plant design
- Process modeling and control
- Operations monitoring (efficiency, emission, equipment)
- Dynamic and transient mode management
- Structural, separation, coatings, and sensing materials for harsh environmental

NETL

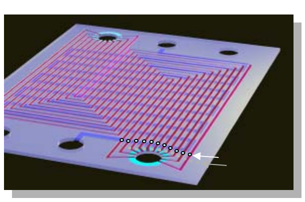
Advanced Research

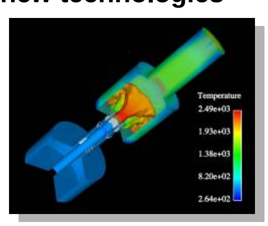
Mission

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

Bridge the gap between fundamental and applied technologies

Reflective of industry needs and responsible for driving new technologies





Develop technologies that address critical needs in Fossil Energy Programs

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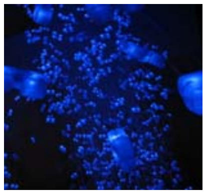
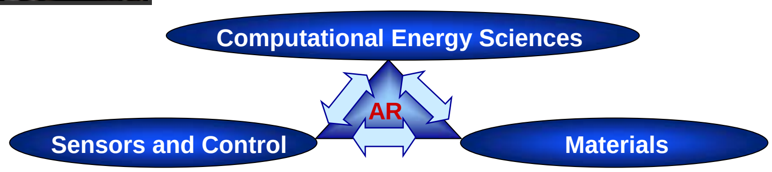
AR Focus and Goals



- **Essential and enabling technology development**
- **program for Advanced Power Systems**
- **Unique mix of programs (budgets) that are focused on that focused are critical and crosscutting technologies**
- **Enhance individual subprograms by range of collaborations and developers and integrated technology efforts**
- **Challenged with identifying novel technologies that address key technology barriers**
- **Focused technology efforts are contributing to deployment of feasible technologies in the 5-15 year timeframe as well as contribution to the FutureGen Initiative**

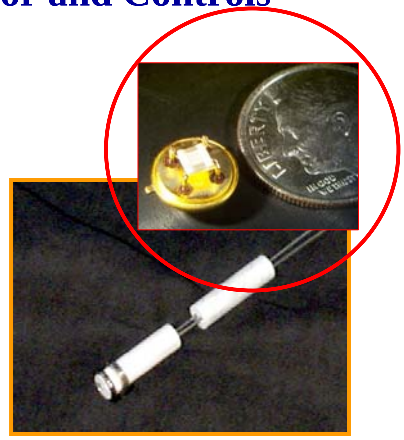


Technology Development Considerations

- **Address next generation "Near Zero Emission" power and fuels production facilities**
  - Attractive investments for the industry
  - Putting megawatts on grid at required rates
  - Performance justifies capital investment for new plants
  - Reliable operation from new (more complex) plants
    - process control will play big time!
- **Programs serve to "buy down" risk for deployment**
- **Foster development that addresses risk early on in technology development**
  - Design via CES activities
  - Construction via Materials Development
  - Operation via Sensors and Controls
- **Developments can be applied to existing fleet for improvement, repowering, life extension**
  - Getting absolute most from existing fleet
    - process optimization will play big time!

Advanced Research
Instrumentation, Sensor and Controls

- **Crosscutting technology**
- **AR is positioned to screen and accept risk**
- **Technology transfer to line programs**
- **Strong stakeholder relationships (developers and users)**
- **Desire to take whole system approach**
- **Time-phased, results driven program**
- **Direction of Program**
  - Continue with development of sensor materials, sensor designs that address a technology gap/stakeholder needs
  - Pursue computational analysis of sensor networking and integration with power systems
  - <u>Identify and initiate advanced control opportunities for advanced power generation in cooperation with CES</u>



SRD Metal Oxide Sensor
NETL Flashback Sensor

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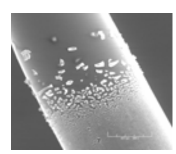
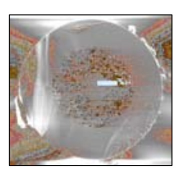
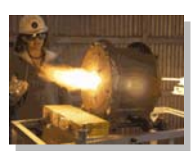
Technology Development Program

- **Sensors and Controls**
  - High Temperature Material and Sensor Designs
  - Sensors Networks and Advanced Control
- **Advanced Materials**
  - Ultrasupercritical Boilers and Turbines
  - High-strength, oxidation and corrosion resistant metallic and intermetallic alloys
  - High Performance Materials
- **Modeling and Simulations**
  - High fidelity models of potential FutureGen systems
  - Advanced power systems using mathematical computational simulations and computer-based models
  - Fuel-cell and gas turbine hybrid models







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ISCS Roadmap

Near Zero Emission Advanced Power Generation System

ISCS Program Goals

Technology Area Goals

Measurement Area Goals

- Physical Measurements	Temperature, pressure & flow for harsh environments
- Gas and Solid Measurements	Low cost gas sensors for high temperature environments Trace level contaminant detection Real time solids characterization
- Control and Condition Monitoring	Creation of artificially intelligent , integrated controls Information creation & exchange for systems management
- Infrastructure Security Monitoring	Measurement and control technology for reliability and security enhancements of related infrastructures

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Sensor and Control Program Delineation

- **Physical Measurements**
  - T,P, Flow, Strain/Stress
- **Solid and Gas Measurements**
  - Coal Quality
  - Syngas
  - >500°C targeted
- **Control and Condition Monitoring**

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

- **Sensor Networking**
- **Advanced Control**
- **System Integration**

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

NETL

Driver for New Sensing Technology

- **Advanced Power Generation:**
  - Harsh sensing conditions throughout plant
  - Monitoring needed with advanced instrumentation and sensor technology.
  - Existing instrumentation and sensing technology are inadequate
- **Coal Gasifiers and Combustions Turbines:**
  - have the most extreme conditions
    - Gasifier temperatures may extend to 1600 °C and pressures above 800 psi. Slagging coal gasifiers are highly reducing, highly erosive and corrosive.
    - Combustion turbines have a highly oxidizing combustion atmosphere.
- **Targeting development of critical on line measurements**
  - Sensor materials and designs are aimed at up to 1600 °C for temperature measurement and near 500 °C for micro gas sensors.
  - Goal is to enable the coordinated control of advanced power plants followed by improvement of a system's reliability and availability and on line optimization of plant performance.

Motivation for Developing New Sensors and Control Technology

- **Low cost, high benefit technology**
- **Existing technology is inadequate**
- **Boosts efficiency of existing facilities and significantly contributes to high reliability**

- **Supports all other power generation technologies and related infrastructures**
- **Makes operation of future ultra clean energy plants possible**
- **Enables new paradigms in plant and asset management beyond traditional process control**

Sensors and Controls Needs

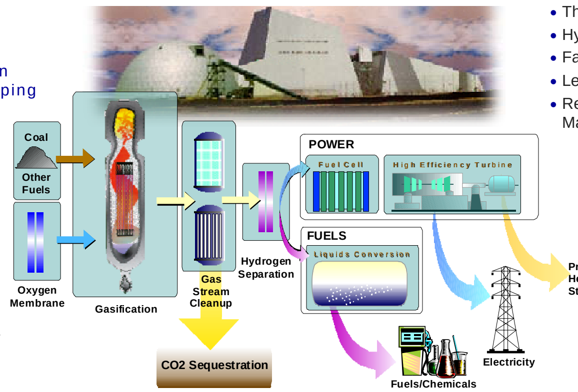
Controls
- Supervisory control
- Integrated control
- Neural nets
- Predictive, adaptive control
- Modeling

Advanced Materials
- High temperature Micro sensor materials
- Nano-derived materials

Gas Purification / Separation Environmental Control
- Mercury Trace Metals
- NOx, SOx
- Ammonia
- CO2 Monitoring

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

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



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

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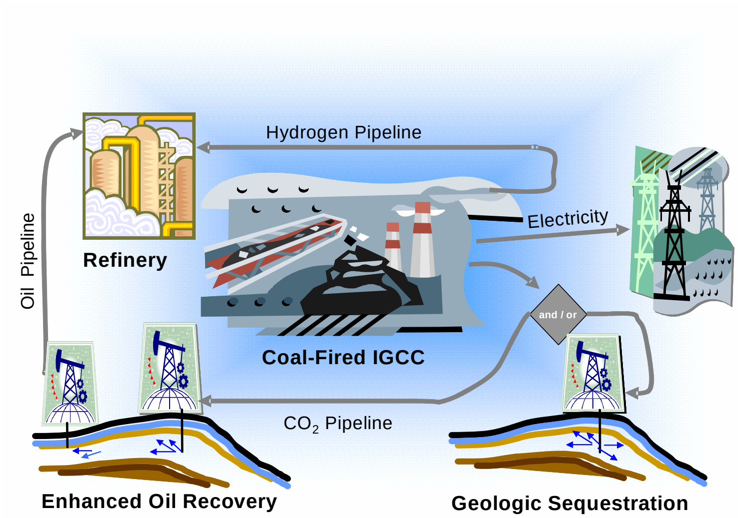
FutureGen - A "Zero Emissions" Plant

- ***FutureGen*** **will test new technologies to capture CO_2 at the power plant**
- ***FutureGen*** **will test large-scale injection into oil fields or into deep geologic formations for permanent storage**



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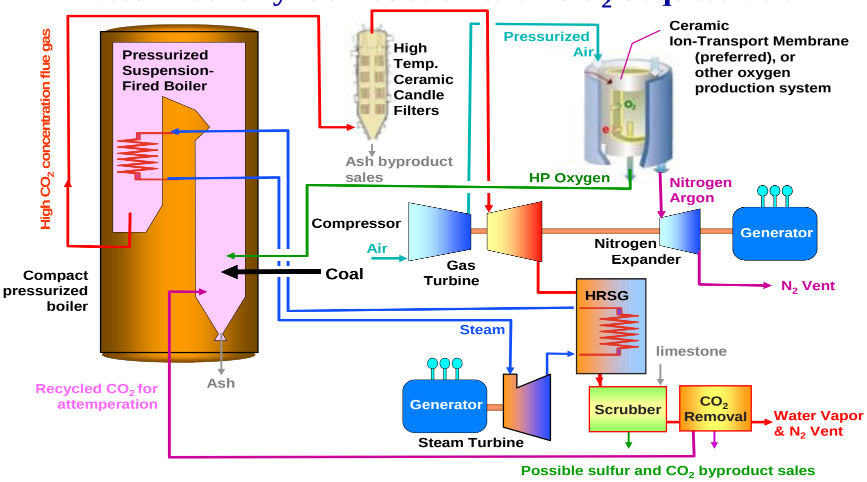
Advanced Combustion

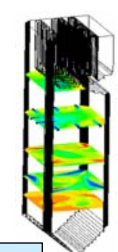
Alternative technologies that enable zero emissions and implementation of CO_2 mitigation strategies

(e.g. Ultrasupercritical/O_2 Combustion, Oxygen Combustion, Chemical Looping)

Pressurized Oxy-Combustion with CO_2 Sequestration



Condition Monitoring and Advanced Control



- **Sensor Networks**
  - Technology advancing in non FE areas including wireless
  - Sensor networks for condition monitoring expected in in 1-5 years
- **Advanced Control**
  - Link to process and component modeling for Model Predictive Control
  - DOE NETL Spring 2006 Process Control Workshop

Stakeholder feedback – build advanced control into plant by incorporating / considering it in early design phases

  - DOE Projects focused on core control of chemical looping and gasification processes
  - Optimization modules (of varying degrees) have been demonstrated
- **Challenge**
  - What data to collect, where to send it, coordinated output…. (Ames, SBIRs, GE, Alstom)

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New Control Projects Added This Year
FY07 Pending Awards

Performer	Project	Type
ALSTOM	Development of Computational Approaches for Simulation and Advanced Controls for Hybrid Combustion-Gasification Chemical Looping	Solicitation
GE	Integrated Sensing and Control for Gasification	Solicitation

New Control Projects Added This Year
National Laboratory and SBIR

Performer	Project	Type
NETL	Fuel Cell/Turbine Hybrid Control Demonstrator	National Laboratory
Ames National Lab	Power Plant Control (High Density Sensor Networks)	National Laboratory
Cybosoft	Intelligent Control of Advanced Power Generation Systems Using Model-Free Adaptive Control Technology.	SBIR
Prime Photonics / B&W	Sensor Data collection for Oxy-Combustion Control Validation	SBIR

New Control Projects Added This Year
University Awards

Performer	Project	Type
Rensselaer Polytechnic Institute	Model Predictive Control of Integrated Gasification Combined Cycle Power Plants	University
University Alliance (PITT, CMU, WVU, …)	Model based control using steady state and dynamic response	University

Summary

- **Range of measurement technologies ready for technology transfer and to focus on practical issues via large scale testing.**
- **More novel technologies approaching test stage**
- **Can capitalize on developments outside of FE for sensor networking**
- **Advanced process control can be applied using today's technology. Requires commitment to consider in early design stages for core control.**

Advanced power Systems will use Virtual Engineering to:

- Understand the interactions between individual components and plant performance
- Optimize plant components from the subcomponent level to the plant performance level
- Integrate and test sensor strategies into a new kinds of power plant
- Aid in engineering decision making including design, construction, operation, maintenance
- Explain to the public and other nations how this technology works
  - With very limited physical prototypes

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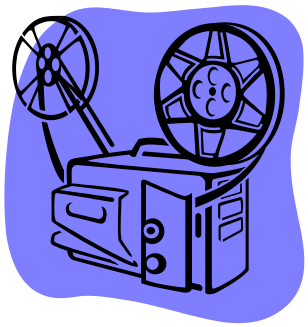
Showtime



Virtual Power Plant with Carbon Management

Backup

Instrumentation and Sensor Needs

(Input from 2001&2002 S&C Workshop)

Advanced Materials

- High temperature Micro sensor materials
- Nano-derived materials

Gas Purification / Separation Environmental Control

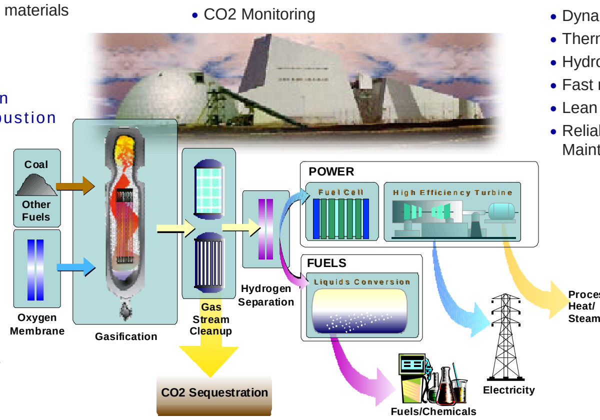
- Mercury & Trace Metals
- NOx, Sox, Nh3
- CO2 Monitoring

Turbines

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

Gasification Advanced Combustion

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

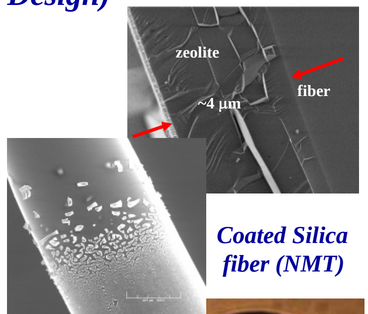


Fuel Cells

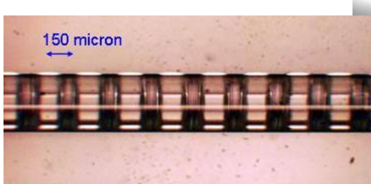
- Catalyst and anode monitoring
- Sulfur
- Reformate Quality
- Flow & Pressure
- Diagnostic Capability

Fiber-based Sensor Development
(Materials and Sensor Design)

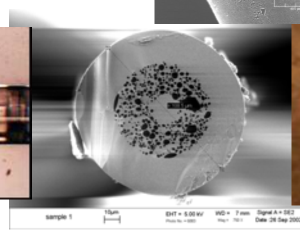
- **Silica-based fiber sensors**
  - Distributed and selective gas sensing
  - Active sensing layers
- **Sapphire-based fiber sensors**
  - Coating materials
  - Single & Multipoint sensing designs
  - Suitable for ultra high temperatures (1600°C)



Coated Silica fiber (NMT)



Distributed Gratings in Sapphire Fiber (PSU)

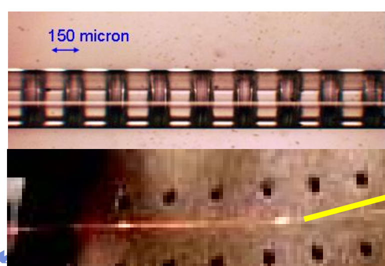


Holey Fiber (VT)

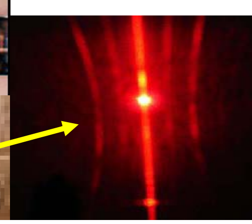
Coated Sapphire Fiber (Prime)

Distributed Sapphire Fiber Sensors
Pressure, Temperature, & Strain

- **Sapphire fibers modified with femto second lasers and/or electric arc to create gratings in the fiber.**
- **Gratings enable multiple sensor elements on a single fiber.**
- **Coated fibers for single and multipoint sensing**
- **Full scale testing planned TECO's RSC via GE and pilot scale combustion testing via B&W**
- **Distributed temperature measurements are an immediate benefit to modeling and model based control development.**

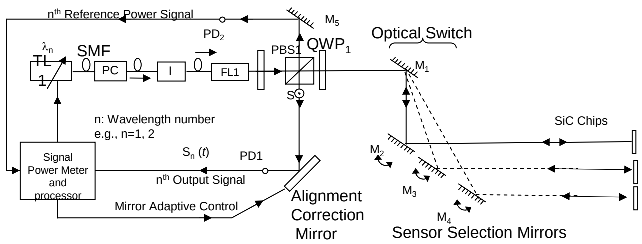


Distributed gratings on fiber



Coated fiber – end view

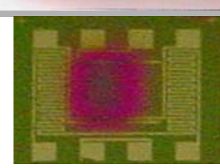
Optical , Wireless, Temperature & Pressure Sensor using SiC Chips

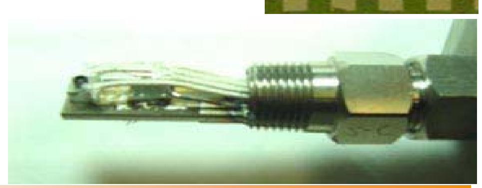


- 6H SiC Chip is thick ~ 300 micron
- Temperature: Localized Optical path length change
- Pressure: Global Wave-front Lensing - magnification change
- Tested in laboratory up to 1000 °C & 600 psi, ~1400 °C expected limit
- Prototype under development for turbine testing (FY2007 Q4)

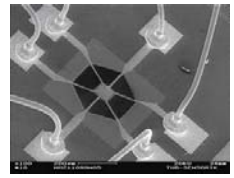
High Temperature (~500 °C) Micro Sensor Development and Testing

- **Ceramic and semiconductor substrate materials**
  - YSZ, Alumina, Silicon Carbide, etc
- **Multigas catalytic active sensing materials**
  - Single gas sensors and sensor arrays
  - NOx, NH_3, CO, CO_2, H_2, O_2, HCl, SO_2, H_2S, HCs
- **Key technology for pervasive sensing, sensor networking and advanced control**
- **Targeting low cost sensors**
  - Initial investment in sensor system and software (~20K)
  - Approximately $50 for replacement of sensor elements with 12 month targeted lifetime
- **Testing is critical**
  - Large amount of lab data demonstrating potential
  - Moving forward with pilot scale and full scale evaluations

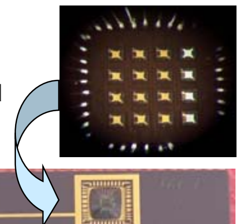




High Temperature Micro Gas Sensor Arrays

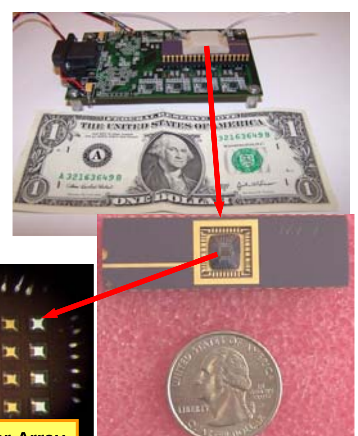
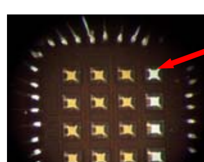
- **Technology Status**
  - Material selection is maturing
  - Backside heater design mature
  - Fabrication methods evolving
  - Lead failure an issue
  - Overall lifetime & performance being addressed
  - Optimized packaging for application is ongoing
  - Variety of algorithms exist for gas identification and quantification
- **Laboratory simulated gas testing**
  - 1-6 months under controlled/clean conditions
- **Pilot scale testing**
  - 1-3 week testing completed at PDSF
    - Accurate gas identification demonstrated
  - Turbine exhaust testing successful
  - Slated for testing in a coal combustion facility




Sensor Research and Development Corporation

Semi-Conductor Metal Oxide Sensor Arrays

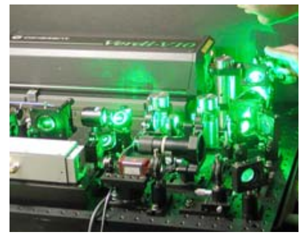
- **Develop continuous, real-time, *in situ* sensors for the detection, identification, and measurement of coal-fired combustion gases**
  - Robust (high temperature < 400°C, corrosive, etc.)
  - High sensitivity (ppb – ppm)
  - Selective detection: CO, CO_2, NO, NO_2, SO_2, NH_3, HCl
  - Customized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

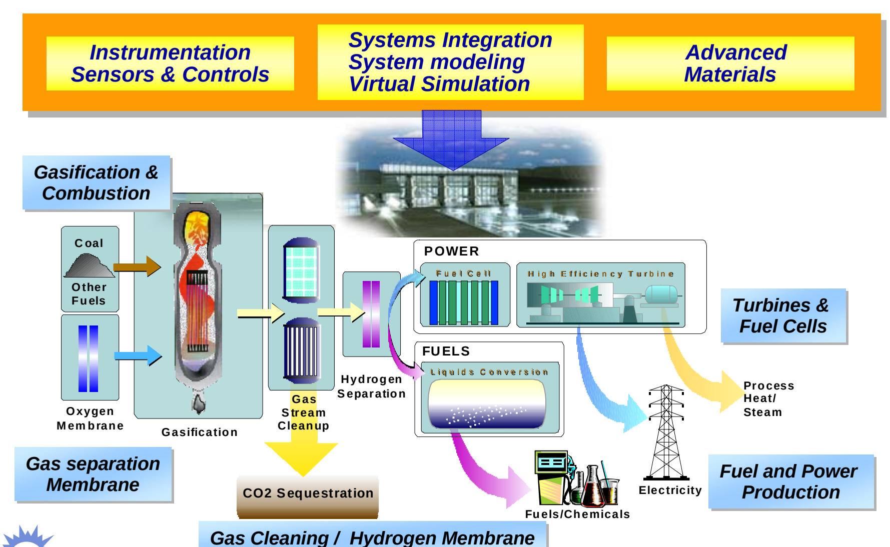
16-Sensor Array

Optical and Laser Based Techniques

- **Novel approaches for temperature and gas species monitoring**
  - Optical materials, new light/laser sources
  - Detection in pressurized vessels
  - Trace level detection
  - (NO_X, SO_X, particulate, Hg, CO, CO_2, etc)
- **Advantages with these techniques**
  - Non-intrusive, rapid, continuous measurements
  - Readily adapted for regulatory monitoring
  - Relative ease in calibration
- **Challenges with these techniques**
  - Optical access
  - Rugged, compact, field ready systems
- **Testing Completed / Underway**
  - Pilot scale coal combustion and turbine exhaust testing (NO & Hg)
  - Full scale power plant testing underway (Nueco/Pegasus CCPI2 Project)



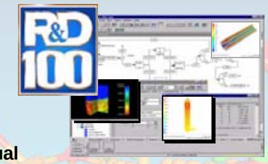
Ultra-Clean Energy Plant



Computational and Basic Sciences Focus Area

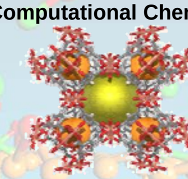
Integrate physical, chemical, and computational models as the preferred method for understanding, predicting, and developing advanced materials and multiscale energy systems from molecular-scale to device-scale to plant-scale.

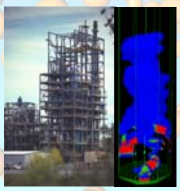
Virtual Environments Laboratory



Advanced Power Plant Simulator

Computational Chemistry

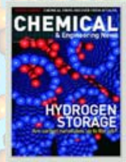




Multi-Phase Flow

Energy Infrastructure and Security Protection

Prediction of Hydrogen Flux Through Sulfur Tolerant Binary Alloy Membranes



Hydrogen Storage

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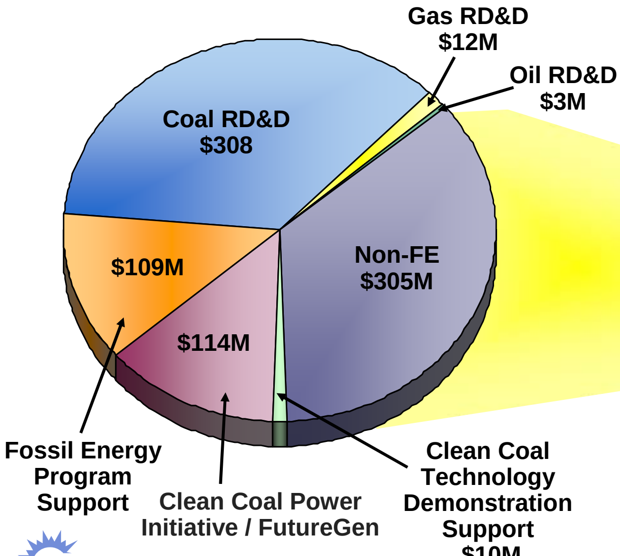
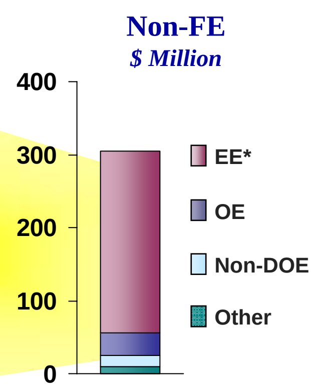
NETL FY 2007 Budget: $861 Million





NETL also financially manages ~$650M for EERE's PMC

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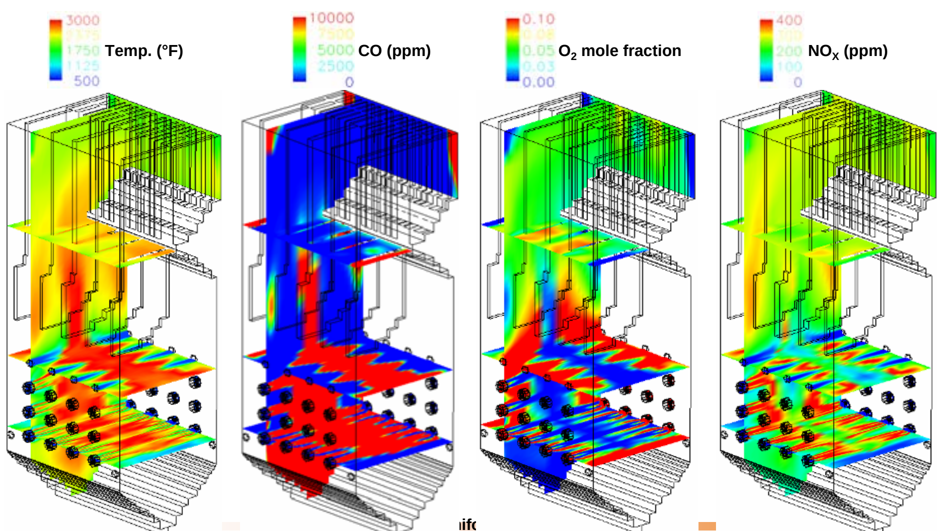
Visualization Research Group

The Visualization Research Group focuses on developing leading edge visualization software and systems to support fossil energy research

Computational Fluid Dynamics for Burner Flow Control Sensitivity

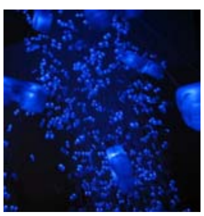


Workshop Objectives- Presentations

- Present updated overview of DOE NETL's Sensor and Control Program and progress since last workshop in March 2006
- Describe NETL's/DOE's role in supporting R&D of process control to help ensure key technologies will be available to meet the needs of future advanced power systems
- Present a conceptual view of a long range vision for future sensors and controls networks for advanced energy systems
- Present updated overview of DOE's FutureGen facility

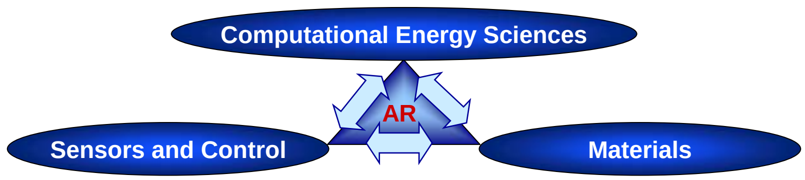
AR Focus and Goals

Essential and enabling technology development program for Advanced Power Systems



- **Unique mix of programs and technology developments that are critical and crosscutting technologies**
- **Challenged with identifying novel technologies that address key technology barriers**
- **Focused technology efforts are contributing to deployment of feasible technologies in the 5-15 year timeframe as well as contribution to the FutureGen Initiative**
- **Enhances individual subprograms by range of collaborations and developers and integrated technology efforts**

Realignment of AR Technology Focus



- **Essential and enabling technology development programs for the Strategic Center for Coal and Power R&D**
- **Focused effort will contribute to deployment of feasible technologies in the 5-15 year timeframe as well as contribution to the FutureGen Initiative**
- **Enhancement of individual subprograms by expanding collaboration, range of developers, and integrated technology efforts**

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AR Challenges and Motivations

- **Addresses both existing and next generation "Near Zero" emission power plants**
  - That serve as attractive investments for the industry
  - Putting megawatts on grid at required rates
  - Getting absolute most from existing fleet
    - process optimization will play big time!
  - Performance matches capital investment for new plants
  - Reliable operation from new (more complex) plants
    - process control will play big time!

- **Programs serve to "buy down" risk for deployment**
- **Must also foster development that addresses risk early on in technology development**
  - Design via CES activities
  - Construction via Materials Development
  - Operation via Sensors and Controls

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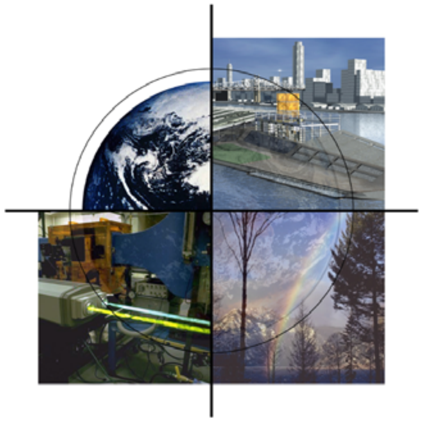
Fossil Energy Advanced Materials Program



National Energy Technology Laboratory - Process Control Workshop

Pittsburgh, PA
June 13, 2007

Robert Romanosky, Advanced Research Technology Manager
National Energy Technology Laboratory

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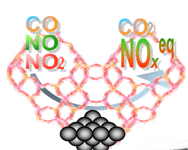
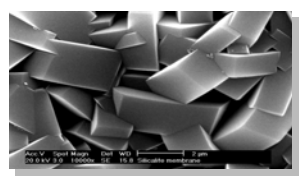
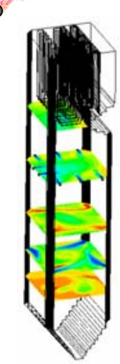
Advanced Research Crosscutting Technologies

Materials





Instrumentation, Sensors, & Controls



Computational Energy Sciences

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Drivers and Benefits of Utilizing ISCS

- **Advanced Power Generation has harsh conditions through out a plant that need to be monitored with new instrumentation and sensor technology.**
  - Coal Gasifiers and Combustions Turbines have the highest and most extreme conditions that need to be monitored for both efficiency and environmental performance.
  - Provide critical measurements that allow the conversion of fossil fuel for power generation to be optimized in real-time.
- **Reduce Total Cost of Ownership of whole systems by developing and supporting control algorithms and condition monitoring technologies**
  - Focus on improving the reliability, availability and maintainability of existing and future power systems.

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Driver for New Sensing Technology

- **Advanced Power Generation has harsh conditions through out a plant that need to be monitored with new instrumentation and sensor technology.**
  - Existing instrumentation and sensing technology are inadequate
  - Coal Gasifiers and Combustions Turbines have the highest and most extreme conditions. Temperatures for these system may extend to 1600 °C and pressures near 800 psi. Slagging coal gasifiers are highly reducing, highly erosive and corrosive. Combustion turbines have a highly oxidizing combustion atmosphere.
- **Targeting development of critical on line measurements**
  - Sensor materials and designs are aimed at up to 1600 °C for temperature measurement and near 500 °C for micro gas sensors.
  - Goal of enabling the coordinated control of advanced power plants followed by improvement of a system's reliability and availability and on line optimization of plant performance.

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Sensors and Virtual Engineering

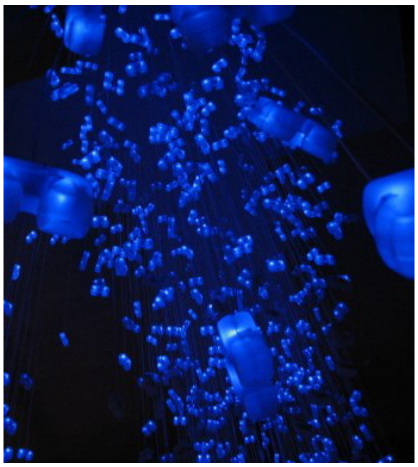
- Sensors are very small and inexpensive
- Massive real time data sets - "data storm"
- Current sensing and control strategies don't work
- A new sensor/control network strategy is needed

Virtual engineering

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

Sensor network questions

- How much onboard computing capacity?
- Tribes/families of sensors?
- Self organization - how to implement and how much?
- Self description?
- Information share - local/global - what?



Overview of the FutureGen Initiative

Tom Sarkus, Director of the Advanced Energy Initiatives Division
U.S. Department of Energy, National Energy Technology Laboratory

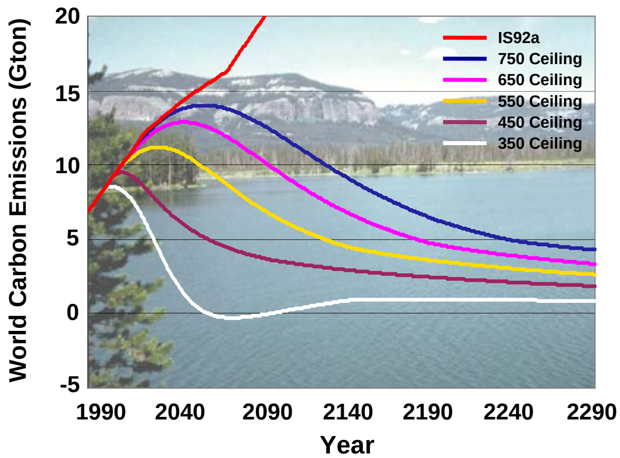
DOE's *FutureGen* Initiative

Workshop on Advanced Process Controls for Near-Zero Emission Power Plants

Pittsburgh, PA
June 13, 2007

Thomas A. Sarkus, FutureGen Project Director
National Energy Technology Laboratory

Scenarios to Stabilize CO_2 Concentrations



Example: 550 ppmv pathway requires 60% reduction from 1990 levels at steady state

*Wigley, T.M.L., Richels, R., and Edmonds, J.A. **Nature 379**, 240-243 (1996)*

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Sequestration Capacity: In Right Places?

Adequate Capacity in U.S.

2,082 Large Sources (100+ ktCO_2/yr) with Total Annual Emissions = 3.8 GtCO_2/yr

- 1,185 electric power plants
- 447 natural gas processing facilities
- 154 petroleum refineries
- 53 iron & steel foundries
- 124 cement kilns
- 43 ethylene plants
- 9 oil sands production areas
- 40 hydrogen production
- 25 ammonia refineries
- 47 ethanol production plants
- 8 ethylene oxide plants

~ 1000 Years

3,800+ GtCO_2 Capacity within 330 US and Canadian Candidate Geologic CO_2 Storage Reservoirs

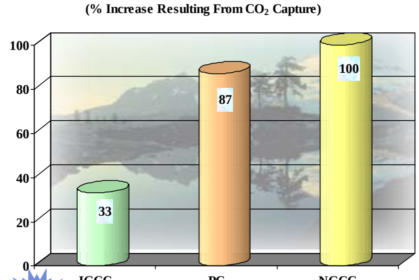
- 3,730 GtCO_2 in deep saline formations (DSF)
- **65 GtCO_2 in deep unmineable coal seams with potential for enhanced coal bed methane (ECBM) recovery**
- **40 GtCO_2 in depleted gas fields**
- 13 GtCO_2 in depleted oil fields with potential for enhanced oil recovery (EOR)

Current "Best Case" Technologies Costly

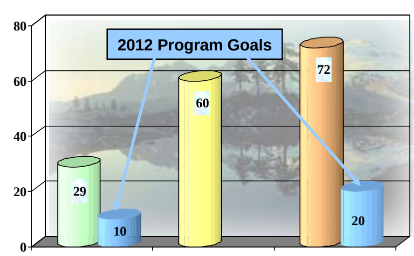
Using State-of-the-Art Scrubbing Technologies

- **5 to 30% Parasitic energy loss**
- **30 to 100% Increase in capital cost**
- ***25 to 100% Increase in cost of electricity***

Effect of CO_2 Capture on Capital Cost
(% Increase Resulting From CO_2 Capture)



Effect of CO_2 Capture on Cost of Electricity
(% Increase Resulting From CO_2 Capture)



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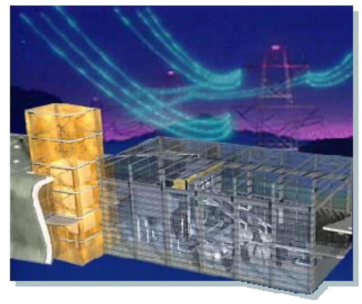
FutureGen Objectives

World's first near zero-emission, coal-based power plant to:

- **Co-produce hydrogen & electricity from coal**
- **Emit virtually no air pollutants**
- **Capture & permanently sequester carbon dioxide**
- **Integrate operations at full-scale – a key step**



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FutureGen: Technology Challenges

- **Establish technical, economic & environmental viability of "zero-emission" coal plants by 2015; thus, creating the option for multiple commercial deployments by 2020**
- **Validate DOE goals (ref. Report to Congress, dated March 2004):**
  - **Sequester >90% CO_2 with potential for ~100%**
  - **>99% sulfur removal**
  - **<0.05 lb/MMBtu NOx**
  - **<0.005 lb/MMBtu PM**
  - **>90% Hg removal**
  - **With potential for an N^{th} plant commercial cost no more than 10% greater than that of a power plant without sequestration**
- **Prototype coal-based power plant of the future**

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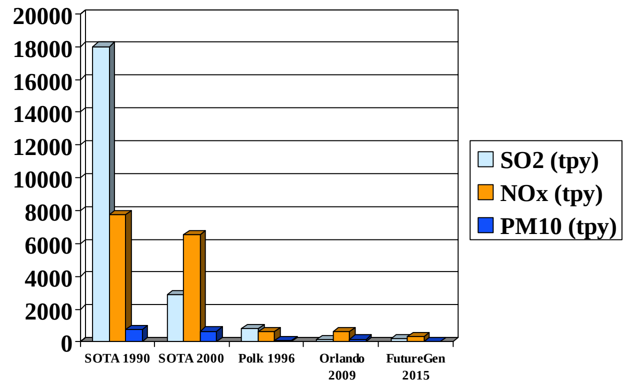
Criteria Pollutant Comparison



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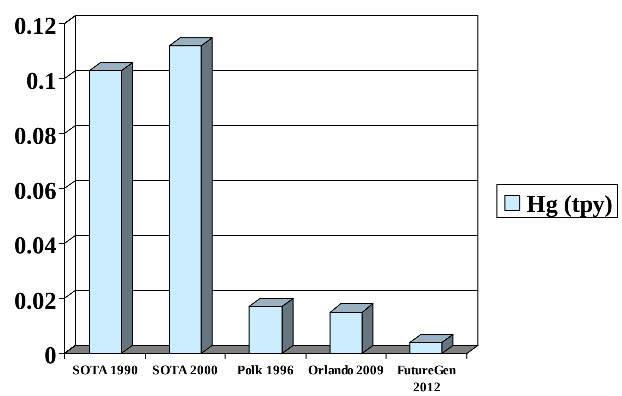
Mercury Emission Comparison



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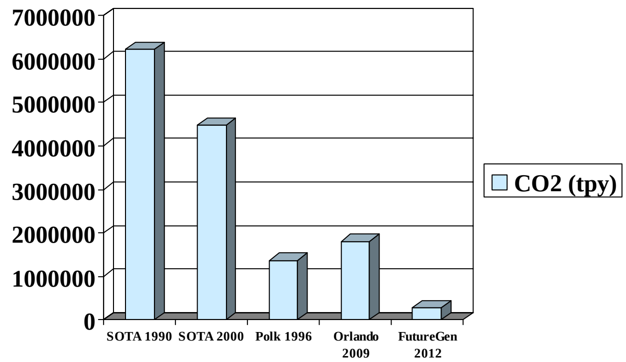
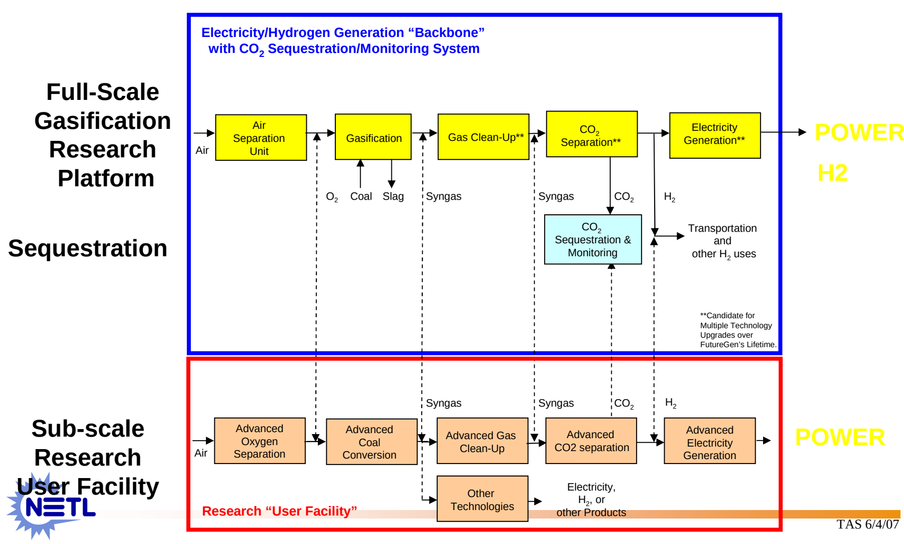
CO_2 Emissions Comparison



FutureGen: Process Features



FutureGen: Cutting-Edge Technologies

- **Can accommodate technology innovations with minimal modifications**
  - Emerging from national & international R&D pipelines
  - Slipstream or full-scale tests
  - Living R&D laboratory
- **Some emerging new technologies**
  - Membrane-based O_2 and H_2 separation
  - High-efficiency hydrogen turbines
  - High-throughput gasifiers
  - Monitoring systems
  - Fuel-cells

***FutureGen* will be a global showcase of very best technology options for coal-based systems with near-zero carbon emissions**

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Cutting-Edge Candidate R&D Technologies for *FutureGen*

Traditional Technology		Research Invention Examples
Commercial Gasifier	→ → → → → →	Advanced Transport Reactor
Cryogenic Air Separation	→ → → → →	O_2 Membranes
Gas Stream Clean-Up	→ → → → → →	Raw Gas Shift Reactor
Amine Scrubbers	→ → → → → → →	H_2 Membranes, "Clathrate" CO_2
Syngas Turbine	→ → → → → → →	Ultra-Low NO_x Hydrogen Turbine
Fuel Cell ($4,000/kW)	→ → → → → →	SECA Fuel Cell ($400/kW Design)
EOR Based	→ → → → → → → →	Sequestration Technology
Plant Controls	→ → → → → → →	"Smart" Dynamic Plant Controls & CO_2 Management Systems
System Integration	→ → → → → →	"First of a Kind" System Integration

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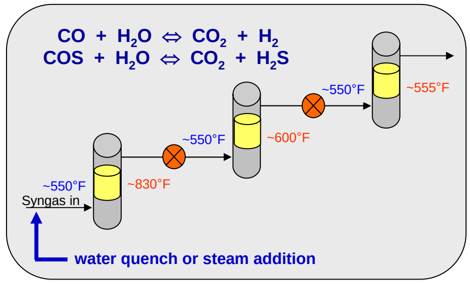
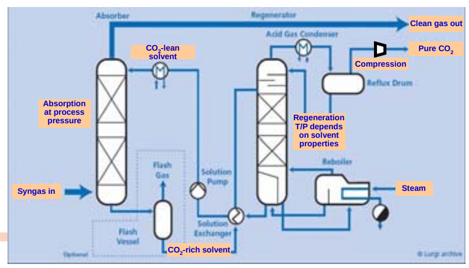
Other Required Process Operations

- **Water Gas Shift Reactors**
  - Convert CO in syngas to CO_2 & H_2

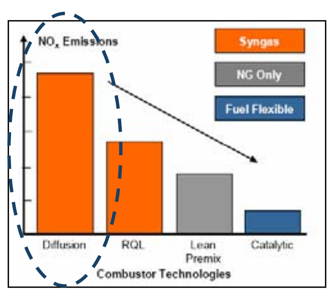


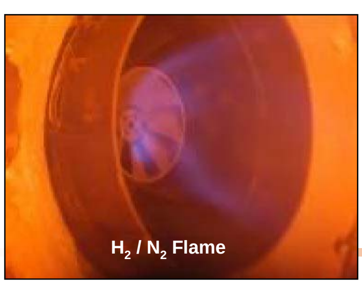
- **Carbon Separation Equipment**
  - Remove CO_2 & H_2S from H_2



H_2 Combustion Is Challenging

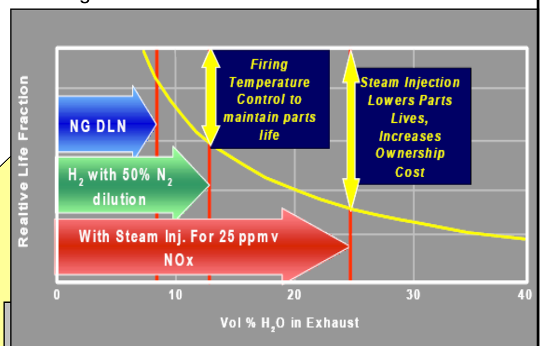
- Requires diffusion type burner due to H_2 flame speed
- Operations will require fuel flexibility
  - ➢ H_2, syngas, NG
- 15 ppm NOx is achievable with H_2 / diluent
  - ➢ Will need SCR
- **Combustor technology improvements needed:**
  - Fuel flexibility
  - Catalytic & premix based combustion





Hydrogen Fuel Affects Gas Turbine Operations

- Gas turbines are 'mass flow' machines
  - More mass throughput = more power
  - Current design geometries based on natural gas
- Fuel input is part of total mass flow through hot section
  - Changing from natural gas to H_2 affects flows and output
  - H_2 / Diluent has higher mass flow
  - Unbalanced mass flow in turbine section can impact compressor stability
- Turbine impacts of H_2 firing:
  - Higher H_2O in exhaust reduces life
  - Requires reduced firing temperatures (lost efficiency)



Gas Turbine

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FutureGen Industrial Alliance, Inc.
Signed Cooperative Agreement with DOE on Dec. 2, 2005

- **American Electric Power**
- **AngloAmerican**
- **BHP Billiton**
- **China Huaneng Group**
- **CONSOL Energy**
- **E.ON U.S.**
- **Foundation Coal**
- **Peabody Energy**
- **PPL**
- **Rio Tinto Energy America**
- **Southern Company**
- **Xstrata Coal**

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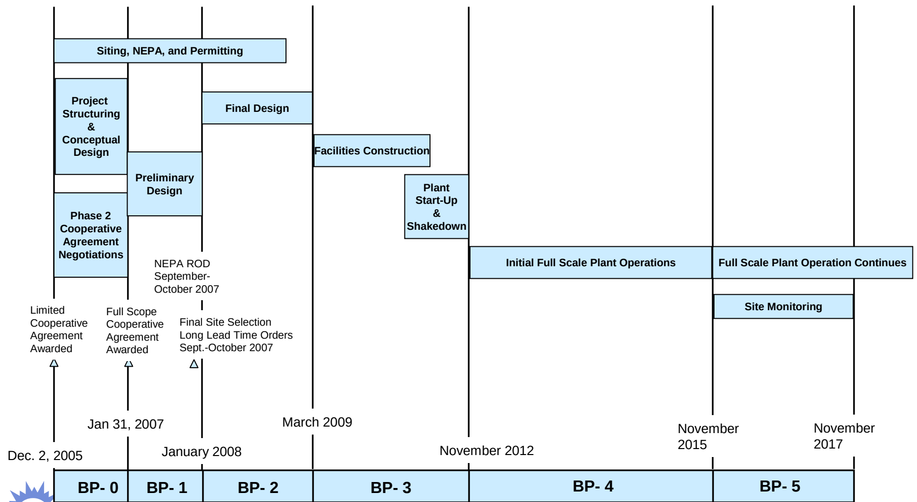
FutureGen Project Schedule



TAS 6/4/07

FutureGen: Financial Requirements

- **Government to provide $1.300 billion (as spent $)**
  - **$1,220 million from DOE Appropriations**
  - **$80 million from 8 Foreign Governments**
    - **India, South Korea, China & Japan**
- **Industry to provide $457 million**
  - **Shared equally among 12 to 15 FutureGen Alliance members**
- **FutureGen facilities to cost $1.365 billion**
  - **Plus $392 million for 3 yrs. operations & 2 yrs. add’l monitoring**
  - **Minus $301 million anticipated electricity revenues**

TAS 6/4/07

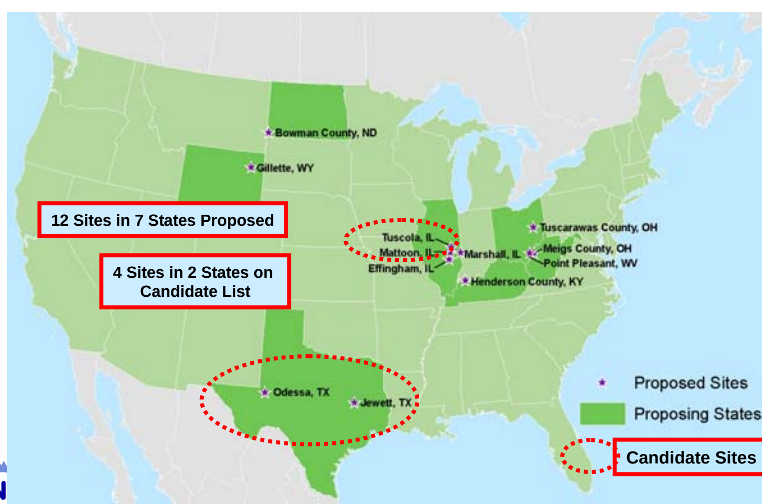
FutureGen: Current Activities

- Site Selection
  - "Final Four" were announced on July 25, 2006
  - NEPA compliance process now underway (ROD ~October 2007)
    DEIS Public Hearings:
    June 19-Midland, TX   June 21-Buffalo, TX
    June 26- Mattoon, IL   June 28-Tuscola, IL
  - Final site to be announced by November 2007

- Plant Design
  - Reviews conducted last year with major technology suppliers
  - Conceptual design & cost estimate completed for 3 configurations
  - ECM subcontractor preparing work packages for Technology RFP

- Sequestration Design
  - Reservoir modeling for each site

FutureGen: Site Selection



Conceptual Design & Cost Estimate

Design Cases

- Two Single-Trains
  - Slurry feed water quench
  - Dry feed water quench
- One Multiple-Stream Hybrid
  - 100% full slurry quench
  - 30% transport gasifier with ITM air separation
- Three coal types
  - Northern Appalachian
  - Illinois Basin
  - PRB

These are design configurations for the conceptual design & cost estimate, not the final designs. The actual designs will be established through competitive bids in 2007.

Conceptual Design & Cost Estimate

Plant Design for Fuel Flexibility

COAL SPECIFICATIONS			
	Mean Property Values		
	Northern Appalachian	Illinois Basin	PRB
AS-RECEIVED (wt%)			
Total Moisture	7	11.5	29
Equilibrium Moisture	2	7.8	27.6
DRY BASIS (wt%)			
Fixed Carbon	53.44	49.3	44.4
Volatile Matter	38.94	40.3	48.9
Ash	7.62	10.4	6.7
DRY BASIS (wt%)			
Ash	7.62	10.4	6.7
Carbon	77.67	71.6	70.3
Hydrogen	5.14	4.9	4.9
Nitrogen	1.47	1.5	0.9
Chlorine	0.1	0.19	0.01
Sulfur	2.49	3.5	0.5
Oxygen	5.51	7.87	17.2
HHV (Dry Basis), Btu/lb	13,980	13,000	12,941

Candidate Site Features

Conceptual Sequestration Design

Mattoon

- Injection on-site
- ~8,000 ft deep
- Mt. Simon sandstone formation

Tuscola

- Injection off-site (~10 miles)
- New pipeline to be constructed
- ~8,000 ft deep
- Mt. Simon sandstone formation

Brazos

- Injection at two sites (~25 and 33 miles)
- New pipeline to be constructed
- ~6,000 ft deep in the Woodbine formation
- ~11,000 ft deep in the Travis Peak formation

Odessa

- Injection off-site (~56 miles)
- Potential to use existing pipeline with minor upgrades
- ~6,000 ft deep
- Guadeloupe Sands

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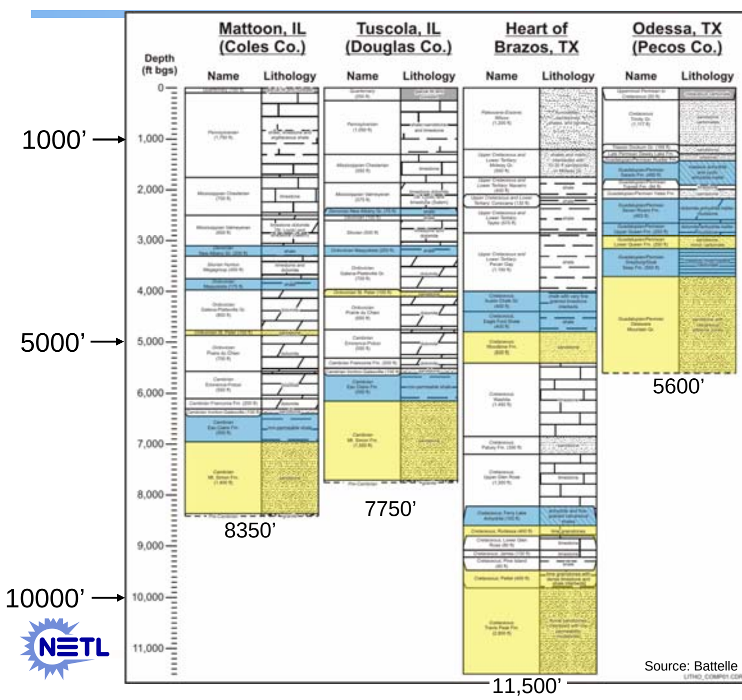

Comparison of Sites by Depth

- Seal
- Injection

Source: Battelle

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FutureGen Project

Supporting FutureGen is a Major Goal of the R&D Programs

- **A $1.8 billion, 10-year project to create the world's first coal-based, near zero-emission electricity plant with carbon capture and sequestration**
- **Industry-led project with government oversight & international participation**
  - Signed Cooperative Agreement with DOE on Dec. 2, 2005
  - Project structuring to Jan. 2007
  - Design to March 2009
  - Construction to November 2012
  - Operations to November 2015
  - Site monitoring to November 2017
- **Industry will choose project site & backbone technologies**
  - Down-selected to four potential sites

Thank You for Your Kind Attention!

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Looking Ahead: Sensor Nets, Modeling, and Decision Science

Dr. Mark Bryden, Interim Chair and Associate Professor Iowa State University,
Program Director for Simulation Modeling and Decision Science

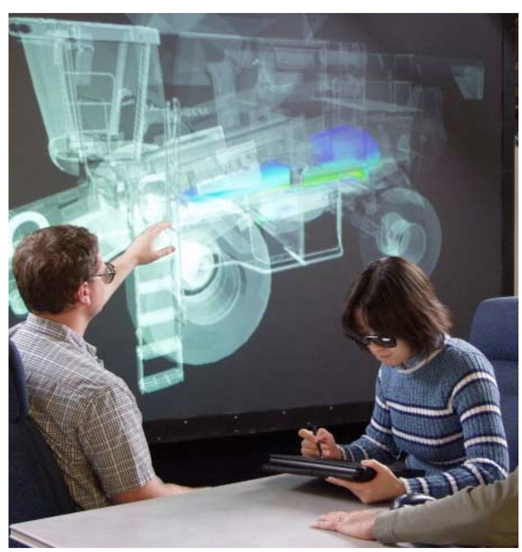
Looking Ahead:
Sensor Nets, Modeling, and Decision Science

Simulation, Modeling, and Decision Science Program

- 12 doctoral students
- 3 masters students

- 2 post docs
- 2 research scientists
- 5 contract employees
- 4-6 undergrads

- 3 professors



30 researchers

The Future

- Sensors are:
  - Small
  - Inexpensive
  - Thinking
  - Multipurpose
- Computing is:
  - Highly capable
  - Ubiquitous
- Complexity is:
  - Almost unmanagable
  - The new frontier

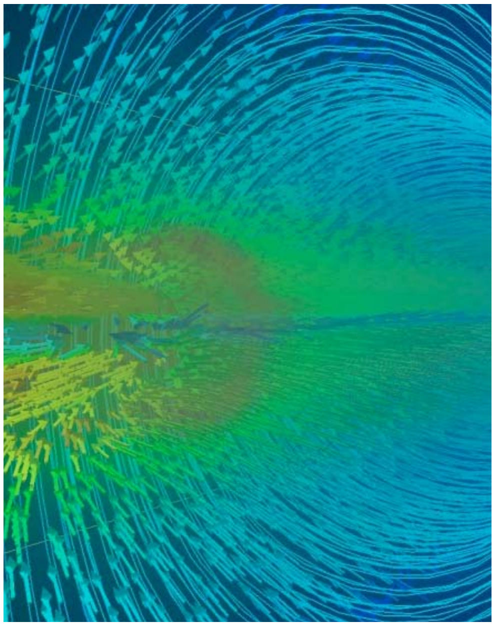
2020

- Sensors will be ubiquitous and cheap
- Sensors will be integrated into modeling and decision science
- Controls will start mean something different than what we mean today
- Engineers will still be solving problems

<u>Consumer Computer</u>

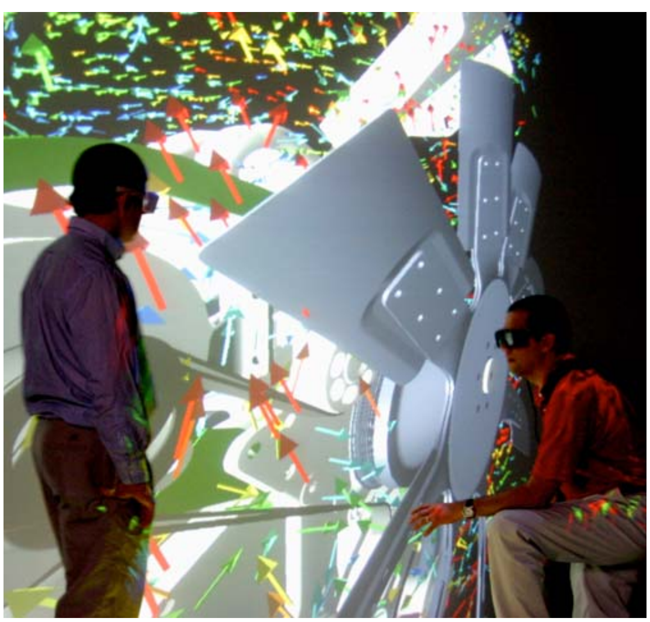
- Multi processor
- 3 Tera hz CPU
- 1/2 T of RAM
- 50 T of disk space

Questions of Interest



- How many sensors?
- What capabilities?
- Information share? Local/global?
- Models for sensor use?
- Heterogenous synchronization?

The Big Questions

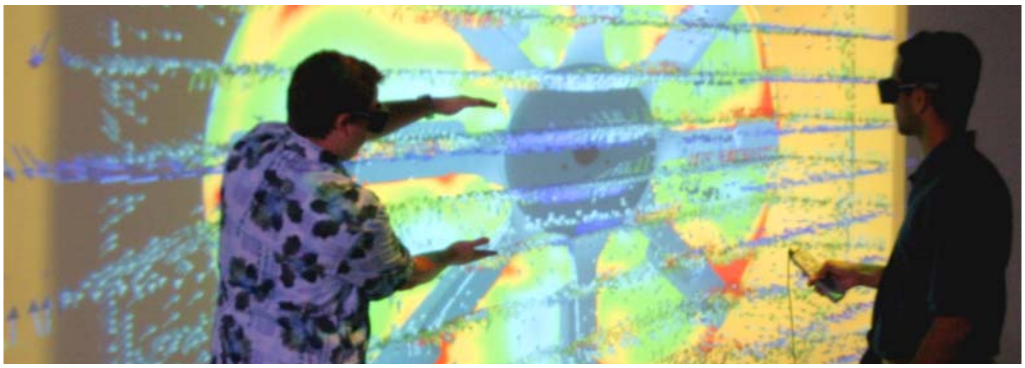


How do humans interact with sensors?

How do you make a decision?

The Goal

Decision making for complex and uncertain systems

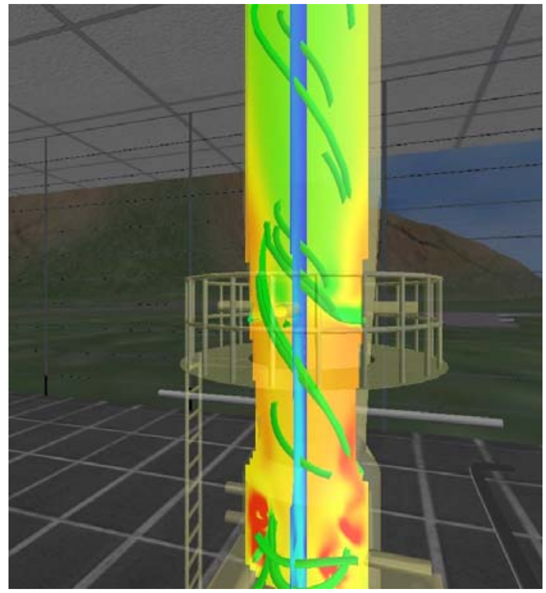


What's needed?

1. Coupling and integration of analysis codes with each other and with sensors
2. Real-time analysis
3. Multi-system analysis and optimization
4. Inverse engineering tools
5. Complexity management tools (self organization,…)
6. Explicit error control and propagation
7. A software framework for research and development

What's not on my list?

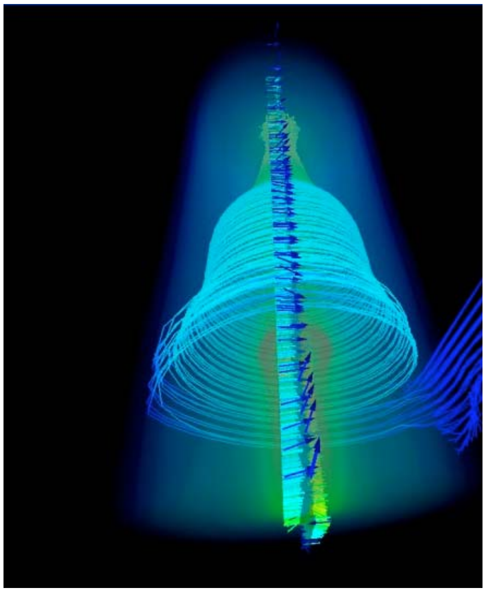
1. Better analysis
2. Virtual reality
3. More grid
4. Turbulent reacting flows
5. …



Where our research efforts are focused

1. Mathematics of integration
2. Practical Self Organization
3. Multi-system analysis
4. Inverse engineering
5. Complexity management
6. Error propagation

Roadblock…Integration



Can hardcode but…

- Must scale
- Span horizontal and vertical
- Real information remains hidden

Need engineering objects

Engineering Objects

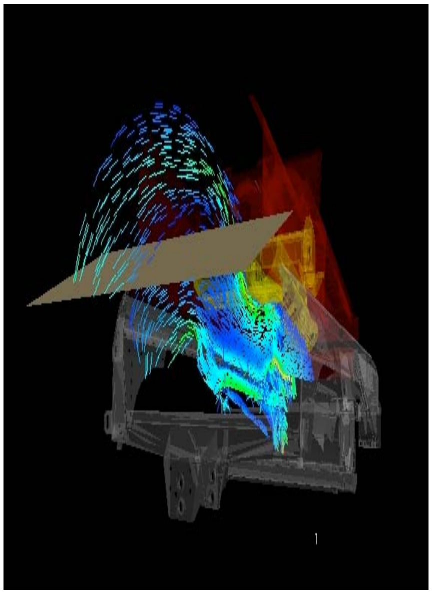
Present Objects

- Complex
- Refactor
- Map from conceptual world to programmatic world
- Resembles simulation or problem being examined

Proposed Objects

- Complex
- Refactor
- Distributed
- Self describing
- Self Organizing
- Map from physical world to virtual world

Foundation of Objects



- Michel Foucault - 1966

  Objects as the mechanism for discourse

- Object-oriented –1965 - present

  Method to manage complexity

- DOME – 1993 - MIT

  World Wide Simulation Web (WWSW)

Roadblock …
Sensor Decentralization

- Decision making occurs at a lower level
  - Components are more autonomous
  - Parallelism can be applied
    - Improved response times
- Implementation becomes more difficult
- Need mechanisms to coordinate the system activities
- Complexity Grows

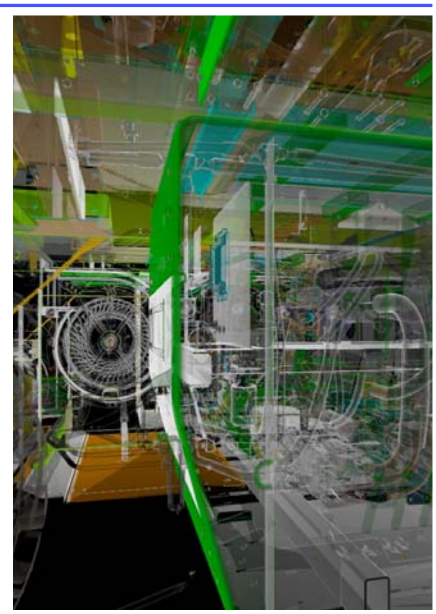
Extended Stigmergy

Stigmergy – Indirect communication of multi-agent groups through environmental elements

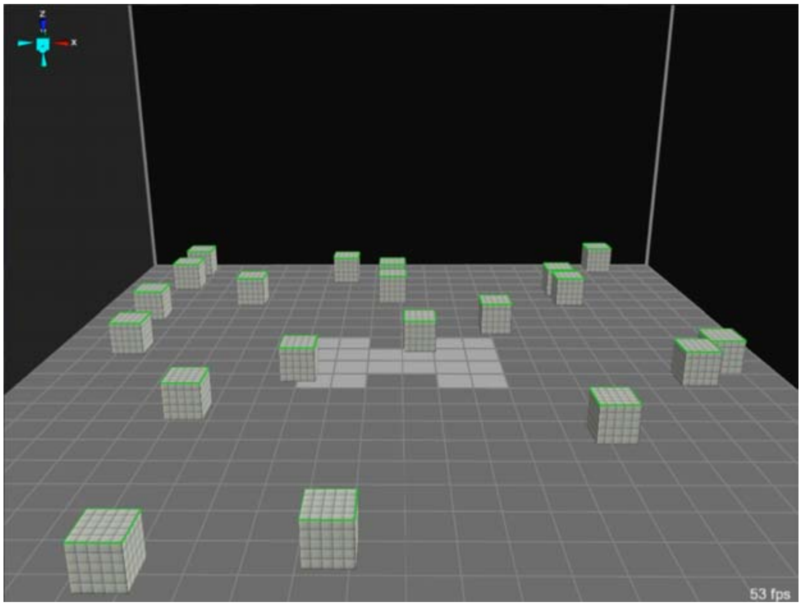
- Originally used to describe the construction of termite nests
- A potentially powerful tool for coordination

Roadblock …
Complex Self Organization

- Sensors need to self identify information based on requests and plant condition
- Multi-level self organization
- Coverage and accuracy are effected
- Real things are amzingly complex



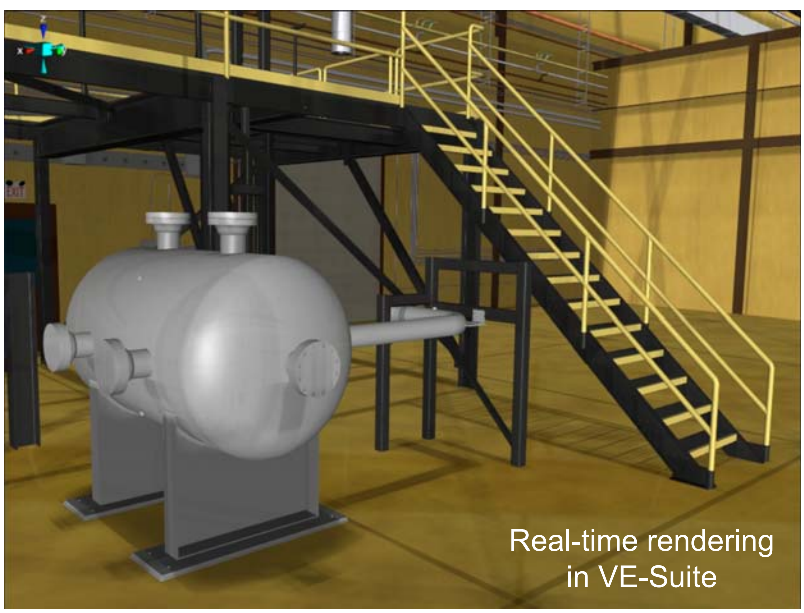
Virtual Sensor World



Where and what kind of sensors?

And when do you use them?

Applied to Real Facilities



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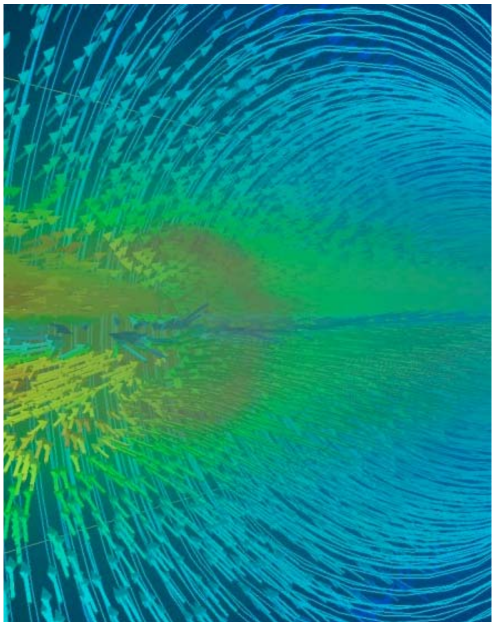

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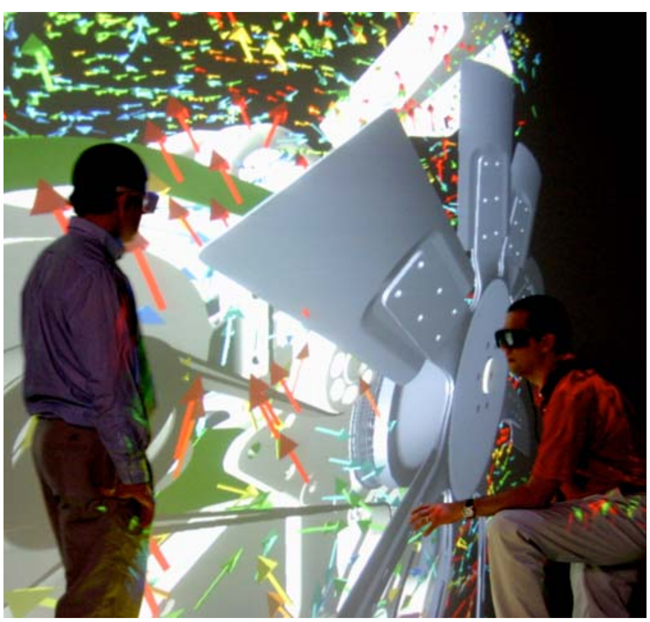

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