Vision 21
Technology Roadmap

NETL
NATIONAL ENERGY TECHNOLOGY LABORATORY

Vision 21 Technology Roadmap

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Vision 21 Technology Roadmap

Executive Summary

Vision 21 is the U.S. Department of Energy's (DOE's) new initiative for developing the technology necessary for ultra-clean fossil fuel-based energy plants, called "Vision 21 energy plants," that will be needed in the coming decades of the 21st century. The goal is to effectively remove *all* of the environmental concerns traditionally associated with the use of fossil fuels for producing electricity and transportation fuels. Achieving this goal will require an intensive, long-range (15-20 year) research and development effort that stresses innovation and commercialization of revolutionary technologies.

Vision 21 energy plants will utilize a modular design philosophy and will comprise "technology modules" selected and configured to produce the desired products from the feedstocks, which would include fossil fuels combined with opportunity feestocks, such as biomass, when appropriate. The technology modules will be based on the advanced technologies which are the focus of the Vision 21 program. These key technologies include:

- combustion and high-temperature heat exchange
- gasification
- gas purification
- gas separation
- turbines
- fuel cells
- synthesis gas conversion to fuels and chemicals
- environmental control
- materials
- controls and sensors
- computational modeling and virtual simulation
- systems analysis and systems integration

Thus, technology modules may include modules for gasifying coal and opportunity feedstocks, removing impurities from the resulting fuel or synthesis gas, separating hydrogen from the synthesis gas for use in fuel cells to generate electricity, and producing additional electricity from the energy remaining in the fuel cell exhaust using gas turbines.

The Vision 21 program aims to develop these key, critical technologies needed to design and build Vision 21 energy plants. Specific types of plants or plant configurations are not emphasized because it is unknown what kinds of plants, feedstocks, and products the market will favor 15-20 years into the future. The program approach includes emphasizing innovation and revolutionary improvements, involving stakeholders in the planning process, producing early benefits (technology "spinoffs"), and stressing flexibility to meet market needs.

Planning for the Vision 21 program has thus far centered upon two industry roadmapping workshops. The first, held in Pittsburgh, PA in December 1998, resulted in a consensus among industry, academia, and DOE participants about which technologies would be key to Vision 21 energy plants, regardless of the specific types or configurations of plants that may be built. These are the technologies listed above.

The product of the second industry workshop, held at the University of Maryland in August 2000, was a series of technology roadmaps that provided, for each Vision 21 technology, (i) a breakdown of each technology into its principal R&D areas, e.g., fuel cell technology was subdivided into the areas of fuel cell stacks, gaseous fuel processing, power conditioning, and balance of plant; (ii) performance and cost objectives including a comparison with the performance of current technology; (iii) obstacles or barriers to achieving the objectives; (iv) the current status of R&D towards overcoming the barriers; and (v) an approach or strategy for overcoming the barriers grouped into near-term (0-5 years), mid-term (5-10 years), and long-term (10-15 years) categories. The technology roadmaps developed during the workshop were reviewed by NETL product managers working with the Vision 21 Team. The result is the series of detailed technology road-maps that are provided in the Appendix.

Summary descriptions of the technology needs for each key Vision 21 technology and a review of current activities are provided in the "Vision 21 Technologies" section of this document. However, for detailed descriptions and prioritization of technology needs and R&D strategies, the reader is referred to the Appendix.

The distinguishing feature of all Vision 21 projects and activities is that they contribute to the technology base needed to design the Vision 21 energy plant. Although Vision 21 projects span a wide range of technology areas, they are not unrelated. On the contrary, each Vision 21 project and activity contributes in some way toward the design of the 21st century ultra-clean energy plant.

NETL is planning a continuing series of specific, focused workshops in the Vision 21 technology areas. Each of these workshops will focus on a single Vision 21 technology or on a small group of related technologies, e.g., gasification and gas cleanup. The purpose of the workshops is to provide opportunities to share R&D results, update and refine the technology roadmaps, and maintain industry interest and involvement. The Vision 21 Technology Roadmap will provide the basis for future solicitations and other activities identified in the Roadmap.

Vision 21 provides a range of benefits to the public. For example, by removing environmental barriers to fossil fuel use, Vision 21 expands our energy resource options. Because near-zero emissions will be achieved independent of fuel type, integrated use of energy resources is encouraged, i.e., the use of energy feedstocks can be optimized to maximize efficiency, and minimize environmental impact and cost. Vision 21 increases the electricity supply and reduces cost. Resolving environmental issues mitigates plant siting concerns and allows the use of lower-cost feedstocks and technologies.

As concluded by the National Research Council, if the ambitious Vision 21 goals can be achieved, "the United States, and the world, will have new methods of fossil-based power generation that would have significant advantages over current methods."[1]

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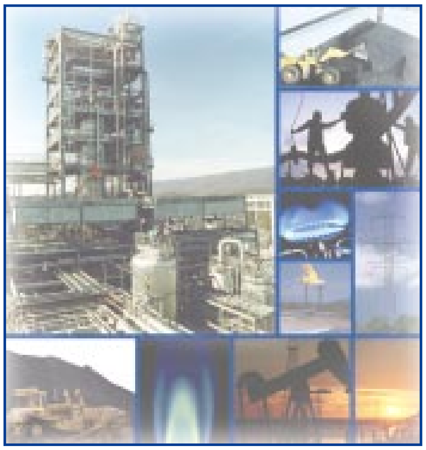
[1]National Research Council, Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes, "Vision 21, Fossil Fuel Options for the Future," National Academy Press, Washington, D.C., 2000.

Vision 21 Technology Roadmap

Overview

Vision 21 is the U.S. Department of Energy's (DOE) new initiative for developing the technology necessary for ultra-clean fossil fuel-based energy plants that will be needed in the coming decades of the 21st century. The goal is to effectively remove *all* of the environmental concerns traditionally associated with the use of fossil fuels for producing electricity and transportation fuels or chemicals. Achieving this goal will require an intensive, long-range (15-20 year) research and development effort that stresses innovation and revolutionary technologies. If Vision 21 is successful, the United States, and the world, will have new methods of fossil-based power generation that would have significant advantages over current methods.

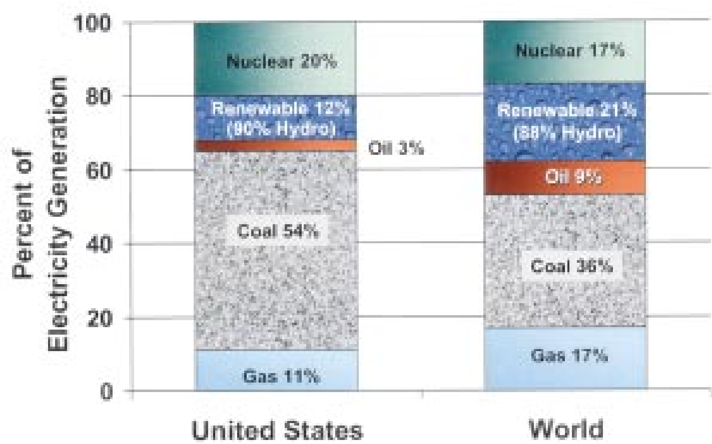


Energy use is growing. In the U.S., total energy consumption is projected to increase from 96 to 127 quads (1 quad = 10^{15} Btu) between 1999 and 2020, an average annual increase of 1.3 percent[1]. Worldwide, energy growth is more dramatic; the projection for world energy consumption is for a 60% increase over the period from 1997 to 2020, or about a 2.6 percent annual increase. In the developing countries, including Asia, the Middle East, Africa, Central and South America, the increase is much higher, about 6.5 percent annually[2].

The U.S. and the rest of the world depends on fossil energy. An important driver for Vision 21 is the recognition that fossil energy will continue to be a substantial part of the future energy mix (see box for other Vision 21 drivers, next page). The United States needs Vision 21 because fossil fuels are our dominant energy source and are likely to remain so well into the 21st century. Fossil fuels account for about 85% of our primary energy sources. Non-fossil sources cannot be ignored and include nuclear (about 8%), hydro (about 4%), biomass (about 3%), and combined solar, wind, and geothermal (about 0.6%). Worldwide the situation is very similar, with 86% of the world's primary energy supply based on fossil fuels.

Fossil fuels dominate electricity generation, both in the U.S. and the world. About 70 percent of the electricity in the U.S. is generated with fossil fuels, about 80 percent of which is coal. Over 60% of the world's electricity is generated with fossil fuels.

Fossil Fuels Dominate Electricity Generation



The most likely scenario for the future is that fossil fuels continue to provide most of the increase in energy demand. The reason for this is that there is no replacement over the foreseeable future. Renewable energy will increase, but not nearly enough to significantly offset fossil fuels. Unless there is a major change in public attitudes, political and nuclear proliferation issues make it unlikely that nuclear power will contribute significantly to growing energy demands.

[1] Annual Energy Outlook 2001, Energy Information Administration, U.S. Department of Energy, Washington, DC 20585, December 2000
[2] International Energy Outlook 2000, Energy Information Administration, U.S. Department of Energy, Washington, DC 20585, March 2000

Environmental concerns associated with the continuing use of fossil fuels must be addressed. The Clean Air Act of 1970 and subsequent amendments have brought about major reductions in emissions of the acid gases, i.e. sulfur and nitrogen oxides, and particulate for new coal-fired power plants. Existing plants are increasingly being required to cut emissions. Many of the improvements are the result of technology developed and demonstrated in the Department of Energy's fossil energy R&D programs and the Clean Coal Technology Demonstration program. Moreover, renewed concern about fine particulate and its precursors (nitrogen and sulfur oxides), trace element emissions (especially mercury), and ozone (and its nitrogen oxides precursor) have created new pressures for cleaner plants. These pressures are unlikely to ease in the future; rather, each new generation of power plants will be expected to be cleaner than the last.

Vision 21 Based on 3 Premises

- We will need to rely on Fossil Fuels for electricity and transportations fuels well into the 21st Century
- It makes sense to rely on a diverse mix of energy resources rather than on a limited subset of resources
- Better technology can make a difference in meeting environmental needs at acceptable cost

Perhaps the biggest change will be driven by concern over global climate change. Emissions of greenhouse gases, especially CO_2 from fossil fuel use, may need to be reduced in the future. Although a portion of this reduction may be achieved through emissions trading and credits for investing in emissions reduction projects in developing countries, it is likely that substantial reductions in carbon emissions will be necessary. Increasing the efficiency of power generation is a step in the right direction, but a technological solution that would provide sufficient reductions in carbon emissions has yet to be identified.

Vision 21 Drivers

- Growing demand, particularly for electricity, both in the U.S. and worldwide
- Recognition that fossil energy needs to be a part of the future energy mix
- Concern about the environment, including global climate change
- Restructuring of the energy industry with new players open to multiple feedstocks and products, and an underinvestment in research and technology development
- Uncertain natural gas prices
- Recognition of the value of "future options," such as the hydrogen economy

Vision 21

Vision 21 is a government-industry-academia collaboration to effectively remove all environmental issues associated with the use of fossil fuels. The approach is to achieve "breakthrough" improvements in the key technologies that will be needed to build ultra-clean Vision 21 energy plants during the early decades of the 21st century. A suite of technology subsystems, or "modules," will be developed that will be the building blocks of Vision 21 plants. These modules will be interconnected in different configurations to utilize fossil fuels and "opportunity" feedstocks and produce market-driven products. The feedstocks, products, plant configuration and size, and environmental controls will be site specific and determined by prevailing market and economic conditions. Because no one knows just what future energy plants will be like, technology development and modular design is emphasized in order to offer plant designers maximum flexibility while minimizing plant design and fabrication costs.

Vision 21 is fundamentally different from the traditional DOE Fossil Energy R&D program to develop improved power system technology. The traditional approach addresses different areas of power technology separately. However, any *single* approach, e.g., gasification combined cycle, advanced turbines, fuel cells, advanced pulverized coal combustion, indirectly fired cycles, and pressurized fluidized bed combustion, cannot achieve the efficiency, environmental performance, and economic performance that will be needed in Vision 21 plants. Where Vision 21 differs from the current R&D portfolio is that Vision 21 aims to *integrate* multiple advanced technologies in order to create systems that achieve breakthrough improvements in performance and cost. Other differences are Vision 21's emphasis on market flexibility, multiple feedstocks and products, and industrial ecology.

Vision 21 Benefits

- **Removes environmental barriers to Fossil Fuel Use**
  - Smog- and acid-rain-forming pollutants
  - Particulate and hazardous air pollutants
  - Solid waste
  - Carbon dioxide
- **Keeps energy costs affordable**
  - Wide range of low-cost Fossil Fuel options available
- **Produces useful coproducts including transporation fuels**
  - Reduces reliance on imported oil and stabilizes oil prices
  - Improves our international balance of trade
- **Continues U.S. leadership role in clean energy technology**
  - Promotes export of U.S. fossil energy and environmental technology, equipment, services
- **Provides the most certain route to achieving our energy, environmental, and economic objectives**
  - Technology innovation is the best way to address the challenges to our electric power and fuel supply infrastructure

Vision 21 is an industry-driven program. Industry involvement, beginning at the planning stages, was actively sought in order to build the commitment needed and to help ensure market relevance of new technologies that are pursued. The technology roadmaps in this document are largely the result of cooperative DOE-industry activities that included two industry workshops. Because of the cross-cutting nature of Vision 21, the range of the kinds of industrial firms in Vision 21 is very broad and includes large and small manufacturing and service corporations, R&D firms, energy (including electricity) producers, software developers, and others. Academia, of course, also needs to play a major role, as do national laboratories and other government organizations. Cost-sharing by industry is also part of the Vision 21 program.

The Vision 21 Energy Plant

The Vision 21 energy "plant" is actually not a single plant or single type of plant configuration. Rather, the Vision 21 energy plant is a group of plants based on advanced technologies and with different configurations that are tailored to meet specific market needs. In most cases, the primary or only product will be electricity, but other products such as clean transportation fuels, chemicals, syngas, hydrogen, and steam, might also be produced in locations where there is a market need and it makes economic sense. The feedstocks into a Vision 21 plant would be a fossil fuel, typically coal or natural gas, or a combination of the two. Alternative feedstocks would be used where and when they are available at the right cost.

Vision 21 Energy Plant Performance Targets

Efficiency-Electricity Generation	60% for coal-based systems (based on fuel HHV[1]); 75% for natural gas-based systems (LHV[1])
Efficiency-Fuels Only Plant	75% feedstock utilization efficiency (LHV) when producing fuels such as H_2 or liquid transportation fuels alone from coal
Environmental	Atmospheric release of: < 0.01 lb/million Btu sulfur and nitrogen oxides, < 0.005 lb/million Btu particulate matter < one-half of emission rates for organic compounds listed in the "Utility HAPS Report"[2] < 1 lb/trillion Btu mercury 40-50% reduction of CO_2 emissions by efficiency improvement, essentially 100% reduction with sequestration
Costs	Aggressive targets for capital and operating costs and RAM[3]; products of Vision 21 plants must be cost-competitive with other energy systems with comparable environmental performance, including specific carbon emissions
Timing	Major benefits from improved technologies begin by 2005; designs for most Vision 21 subsystems and modules available by 2012; Vision 21 commercial plant designs available by 2015

[1] HHV = higher heating value   LHV = lower heating value
[2] *Study of Hazardous Air Pollutant Emissions from Electric Utility Steam Generation Units - Final Report to Congress,* Volume 2, EPA-453/R-98-004b, 1998
[3] Reliability, Availability, and Maintenance

Thus, "opportunity" feedstocks such as biomass, municipal waste, and petroleum residues, could be utilized in many applications.

Vision 21 energy plants will utilize a modular design philosophy and will comprise "technology modules" selected and configured to produce the desired products from the feedstocks. The technology modules will be based on the advanced technologies which are the focus of the Vision 21 program.

Thus technology modules may include modules for gasification, combustion, gas separation and purification, high-temperature heat exchange, fuels and chemicals production, and power generation.

Vision 21 plants will likely be large stand-alone facilities, generally larger than 30 MWe. They may be central station facilities or be integrated with industrial or commercial operations. Small distributed power generation is not considered to be part of Vision 21, although near-term spin-off applications for distributed power may occur and Vision 21 plants could be designed as an integral part of a distributed power system concept.

Vision 21 plants will have near-zero emissions (see box on previous page). Carbon dioxide emissions will be reduced compared to conventional energy plants as a result of the higher thermal efficiencies of Vision 21 plants. Most Vision 21 plants will also be "sequestration ready." This means that it will be relatively simple and inexpensive to separate nearly pure CO_2 from the gases leaving the plant. Such a characteristic of Vision 21 plants might be achieved by using oxygen in place of air in either gasification- or combustion-based plants.

The Vision 21 Program

Vision 21 focuses on developing the key, critical technologies that will be needed to design and build Vision 21 energy plants. Specific types of plants or plant configurations are not emphasized because it is unknown what kinds of plants, feedstocks, and products the market will favor 15-20 years into the future. DOE has no intention of imposing on the market any preselected approaches, technologies, or kinds of plants.

The Vision 21 program elements are systems analysis and systems integration, enabling technologies, supporting technologies, and plant design (see box below).

Vision 21 Program Elements

Systems analysis will be used to develop reference configurations that satisfy the Vision 21 performance targets, define performance targets for individual subsystems ("modules") and components, identify technology needs, determine costs of Vision 21 plants, and analyze market trends.

Systems integration know-how will be used to combine high-performance modules and components into very clean, efficient, reliable, low-cost energy plants.

Enabling technologies, like gasification and advanced combustion, form the building blocks of Vision 21 plants.

Supporting technologies, like computational modeling and virtual simulation, are cross-cutting technologies that are necessary for the development and design of Vision 21 modules, components, and complete plants.

Plant designs will be developed for prototype and commercial Vision 21 plants. Designs will also be produced for plant modules and components.

Vision 21 Technology Roadmap

Program Approach

- Focus on key technologies and systems integration
- Stress innovation and revolutionary improvements
- Involve stakeholders
- Produce early benefits ("spinoffs")
- Emphasize flexibility to meet market needs

The products of the Vision 21 program will be the technology basis for Vision 21 energy plants, improved design and simulation tools, and "spin-off" technologies that would have various, including non-energy, applications.

Technology basis for Vision 21 plants. The primary product would be designs for modular subsystems and components and systems integration know-how needed to design and build complete plants. Reference plant concepts will be created to evaluate plant performance and develop systems integration knowledge.

Improved design and simulation tools. Design, optimization, and visualization software, including the virtual simulation capability, will be available for Vision 21 and other energy and non-energy applications.

Spin-off technologies. These include low-cost oxygen and hydrogen separation technology, gas cleaning and purification technology, better catalysts for producing fuels and chemicals from low-valued raw materials, more efficient lower cost environmental control technology, and improved materials for service under aggressive high-temperature conditions (see box below).

Time line for Vision 21 Spin-offs

2003
- 60% efficient fuel cell-turbine hybrid system demonstrated

2004
- High-temperature (2,300°F) air heater 1,000-hour test
- Improved materials for high-temperature service

2005
- Computer visualization integrated with scientific and engineering simulations
- Computer design and simulation tools

2006
- Prototype air separation module tested

2007
- Advanced $PM_{2.5}$ control technology ready for implementation of more stringent PM standards

2008
- Commercial air separation membranes provide low-cost oxygen
- Advanced fuel-flexible gasifiers commercial
- Advanced turbine technology available

2010
- Hydrogen separation membranes provide low-cost H_2 for power and fuels processing
- Ultra-high temperature (3,000°F) air heater tested
- 70% efficient fuel cell-turbine hybrid system demonstrated

Management Approach and Business Strategy

Vision 21 is a long-range, cost-shared, industry-driven R&D program designed to produce public benefits from the present to 2015 and beyond. Planning is a cooperative effort of the DOE Office of Fossil Energy and the National Energy Technology Laboratory (NETL), other DOE organizations and national laboratories, state and local government, universities, and private industry.

Implementation

To implement Vision 21, partnerships and linkages are being created with industry, universities, private and public R&D laboratories, and federal and state agencies. NETL plans to issue a series of competitive solicitations, create consortia, and develop CRADAs and other agreements. The initial Vision 21 solicitation, titled "Development of Technologies and Analytical Capabilities for Vision 21 Energy Plants," was issued on September 30, 1999, and remained open for a one-year period that included three separate closing dates for proposal submissions. Program areas of interest were intentionally kept broad in order to encourage creativity and innovativeness by allowing potential offerors maximum flexibility. Thirteen projects have been awarded as of January 2001 and additional selections are anticipated during the second quarter of fiscal year 2001. These projects have a combined value of $32 million, of which $24 million is provided by DOE.

The Vision 21 program comprises not only the projects that resulted from the above solicitation and that will result from future Vision 21 solicitations, but also the ongoing activities in traditional R&D program areas. Ongoing activities which are oriented towards achieving revolutionary, rather than evolutionary, improvements in performance and cost, and share common objectives with Vision 21, are effectively Vision 21 activities. For example, in the fuel cells program area, development of advanced fuel cell/turbine hybrids with 70-80% efficiencies is a Vision 21 activity whereas molten carbonate fuel cells for distributed generation applications is not. In the gasification program area, development of ion-electron conducting membranes for separating oxygen from air is clearly a Vision 21 activity; improving fuel gas desulfurization sorbents is not.

The distinguishing feature of all Vision 21 projects and activities is that they contribute to the technology base needed to design the Vision 21 energy plant. Although Vision 21 projects span a wide range of technology areas (e.g., see box "Key Vision 21 Technologies"), they are not by any means unrelated. On the contrary, each Vision 21 project and activity contributes in some way toward the design of the 21st century ultra-clean energy plant.

The Vision 21 Technology Roadmap will provide the basis for future solicitations and other activities. Future procurements are likely to be focused on specific technology needs identified in the Roadmap. Individual technology roadmaps will be kept up to date by implementing a continuing series of Technology Workshops. Each workshop would focus on a single Vision 21 technology, such as gasification, gas separation, virtual simulation, or systems integration. Innovation and "out-of-the-box" thinking would be strongly emphasized. These workshops will provide an instrument for investigators working in the same technology area to communicate the results of their projects, to exchange the latest ideas and views about technology advancements, and to review and revise the technology roadmaps. Vision 21 Program Reviews will also be held periodically. The Program Reviews will provide an opportunity for teams of Vision 21 investigators to exchange information about all of the technologies important to the Vision 21 energy plant.

Program Activities

The Vision 21 program includes the development of subsystems (technology modules such as turbines, fuel cells, gasification systems), components (e.g., heat exchangers, pumps), design tools, and the concomitant modeling analysis, and experimental work.

The scale of the latter will range from laboratory-, bench-, and pilot-scale, up to and including equipment sizes needed to obtain data to confirm the feasibility of prototype- and commercial-scale plants. However, construction and operation of large commercial facilities are not currently part of the Vision 21 program. These activities, the timing of which will depend on progress in technology development and the prevailing economic conditions and market forces, will be left to private industry. DOE's role will be to facilitate the transfer of the Vision 21 technology data base to industry.

Program Management

The matrix management structure already in place at NETL will be applied to managing the Vision 21 program. The Vision 21 Team will work with NETL product managers, headquarters FE personnel, industry, universities, and other Vision 21 stakeholders, to ensure that all Vision 21 program activities (including planning, procurement schedules, budgets, communications, review and evaluation, etc.) are conducted in a consistent and coordinated manner. NETL product managers will continue to have overall responsibility for both the Vision 21 and other portions of their programs. As with other programs, management of individual Vision 21 projects will be the responsibility of the Office of Project Management.

Vision 21 Technologies

Many of the initial building blocks for Vision 21 energy plants are emerging from DOE's advanced technology programs. Fifteen years ago, the Clean Coal Technology Demonstration program (CCT) was initiated with the objective of demonstrating a new generation of advanced coal utilization technologies. The current Coal & Power Systems R&D program focuses on developing technology that ensures the availability of a reliable and diverse energy supply, clean and affordable electric power and transportation fuels, and technology options to address global climate change. Vision 21 builds on the successes of the CCT and R&D programs. Activities in the current R&D program that are relevant to Vision 21 are being integrated into the Vision 21 program. Typi-

Key Vision 21 Technologies

Combustion and High-Temperature Heat Exchange

Gasification

Gas Purification

Gas Separation

Turbines

Fuel Cells

Synthesis Gas Conversion to Fuels and Chemicals

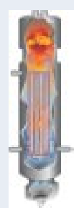
Environmental Control Technology

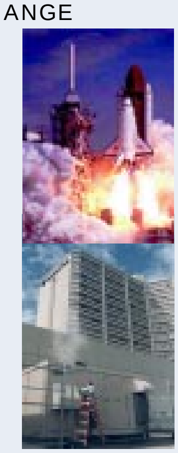
Materials

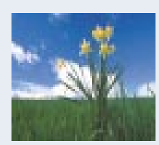
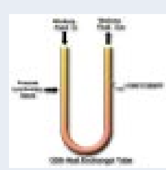
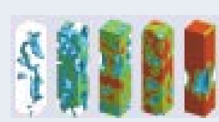
Controls and Sensors

Computational Modeling and Virtual Simulation

Systems Analysis and Systems Integration





cally, Vision 21 activities include longer range (>5 years to market) R&D to develop new technical approaches with aggressive performance targets that will provide step-change improvements compared to current technology. Examples of Vision 21 technical approaches include ion conducting membranes for separating oxygen from air and gas turbine-fuel cell hybrid systems with 70-80% efficiency.

Two Vision 21 Roadmapping Workshops were held early in the Vision 21 planning process. The first Workshop, held in Pittsburgh in December 1998, resulted in a consensus among industry, academia, and DOE participants about which technologies would be key to Vision 21 energy plants, regardless of the specific types or configurations of plants that may be built (see box on previous page).

The product of the second industry workshop, held at the University of Maryland in August 2000, was a series of technology roadmaps that provided, for each Vision 21 technology, (i) a breakdown of each technology into its principal R&D areas, e.g., fuel cell technology is subdivided into the areas of fuel cell stacks, gaseous fuel processing, power conditioning, and balance of plant; (ii) performance and cost objectives including a comparison with the performance of current technology; (iii) obstacles or barriers to achieving the objectives; (iv) the current status of R&D towards overcoming the barriers; and (v) an approach or strategy for overcoming the barriers grouped into near-term (0-5 years), mid-term (5-10 years), and long-term (10-15 years) categories. The technology roadmaps developed during the workshop were reviewed by NETL product managers working with the Vision 21 Team. The result is the series of detailed technology roadmaps that are provided in the Appendix. Summary descriptions of the technology needs for each key Vision 21 technology and a review of current activities are provided below.

Combustion and High-Temperature Heat Exchange

Overview

Vision 21 will address a range of combustion topics that are likely to be important for Vision 21 plants, including nitrogen-free combustion, ultra-low NOx combustion, and fuel-flexible combustion. Nitrogen-free combustion, e.g., using oxygen or metal oxide oxygen carriers, would result in a concentrated CO_2 stream available for sequestration. Ultra-low NOx combustion will minimize the need for relatively expensive flue gas treatment in order to reduce NOx levels at the plant "stack" to below the Vision 21 target of 0.01 lb/million Btu. Fuel-flexible combustion technology is needed to utilize "opportunity" feedstocks, such as biomass and petroleum coke along with the main fuel, typically coal. High-temperature heat exchange is also needed for gasifier fuel gas cooling and for high-efficiency indirectly fired cycles. The Vision 21 objective is to develop alloy and ceramic tube heat exchangers capable of service at temperatures of up to 2300°F and 3000°F, respectively. Combustion technology will also play an important role in Vision 21 plants based on gasification. These plants may need advanced technology for fuel-gas combustion external to a gas turbine, char combustion (e.g., char from a partial gasifier), and gasification process tail-gas incineration.

Current Activities

In a project selected under the recent Vision 21 solicitation (see Management Approach and Business Strategy - Implementation on Page 7), Clean Energy

Systems (Sacramento, CA) will develop a "rocket engine" steam generator to power an advanced turbine, generating electricity and emitting only steam and a stream of carbon dioxide ready for sequestration. Extremely high-intensity mixing and combustion is achieved by employing rocket engine technology in the design of the steam generator. As a result, the size of the steam generator required for a 500 MW power plant can be reduced by about one order of magnitude. The reduction in size should lead to greatly reduced cost. Other potential benefits are increased transportability and ease of siting. Thermal efficiencies for electric power plants based on this technology are expected to be in the range of 60-65 percent with advanced turbines operating at temperatures of 2600^{o}F and pressures of about 3,000 psia.

In the heat exchange area, metal alloy heat exchangers, capable of 2000^{o}F operation, are being tested at process development unit scale and will be available within a few years. Higher temperature heat exchangers, capable of 3000^{o}F operation will need to be based on ceramics. Appropriate materials are being developed with testing of an air heater expected by 2010.

Gasification

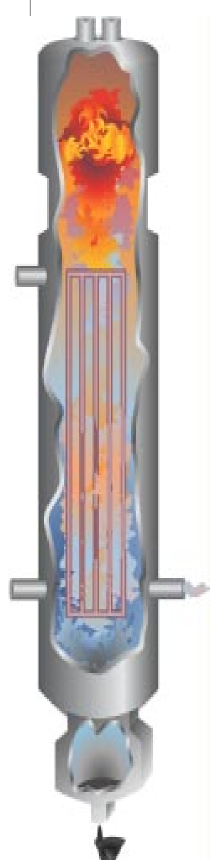
Overview

Gasifiers with improved flexibility, greater reliability, and lower life cycle costs are targeted for Vision 21 applications. Improved gasification technology is needed, including advanced gasifiers with the capability to process up to 30 percent opportunity feedstocks (e.g., biomass, petcoke) along with coal, improved cold gas efficiency (>82%) and availability (>95%); and better, lower cost methods of transporting solids to and from gasifiers, including improved, fuel-flexible gasifier feed systems. One type of advanced gasifier being studied at the Power Systems Development Facility (PSDF) in Wilsonville, AL, is the transport gasifier. Another type of gasifier, also to be studied at the PSDF, is a partial gasifier. Other advanced gasifier concepts may also be explored. Most gasifiers are designed to process one particular feedstock, such as coal, thus limiting the gasifier's ability to process low-cost opportunity feedstocks. Usually, these alternate feedstocks will be fed in combination with coal. Current lockhopper systems are unreliable and need to be replaced with better, more efficient feed systems.

Current activities

Foster Wheeler Development Corporation (Livingston, NJ) and GE Energy & Environmental Research Corp. (Irvine, CA) are developing, respectively, a more flexible gasification technology and a potentially revolutionary approach for producing hydrogen and sequestration-ready carbon dioxide from coal.

Foster Wheeler, teaming with Nexant, Praxair, Reaction Engineering International, Corning, and ADA Technology, is developing a pressurized circulating fluidized bed partial gasification module that produces gaseous and solid fuels for use in fuel-flexible high-efficiency plants that will accomodate the most advanced gas and steam turbines. This new approach will use a lower temperature than today's gasification plants, possibly leading to greater reliabililty, and will convert the feedstock, which can include coal, biomass, and low-rank fuels, into both a gaseous and clean solid fuel. The proportions of gaseous and solid fuels can be varied, providing more flexibililty in terms of product slate and load following. The development program will include the construction and testing of a pilot-scale partial gasification module. GE Energy & Environmental Research Corporation, teaming with Southern Illinois University and the California Energy Commission, is developing an advanced gasification-combustion (AGC) process that produces hydrogen for fuel cells or combustion turbines and sequestration-ready carbon dioxide. The AGC module consists of three fluidized bed reactors, can be readily integrated into



Vision 21 power systems, does not require oxygen, and offers the benefits of low cost, high efficiency, and low emissions. Activities include lab-, bench-, and pilot-scale testing to demonstrate the concept, engineering analysis to develop design criteria, and economic analysis to evaluate market potential.

Gas Purification

Overview

Fuel or synthesis gas produced in gasification processes will be used to generate electricity with gas turbines or fuel cells, or may be processed to clean transportation fuels or high-value chemicals. Associated with each of these applications are gas purity requirements that must be satisfied in order to avoid damage to downstream equipment, e.g., turbines, fuel cells, or process catalysts. These purity requirements are usually far more stringent than what is needed to meet environmental regulations. Purification technology is needed to remove both particulate and gas-phase contaminants. Ash bridging and filter durability are key concerns with particulate filters. The approach for gaseous contaminant control is usually to employ sorbents. Sorbent performance, cost, regenerability, and attrition resistance are common barriers. Operating temperatures vary widely depending on the application but could be as high as 1550ºF. Existing facilities, including Clean Coal demonstration projects and the PSDF, will be used to the maximum extent possible to develop and test advanced gas purification systems.

Current activities

Technologies are being developed to produce a synthesis gas product that meets the purity requirements for use with fuel cells or for subsequent conversion to fuels and chemicals. The goal is to achieve costs for these advanced systems that are equal to or less than conventional amine-based technologies and with improved overall system thermal efficiency. Siemens Westinghouse Power Corporation (SWPC) and Research Triangle Institute (RTI) are developing novel process concepts that can achieve the above goals. In the first project phase, each team will demonstrate their concept in the laboratory and address technical and economic feasibility through preliminary engineering analysis, systems studies, and market analysis. The second phase will entail bench-scale experiments to verify their technology's operability and establish parametric limits of process operations.

SWPC is working with the Gas Technology Institute to develop an innovative process for hot synthesis gas cleanup that involves two cleanup stages integrated in series. A moving-bed filter-reactor first stage reduces the primary contaminants (H_2S, HCl, particulate) to about one part-per-million while final polishing to parts-per-billion levels is conducted in the barrier filter-reactor second stage.

RTI has teamed with MEDAL (Membrane DuPont and Air Liquide), North Carolina State University, Prototech, Inc., and SRI International to develop a process that integrates a polymer membrane and a regenerable ZnO-coated monolith for sulfur removal to parts-per-billion levels with inexpensive high-surface-area materials and acidic adsorbents for HCl and NH_3 removal to parts-per-billion levels. This technology also has potential for simultaneously producing a concentrated stream of CO_2.

Selective catalytic oxidation of hydrogen sulfide (SCOHS) technology currently being developed at NETL integrates gas conditioning (e.g., amine or hot gas desulfurization) and gas treating (e.g., Claus or direct sulfur recovery process) systems into a single overall process. Micro-porous catalysts are used to oxidize the H_2S in the synthesis gas stream to elemental sulfur at temperatures between 280 and 350ºF. The elemental sulfur produced is deposited within the pores of the catalyst and is recovered upon regeneration of the catalyst. This process has the potential for removing H_2S to parts-per-billion levels and is highly selective towards elemental sulfur.

Gas Separation

Overview

More efficient, lower cost gas separation systems are needed to produce oxygen for combustors and gasifiers; hydrogen for fuel cells, turbines, and process applications; and carbon dioxide for sequestration. In an integrated gasification combined cycle plant, for example, oxygen production can account for 15-25% of the cost of the plant and consume 15-20% of the power output. Improvements in air separation technology can have a profound impact on the economics. The availability of low-cost oxygen will also enable the use of oxygen-enriched combustion in "sequestration-ready" systems that produce a concentrated stream of CO_2. Low-cost technology for separating H_2 from synthesis gas would create significant opportunities in fuel cell power and chemicals synthesis, and in other areas. Ion-electron conducting membranes and other novel concepts are being explored for O_2 and H_2 separation. One novel approach for CO_2 separation is CO_2 hydrates. This technology offers a low-temperature approach for the production of CO_2 and high-purity hydrogen from a "shifted" synthesis gas produced by the gasification of carbon-based feedstocks.

Current activities

Vision 21 projects are underway to develop more efficient, lower cost technology for separating oxygen from air and hydrogen from syngas. Siemens-Westinghouse Power Corporation (Pittsburgh, PA) and Praxair, Inc. (Tonawanda, NY) are developing zero emission power plants that integrate solid oxide fuel cells (SOFCs) with oxygen transport membranes (OTMs). The exhaust products of the SOFC will consist of only steam and carbon dioxide; thus, carbon dioxide can be easily recovered for eventual sequestration. OTM technology provides a much more efficient method of supplying the oxygen necessary to oxidize the remaining fuel in the SOFC exhaust than conventional cryogenic air separation technology. In addition, the comparable operating temperatures of SOFCs and OTMs (~2000°F) allow for very efficient and cost-effective integration.

Two projects are concerned with separating hydrogen from gas mixtures using ceramic, ion-conducting membranes. Such membranes, being non-porous, produce pure hydrogen. Although other methods for separating hydrogen exist, e.g., pressure swing adsorption, porous membranes, methanation, nitrogen wash, and palladium membranes, such methods are either expensive or produce low-purity hydrogen. Eltron Research (Boulder, CO) and its partners will optimize the composition and microstructure of the ceramic membrane materials for proton/electron conduction and chemical stability, and develop dense membrane structures that enable a hydrogen separation rate over 10 $cm^3/min/cm^2$. A small-scale prototype will be built and tested and the strategy developed for technology scale-up. ITN Energy Systems (Wheat Ridge, CO) will develop a hydrogen separation system based on a composite membrane with functionally graded materials and plasma spray manufacturing techniques. The goal is to demonstrate a laboratory-scale prototype with hydrogen flux rates of 50 $cm^3/min/cm^2$ at 1100-1650°F.

Turbines

Overview

Areas of interest in turbine development include fuel flexible turbines, turbines for large-scale fuel cell hybrid systems, "sequestration-ready" turbines that use hydrogen or burn natural gas in oxygen, and other innovative turbine concepts. Building upon existing platforms such as Advanced Turbine Systems, turbine technology will be extended by applying expertise in heat transfer, fluid

dynamics, and advanced materials. Performance targets are 60% efficiency (higher heating value) for systems based on coal with emissions of NO_x and SO_2 at single digit levels. Vision 21 turbines will operate at extremely high temperatures (3000°F) and will be integrated with fuel gas cleaning and air separation systems. System dynamics will be a major factor in designing turbines for fuel cell hybrid systems. Natural gas/oxygen and hydrogen turbines must overcome challenges related to mixing and ultra-high temperature operation. High-temperature steam turbines will also be needed in some Vision 21 applications.

Current activities

Under the concluding ATS program, the major turbine manufacturers General Electric and Siemens-Westinghouse have developed ATS machines with improved efficiency and environmental performance compared with previous gas turbines. Both firms are planning to demonstrate and commercialize the ATS machines. These designs are serving as a platform to develop even more advanced turbines that will have the efficiency, environmental performance, and fuel flexibility needed for future Vision 21 energy plants. A group of companies, including General Electric, Pratt & Whitney, Rolls-Royce, and Siemens-Westinghouse, is identifying potential markets, public benefits, technical risks, and development needs for these turbines, called "Next Generation Turbines (NGT)." In related activities, CFD Research is leading a team developing advanced computational tools to design ultra-low emission combustion systems for gas turbines. Oak Ridge National Laboratory is working to develop improved materials and manufacturing technologies, such as thermal barrier coatings, that will be used in ATS and NGT turbines. The South Carolina Institute for Energy Studies is also developing technology improvements that will raise the performance levels of turbine systems to meet Vision 21 objectives.

Turbines and fuel cells are being combined in "hybrid" systems that promise to provide unprecedented efficiencies for generating electricity. Fuel Cell Energy will test a 250 kW hybrid power system with 65% efficiency, an unprecedented efficiency even for a natural gas-fueled system, and will prepare a design for a 40 MW system. Efficiencies of later generation hybrid systems are expected to approach 80%. Ramgen is working on a novel pre-prototype, ramjet-like engine that can be a component in Vision 21 energy plants. Use of the engine on opportunity fuels, especially on coal bed methane, is of interest.

Fuel Cells

Overview

Fuel cell activities focus on the development of ultra-clean, high-efficiency fuel cell/turbine electric power plants that can reduce NO_x, SO_2, and CO_2. Fuel cell stack modules will be developed with 80,000 hour minimum operating lives and a capital cost of $100-200/kW; new technologies will be needed to achieve these targets. Scale-up of fuel cells to sizes larger than 30 MW for use in large-scale applications will be a major challenge. Gaseous fuel processing will also be needed for cleanup, conditioning, and reforming. Power conditioning will be required to meet power quality requirements.

Current activities

In the fuel cell area, FuelCell Energy (Danbury, CT) and Siemens-Westinghouse (Pittsburgh, PA) are developing molten carbonate and solid oxide fuel cells, respectively. These types of fuel cells operate at high temperatures (~1800°F) and integrate well with high-efficiency, gasification-based Vision 21 plants. Development activities range from component development through complete power plants, including eventual construction and demonstration of full-scale megawatt-class fuel cell power plants. This work, which is guided by a philosophy of product improvement and cost reduction, will lead to the development of fuel cells that can compete in the market for use in Vision 21 plants.

Fuel Cell Energy is teaming with Capstone Turbine to develop a fuel cell/gas turbine “hybrid” power system with 65-80% efficiency when fueled with natural gas (see “Turbines - *Current activities*”). Siemens-Westinghouse Power Corporation, teaming with Praxair, is developing a technology that would create zero-emissions Vision 21 energy plants using solid oxide fuel cells and ceramic oxygen-transport membranes (see “Gas Separation - *Current activities*”). This approach modifies the design of a tubular solid oxide fuel cell by integrating an afterburner stack of oxygen transport membranes with the fuel cell. The membranes provide oxygen to combust unburned fuel remaining in the fuel cell exhaust, converting the unburned fuel to carbon dioxide and steam. The carbon dioxide can then be easily separated for eventual sequestration by condensing the steam.

The Solid State Energy Conversion Alliance (SECA) has been created to bring industry, national laboratories, and universities together to realize significant improvements in the economics of fuel cell production and use. While not part of Vision 21, the technology developed in SECA will be leveraged to create future, highly advanced Vision 21 systems.

Synthesis Gas Conversion to Fuels and Chemicals

Overview

Synthesis gas conversion will be based largely on advanced Fischer-Tropsch (FT) technology using 3-phase slurry reactors. A Vision 21 objective is to establish a small commercial-scale FT reactor (~10,000 barrels/day) integrated with an IGCC plant. A high yield to diesel fuel (>50% C10-C20) is desired. Cost targets are $15,000 bbl/d capital and <$5/bbl operating. Methanol synthesis is another high-interest area. Methanol is a candidate feedstock in a variety of applications, including fuel cells, turbines, and automotive engines. Alternative fuels and chemicals (e.g., dimethyl ether, olefins, acetic anhydride) from syngas may also be appropriate co-products for some Vision 21 plants. Non-syngas routes to fuels and chemicals will also be pursued. Examples are pyrolytic and extraction processes, and hydrocarbon coupling reactions.

Current activities

Fuels/chemicals activities are centered on advanced synthesis R&D and early entry co-production plants, which are forerunners of Vision 21 plants. The advanced R&D activities are mainly directed toward hydrogen production, FT catalyst development, and hydrogen separation membranes. Three awards have been made under an early entry co-production solicitation: teams are led by Global Energy, Inc., Texaco, and Waste Management & Processors (WMPI) of Gilberton, Pennsylvania.

The facility proposed by WMPI would gasifiy anthracite waste fines and produce a high-quality, zero-sulfur transportation fuel and electric power. Nexant Inc., an affiliate of Bechtel National Inc, Texaco Global Gas and Power, and SASOL Technology Ltd., are in partnership with WMPI. In the Global Energy, Inc. project, the company will apply its gasification process to Air Products and Chemicals liquid phase methanol technology, which produces methanol from coal-based feedstocks. Both technologies are being successfully tested at separate locations through DOE’s Clean Coal Technology Demonstration program - the Wabash River Coal Gasification Repowering Project, a joint venture of Dynegy and PSI Energy, Inc., and the Commercial-Scale Demonstration of the Liquid Phase Methanol Process. Siemens-Westinghouse will lend its expertise in advanced turbines, while Methanex will help produce and market the chemical-grade methanol, to be used by Dow Corning and Dow Chemicals. Texaco, in partnership with Brown & Root Services, GE Power Systems, and Praxair, Inc., proposes a co-production plant in which a coal slurry is gasified in a Texaco gasifier. After desulfurization, the synthesis gas is converted to zero-sulfur fuels via FT synthesis followed by uprading to diesel fuel and naptha. Electric power, produced by a turbine fueled with syngas, light FT products, sulfuric acid, and steam are co-products.

Environmental Control Technology

Overview

Environmental control issues comprise air, water, and solid waste emissions. Important topics in the air emissions category include control of NO_x, SO_2, particulate matter, mercury, volatile organic compounds, and ammonia. Vision 21 targets for the levels of acid gases emitted from coal-based plants are an order of magnitude below projected regulatory requirements and are about equivalent to emissions levels from the best natural gas-based plants. This is consistent with the Vision 21 "philosophy" that the environmental performance of Vision 21 plants should be independent of the feedstock type. Water efforts are directed at significantly reduced consumption and near-zero discharge for Vision 21 plants. The costs of water management must be sufficiently low to ensure that total plant costs remain competitive. The quantitites of solid waste produced in Vision 21 plants will be minimized to the maximum extent practicable. Solids that would otherwise be classified as wastes will either be recycled for further processing or converted to marketable products. Research needs are directed at improving the efficiency and reducing the costs of air emissions control technology. Work on a number of advanced technologies is already underway in the program areas, e.g., the environmental control technology program, that support Vision 21. The scale of testing of the more promising approaches will be increased in order to demonstrate commercial feasibility.

Current activities

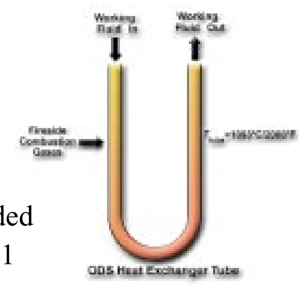
The NETL environmental control technology program is providing science and technology related to ambient air quality and emissions from power systems. NETL is carrying out focused programs on fine particulate/air toxics , by-product recovery and utilization, water and carbon dioxide.

The effort to utilize coal combustion by-products and to develop applications for gasifier slag are being expanded. This work provides the base for evaluating recovery options for solids from Vision 21 plants.

Exploratory studies have been completed to review options for addressing greenhouse gas emissions. NETL is sponsoring the development of six promising concepts that could offer advanced, low-cost approaches for reducing the buildup of greenhouse gases in the atmosphere. Vision 21 will utilize the results of this work to guide and evaluate overall plant concepts for achieving environmental goals.

A current activity is the identification of environmental control needs for Vision 21 plant concepts. This includes the need for final control technology beyond the gas purification technology for process requirements, options for minimizing water use, and innovations in plant design that can achieve near-zero emissions.

Materials



Overview

Advanced structural and functional materials are needed for a wide range of Vision 21 applications. These include:

- high-temperature heat exchange materials for steam cycle components (superheaters, reheaters, recuperators)
- high-temperature heat exchange materials for air heaters
- ultra-high-temperature intermetallics for gasification and combustion systems
- refractory materials for gasification and combustion systems
- hot-gas filter materials
- gas separation membrane materials (for producing hydrogen, oxygen, carbon dioxide)
- turbine airfoils and shrouds
- turbine combustors and transitions
- turbine combustion catalysts
- fuel cell materials

Materials of interest include advanced wrought alloys, oxide-dispersion-strengthened (ODS) alloys, ODS iron aluminides and ferritic alloys, oxide and non-oxide based monoliths for hot-gas filtration and other applications, advanced ceramics and composites, single crystal airfoils and other turbine components, and thermal barrier coatings. Activities will comprise development of new materials as well as improvements to existing materials. Work will be a cooperative effort between the national laboratories, universities, and industrial developers and users of advanced materials.

Current activities

Materials projects are being carried out as part of the respective technology programs (e.g., in the turbines program, the development of turbine materials and coatings capable of surviving the hostile environment of coal gas-fired systems represents a major challenge; in the fuel cells program, materials that support advanced fuel cell technology; and in the gas separations area, the development of hydrogen membrane materials. Additional materials projects are being carried out as part of the Coal and Power Systems Advanced Research program in Materials.

Reliable high-temperature heat exchanger tubing is important to meet efficiency goals. Huntington Alloys, Huntington, WV, is leading an effort to develop oxide dispersion strengthened alloys (ODS). Additional technical expertise is being supplied by Foster Wheeler Development Corporation (FWDC), Oak Ridge National Laboratory (ORNL), University of California, San Diego (UCSD), Michigan Technological University (MTU), and the Edison Welding Institute (EWI). The effort supports development of advanced materials that are needed to meet the efficiency goals of the Vision 21 program. The participants will initially use a known class of ferritic materials, e.g., FeCrAls and FeAls, that have been shown to be fairly resistant to conventional coal combustion and gasification environments, and will further enhance the properties of such materials (improved high-temperature creep resistance, greater corrosion resistance, higher tensile strength, etc.) using oxide (Y_20_3)-dispersion strengthening to produce ODS-type alloys.

Materials projects are also incorporated in the respective technology programs. An example is the development of hydrogen membrane materials cited in the Gas Separations area.

Controls and Sensors

Overview

Vision 21 plants will be highly integrated complexes of advanced technology modules. Control of these plants will require sophisticated new algorithms that utilize advanced computer technology to control and optimize plant efficiency and emissions performance. Knowledge of failure modes and operability problems needs to be improved in order to advance Vision 21's "smart" design approach for reducing costly equipment redundancy. Conventional thinking tends to treat sensors as an add-on in the design stage and not as an integral part of the design. Existing sensors are largely inadequate for Vision 21 plants. New sensors and measurement techniques will be needed to measure contaminants, including regulated pollutants, to ultra-low levels. These sensors will often need to operate in very harsh environments, i.e. high temperatures and corrosive fluids, while maintaining high reliability.

Current activities

Sensor Research Corporation, Orono, MA, is currently developing solid oxide surface acoustic wave sensors for the detection of several species, e.g., NOx, SOx, NH_3, H_2S, in gasification environments. In addition, systems integration and engineering issues are being addressed by research at the National Fuel Cell Research Center (see Systems Analysis/Integration). The goal of this project is to develop an understanding of the complex nature of integrating multiple advanced technologies into a Vision 21 plant. The work will form the foundation for the control systems necessary to operate a Vision 21 plant.

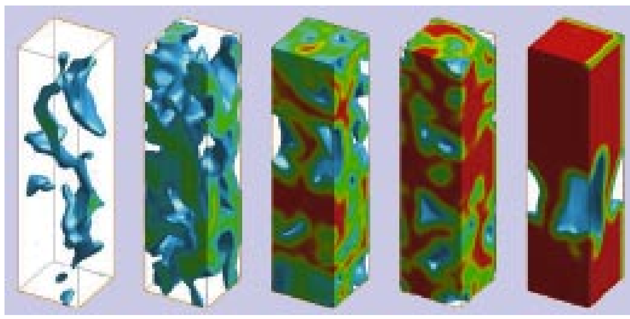
Computational Modeling and Virtual Simulation

Overview

Computer simulation can provide a cost effective complement to experimental development. The advanced modeling initiative will assist in the design process by providing physically based simulations of Vision 21 plant components, subsystems, and complete plants. Transient 3-D simulations will realistically account for all of the physically relevant phenomena such as fluid flow, heat transfer, chemistry, mechanical stresses, etc. The concept of the "virtual simulation" is to unify all computer-related plant design activities into an integrated suite of codes which can exchange information easily and accurately. The virtual simulation will have a visualization submodel that is based on 3-D solid modeling. This information can be passed to computer-aided design (CAD) software to generate drawings, piping & instrumentation diagrams, etc., and provide a realistic visual simulation of plant layout and operation. The computational modeling and virtual simulation activity will progress on multiple tracks. These include:

- modeling and virtual simulation infrastructure (includes physical plant and process visualization software, cluster computing capability, information systems, communications architecture)
- mechanistic modeling of fundamental phenomena to permit analysis and visualization of a unit operation
- subsystem (e.g., gasifiers, turbines, fuel cells) operation
- plant virtual simulation (includes integrated plant steady-state and dynamic simulation including process control)

Computational modeling and virtual simulation activities will be performed by national laboratories, universities, and industrial firms including architecture and engineering (A&E) firms.



Computer software to simulate gas-particle flow in fluidized beds, including gasifiers, fluidized bed combustors, and pneumatic transport
Princeton University, Princeton, NJ

Current activities

Four projects have thus far been selected under the recent Vision 21 solicitation (see MANAGEMENT APPROACH and BUSINESS STRATEGY - Implementation). Fluent, Inc., of Lebanon, NH, together with Alstom Power, Aspen Technology, Intergraph, and West Virginia University received an award for the project "Software Integration for Vision 21 Virtual Demonstration." This team will begin building a virtual simulation system that would allow designers to model a fully functional Vision 21 plant on a computer. Computational fluid dynamics capabilities will be linked to process flow sheet models such as that of Aspen Technology. Subsystem models, dynamic response and control codes, and visualization tools will be integrated to produce the virtual simulation system. NETL researchers have been working with Fluent for several years to lay the framework for this type of simulation capability.

Additional projects were selected that will advance the state of the art. Reaction Engineering International, of Salt Lake City, UT, together with a number of supporting commercial firms and universities, received an award for the project, "A Computational Workbench Environment for Virtual Power Plant Simulation." This team is developing new process simulation software, including treatment of transients, for Vision 21 plants. Special modules will be developed to treat boilers, fluidized bed reactors, gasifiers, combustors, fuel cells, and gas cleanup modules. The resulting software will allow models of varying complexity to "talk" to one another. The software will feature "plug and play" capability and will be PC friendly.

Princeton University, Princeton, NJ, will develop a "Coarse-Grid Simulation of Reacting and Non-

Reacting Gas-Particle Flows." This project will develop improved methods for simulating bubbling beds, spouted beds, and circulating fluidized beds, including those with chemical reactions. Fine computational grids, which require powerful computers and long computation time, are normally needed to preserve detail in this type of calculation. However, the approach to be developed by Princeton University will allow the use of a coarse grid yet still preserve detail. A team led by CFD Research Corporation of Huntsville, AL, won an award for the project, "LES Software for the Design of Low Emission Combustion Systems for Vision 21 Plants." The team will develop software based on Large Eddy Simulation that will lead to improved design capabilities for low emission combustion systems such as combustors for gas turbines. An industrial consortium including leading turbine manufacturers is cooperating on this project, the pre-competitive results of which will raise the baseline state-of-the-art to higher levels.

In addition to the contracted research described, workers at NETL are performing simulations and evaluations of process flowsheets employing advanced components for power generation, including fuel cells and turbines. Taken together, these activities will lead to improved methods for process design and simulation of ultra-high performance fossil fuel based energy plants.

Systems Analysis/Integration

Overview

Systems analysis includes market analysis (forecasting and scenario analysis), process definition of Vision 21 plant concepts, development of "reference" plant concepts, plant operation analysis, economic analysis, and commercial plant evaluation. Definition of Vision 21 plant concepts will result in designs of technology "modules" that can be integrated to meet Vision 21 performance targets. Plant flowsheets will be developed. Several reference plants will be selected for detailed study. Quantitative estimates of efficiency, emissions, cost, and reliability benefits from proposed process innovations will be developed. A perspective on technology needs will be developed and gaps will be identified. Vision 21 plants will use multiple technology modules and have special systems integration issues. Systems integration comprises systems engineering, dynamic response and control, and industrial ecology. Systems engineering concerns the configuration of Vision 21 plants, the design of subsystems and components, and subsystem and component interconnections. Good systems engineering ensures that subsystems and components are compatible with one another, that the design of the plant is as simple as practicable, and that plant capital and operating costs are as low as possible. High thermal efficiency requires "tight" integration of subsystems in order to achieve maximum heat recovery, maximum utilization of feedstocks, and minimum production of disposables. However, tight integration leads to complex interdependencies among the various subsystems, potentially leading to serious startup, control, and reliability issues. New control strategies and improved control software and hardware will need to be developed.

Vision 21 also offers opportunities for industrial ecology, i.e., utilizing output streams that would otherwise be considered waste as input streams for additional processing or recycle. Ideally, the application of industrial ecology principles would eliminate all waste products.

Current activities

To date, one systems integration project has been selected under the recent Vision 21 solicitation. The National Fuel Research Center, Irvine, CA, with help from KraftWork Systems, Inc., Spencer Management Associates, and Pratt & Whitney Aircraft, were selected for the project, "Systems Integration Methodology." This project will define engineering issues associated with integrating key subsystems and components into Vision 21 plants, and will develop new methods for design and prediction of operating characteristics of power plants employing fuel cells and fuel cells combined with gas turbines (hybrids). The issues to be addressed will be primarily technical, but important economic and market issues will also be included. This important effort will show how advanced energy technologies can be combined to meet Vision 21 objectives.

APPENDIX

Figure A1 shows the functional tasks for the Vision 21 program, the relationships among tasks, and the progression throughout the 15-year program time-frame. Figure A2 is a block flow diagram of a generic Vision 21 plant that gives an overview of the technologies and capabilities that may be important for different plant sections. Figure A3 is an artist's rendition of a representative Vision 21 plant that shows how the key technologies play in the overall plant. Important milestones are also given for each technology.

The technology roadmaps are intended to be "living" documents that provide technical and module performance objectives and targets, barriers to achieving the objectives, and strategies for overcoming the barriers in order to achieve Vision 21 goals. As the Vision 21 program continues, industrial experts in each technology area will collaborate with the DOE to adjust, refine and update the roadmaps as needed.

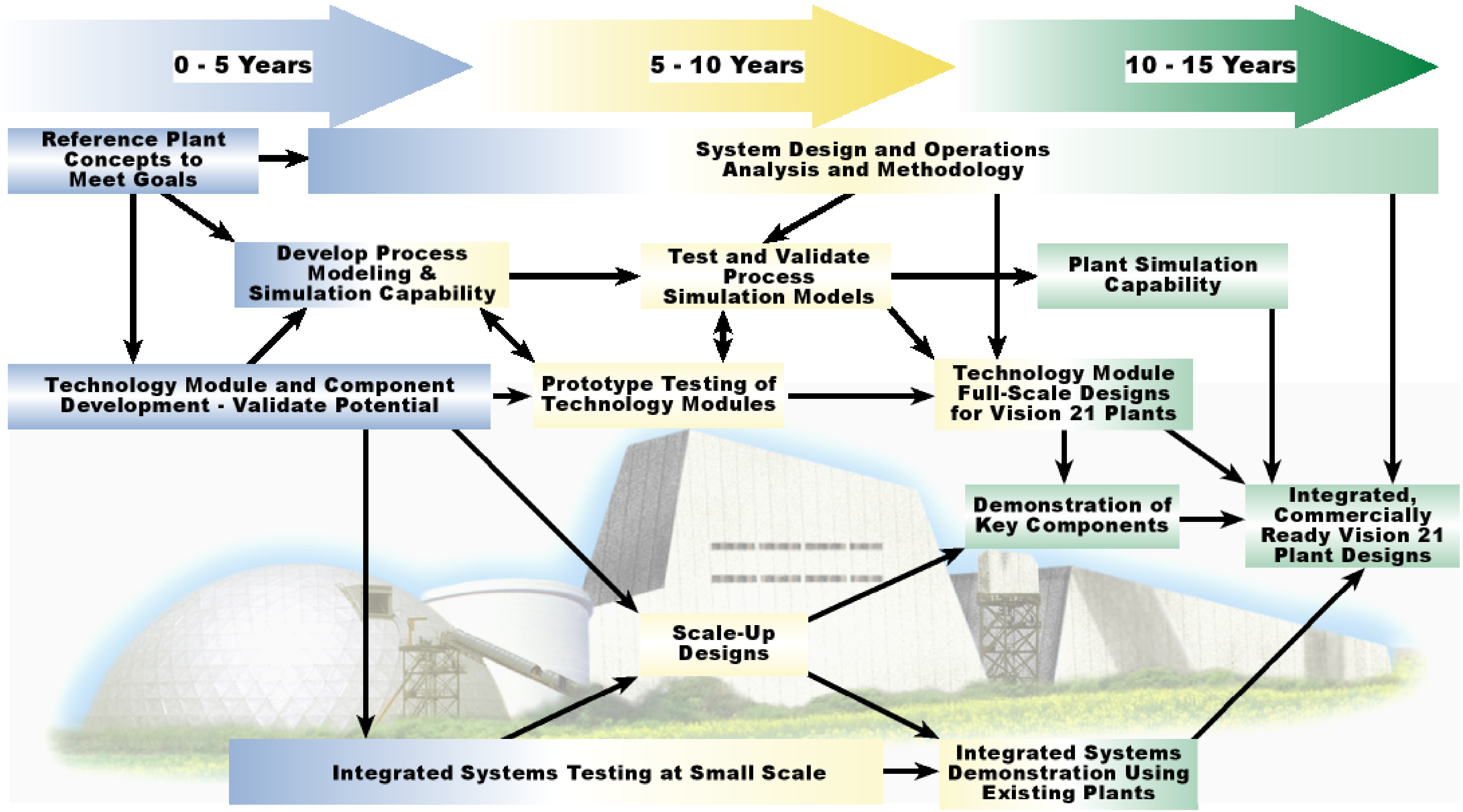
The terminology used in the roadmaps is summarized in Table A1. Vision 21 cost objectives are used in selected roadmaps. It needs to be emphasized that the cost objectives will depend on the application, i.e., on the type of plant, feedstocks, and products (e.g., electricity only, electricity and fuels). The cost objectives for each plant section (technology module) will also depend on the Vision 21 plant design selected to meet the market need, and on the total plant cost. Figure A4 is an example of how technology module costs might relate to total plant cost for an electric power application using an oxygen-blown gasification plant.

The roadmaps for each technology area follow:

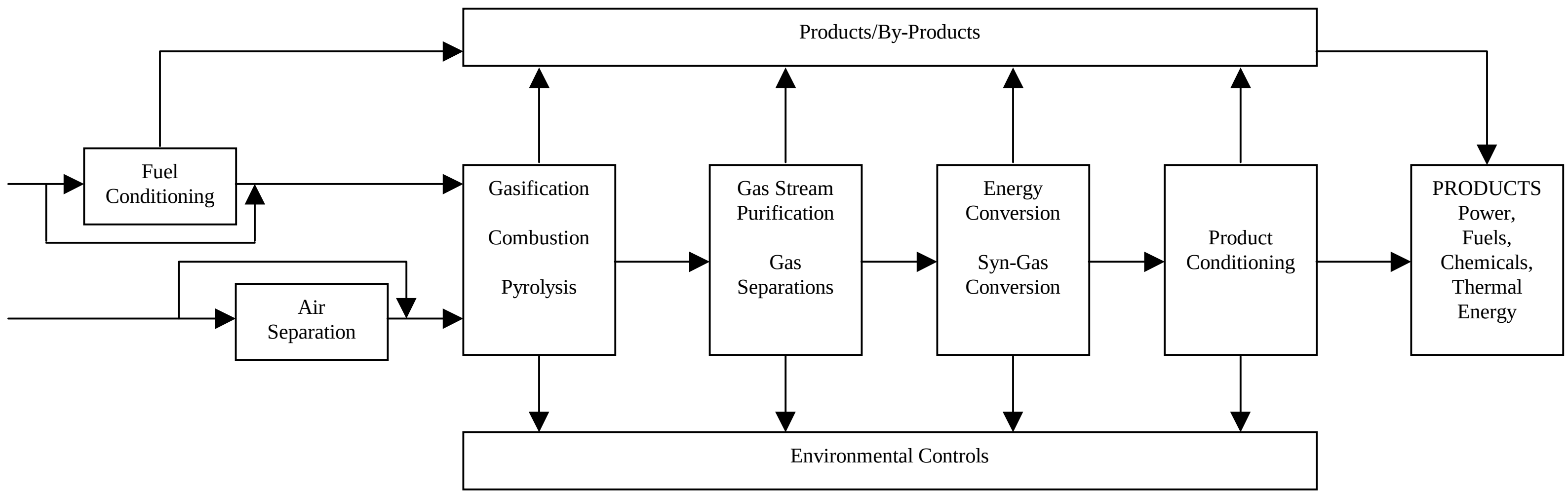
- Combustion and High-Temperature Heat Exchange
- Gasification
- Gas Purification
- Gas Separation
- Turbines
- Fuel Cells
- Synthesis Gas Conversion to Fuels and Chemicals
- Environmental Control Technologies
- Materials
- Sensors and Controls
- Computational Modeling and Virtual Simulation
- Systems Analysis and Systems Integration

Figure A1

Vision 21 Technology Roadmap



Systems Analysis, Design, and Operation Capability

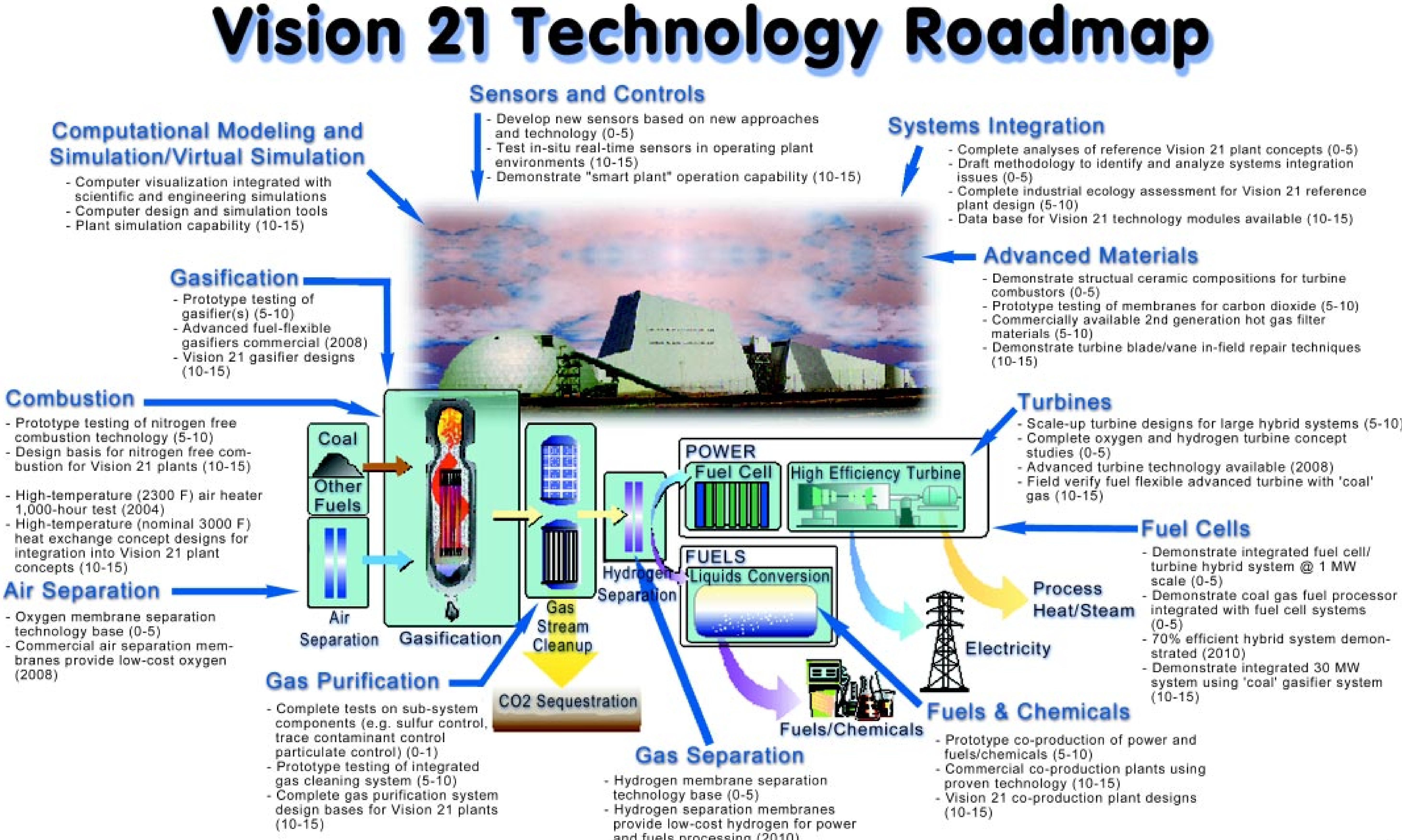


Air Separation	Solids Feed Gasifier Combustor High Temp. Heat Exchangers	Gas Cleaning Particulate Gas Contaminants Gas Separations Hydrogen Carbon Dioxide	Combustion Turbines Turbine Expanders Fuel Cells Steam Turbines Syn-Gas Conversion F-T Liquids Methanol

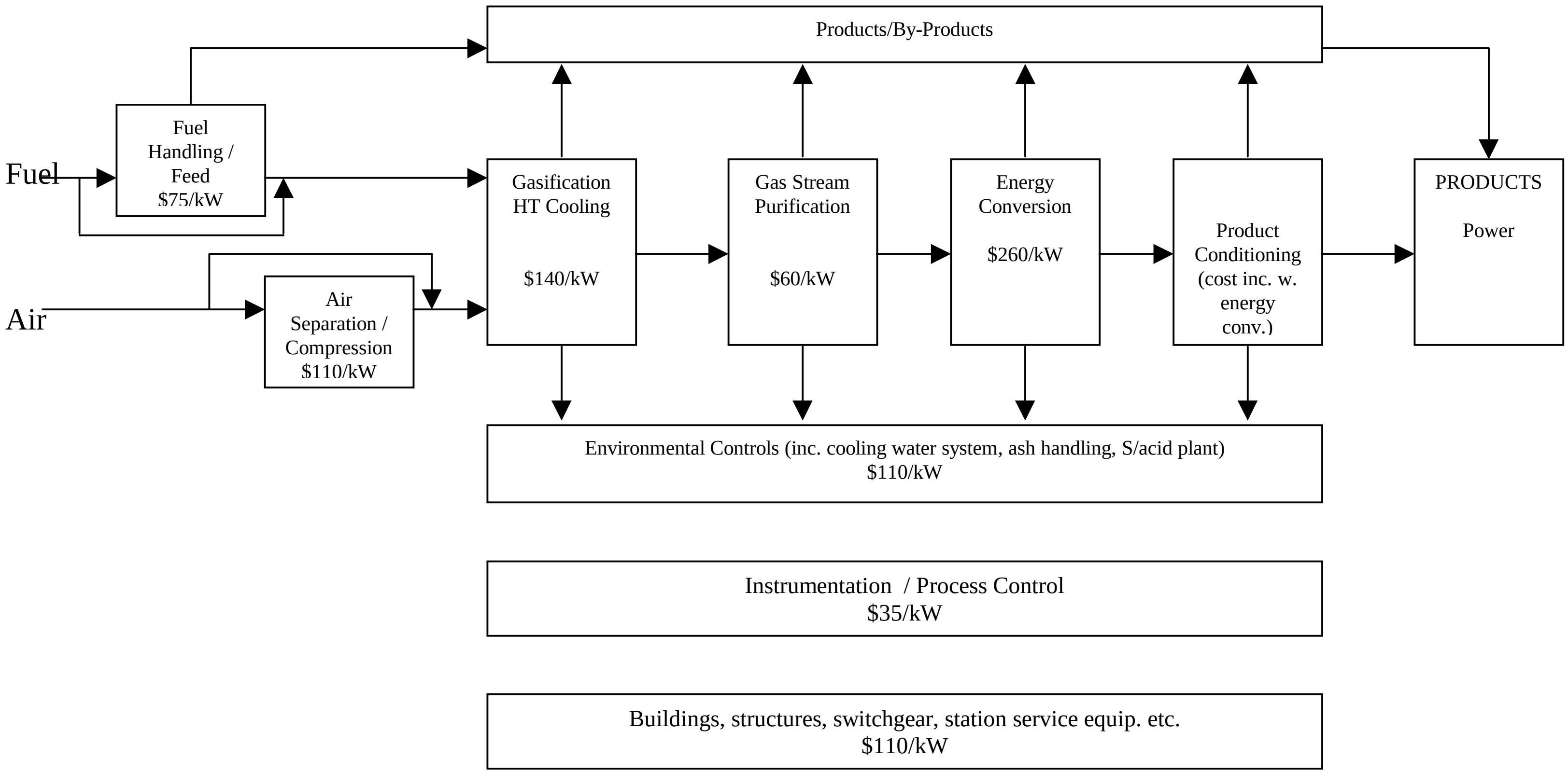
Instrumentation, Process Control, By-Product Recovery, Emissions Control

Figure A2 - VISION 21 PLANT –TECHNOLOGY/CAPABILITY OVERVIEW

Figure A3.



Vision 21 Technology Roadmap
Sensors and Controls
- Develop new sensors based on new approaches and technology (0-5)
- Test in-situ real-time sensors in operating plant environments (10-15)
- Demonstrate "smart plant" operation capability (10-15)
Computational Modeling and Simulation/Virtual Simulation
- Computer visualization integrated with scientific and engineering simulations
- Computer design and simulation tools
- Plant simulation capability (10-15)
Systems Integration
- Complete analyses of reference Vision 21 plant concepts (0-5)
- Draft methodology to identify and analyze systems integration issues (0-5)
- Complete industrial ecology assessment for Vision 21 reference plant design (5-10)
- Data base for Vision 21 technology modules available (10-15)
Gasification
- Prototype testing of gasifier(s) (5-10)
- Advanced fuel-flexible gasifiers commercial (2008)
- Vision 21 gasifier designs (10-15)
Advanced Materials
- Demonstrate structual ceramic compositions for turbine combustors (0-5)
- Prototype testing of membranes for carbon dioxide (5-10)
- Commercially available 2nd generation hot gas filter materials (5-10)
- Demonstrate turbine blade/vane in-field repair techniques (10-15)
Combustion
- Prototype testing of nitrogen free combustion technology (5-10)
- Design basis for nitrogen free combustion for Vision 21 plants (10-15)
- High-temperature (2300 F) air heater 1,000-hour test (2004)
- High-temperature (nominal 3000 F) heat exchange concept designs for integration into Vision 21 plant concepts (10-15)
Turbines
- Scale-up turbine designs for large hybrid systems (5-10)
- Complete oxygen and hydrogen turbine concept studies (0-5)
- Advanced turbine technology available (2008)
- Field verify fuel flexible advanced turbine with 'coal' gas (10-15)
Coal
Other Fuels
POWER
Fuel Cell
High Efficiency Turbine
FUELS
Liquids Conversion
Hydrogen Separation
Air Separation
Gasification
Gas Stream Cleanup
CO2 Sequestration
Process Heat/Steam
Electricity
Fuels/Chemicals
Fuel Cells
- Demonstrate integrated fuel cell/turbine hybrid system @ 1 MW scale (0-5)
- Demonstrate coal gas fuel processor integrated with fuel cell systems (0-5)
- 70% efficient hybrid system demonstrated (2010)
- Demonstrate integrated 30 MW system using 'coal' gasifier system (10-15)
Air Separation
- Oxygen membrane separation technology base (0-5)
- Commercial air separation membranes provide low-cost oxygen (2008)
Gas Purification
- Complete tests on sub-system components (e.g. sulfur control, trace contaminant control particulate control) (0-1)
- Prototype testing of integrated gas cleaning system (5-10)
- Complete gas purification system design bases for Vision 21 plants (10-15)
Gas Separation
- Hydrogen membrane separation technology base (0-5)
- Hydrogen separation membranes provide low-cost hydrogen for power and fuels processing (2010)
Fuels & Chemicals
- Prototype co-production of power and fuels/chemicals (5-10)
- Commercial co-production plants using proven technology (10-15)
- Vision 21 co-production plant designs (10-15)



Reference Plant Capital Cost: $900/kW

Nominal 500 MW Oxygen-Blown Gasification Based Vision 21 Plant for Power Generation – Eff. 60%

Figure A4 - VISION 21 PLANT – CAPITAL COST EXAMPLE

Table 1 - ROADMAP TERMINOLOGY

Technology / Capability	• Vision 21 Plant Sub-System or Component Examples: gasifier, combustion turbine, gas cleaning – particulate control subsystem, heat exchanger (component) • Supporting Technology Examples: gas separation membrane materials, high temperature sensors/instrumentation • Systems Analysis/design/operation capability (software/methodology) Example: dynamic simulation of plant operation • Product of an Analysis Example: market analysis
Vision 21 Technology Objectives: Performance and Cost	Performance and cost objectives for Vision 21 plant components; may have multiple objectives as function of application; quantitative estimates Example: Gas Cleaning – Gas Contaminant Control Performance: Composition For Power (turbine requirement) Alkali 0.1-0.5 ppm Halides 0.6-3.0 ppm V 0.05-0.2 ppb Sulfur to meet environmental target: <0.01 lb/million Btu Composition For Fuels & Chemicals Sulfurs 60 ppb Halides 10 ppb NH3 10 ppb Reliability (to be specified) Usable By-Product Cost: <$60/kW for oxygen-blown gasification system for power
Current Status: Technology Performance and Cost	Performance and cost estimates for component if it is available today (commercial or demonstration) Example: Gas cleaning for gas contaminant control Performance: Cold gas cleaning commercial for power application; Cost: $130/kW (est. for oxygen blown system)
Barrier	Any obstacle to technology deployment. Examples of barriers: Attrition resistant sorbent Low cost manufacturing Filter durability Access to vendor intellectual property Examples that are not barriers (part of approach): Component not developed Design not available Need to test at large scale
Current Status	Status related to achieving Vision 21 objectives or in relation to barriers.
Approach	Activities proposed (or being implemented) over the given time period to remove the barriers and required to achieve Vision 21 technology and plant objectives.

TECHNOLOGY AREA: Combustion and High Temperature Heat Exchange

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Nitrogen-Free Combustion (Sequestration Ready) e.g., combustion using oxygen or metal oxide oxygen "carriers"	• Produce concentrated CO_2 product gas available for sequestration	• \$150/kW (For concepts that incorporate gas cleaning such as advanced PFBC, the cost objective includes both combustion and gas cleaning	• Technology not available for power generation	• Technology not available for power generation
Ultra-low NOx Combustion (solid fuel combustion – see gas turbine roadmap for syngas combustion)	• 0.01 lb NOx/10^6 Btu (by 2015) • Intermediate target of 0.05 lb NOx/10^6 Btu by 2010 • N_2O emission target (TBD) • Output based standards lb/kWh (option TBD)	• \$25/kW incremental cost relative to system w/o NOx control (total combustion cost depends on cycle)	• 0.15 lb NOx/10^6 Btu	• \$25/kW incremental pc boiler cost relative to system w/o NOx control
Fuel Flexible Combustion (within Vision 21 combustion systems)	• Fuel feed flexibility: coal + up to 30% alternate fuel (note: 100% biomass and petcoke option for sub-system <100MW) • Availability and performance– same as coal only	• Combustion cost depends on cycle	• Co-firing of biomass is being implemented – system cost and performance below Vision 21 objectives	• Modification costs for co-firing are function of specific plant and feed.
Combustion Process for Fuel-Gas Combustion External to Turbine (Technology development incorporated with turbine roadmap)	See Turbine Roadmap • Combustor design integrated with upstream fuel processing (e.g., gasifier or carbonizer) including gas cleaning; low NOX emissions	See Turbine Roadmap	See Turbine Roadmap	See Turbine Roadmap
High Temperature Heat Exchange e.g. High Temperature Air Furnace (see gasification roadmap for syn-gas cooling)	• Heating air or fluid to 3000°F (temperature target to be determined by systems analysis/integration)	• Cost depends on combustor design and on material to be developed	• Heating air to 2000°F demonstrated in pilot plant	• Unknown (cost projections becoming available)

TECHNOLOGY AREA: Combustion and High Temperature Heat Exchange

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Char Combustion (e.g. char from gasifier used in hybrid IGCC concept)	• >99% carbon burnout • vitiated air for oxidant • low excess air (specific performance determined by cycle analysis)	• <$100/kw	• Anthracite fired boilers (CFB and suspension) are commercial • 30% carbon in char from PFBC partial gasifiers	• Cost for commercial char combustors applicable for Vision 21 plants not reported.
Gasification Process Tail-Gas Incineration	• 99% oxidation of low and variable quality off-gas			
Pressurizsed Solids Feed System (For pressurized combustion, PFBC, pressurized fluidized bed carbonizer, etc.) (see Gasification technology roadmap)	See Gasification Roadmap	See Gasification Roadmap	See Gasification Roadmap	See Gasification Roadmap
Advanced Sorbents for PFBC (see Gas Purification roadmap)	See Gas Purification Roadmap	See Gas Purification Roadmap	See Gas Purification Roadmap	See Gas Purification Roadmap

TECHNOLOGY AREA: Combustion and High Temperature Heat Exchange

Technology	Barrier	Current Status	Approach 0-5 years	Approach 5-10 years	Approach 10-15 years
Nitrogen-Free Combustion (e.g. combustion of solid fuels using oxygen)	• Low-cost oxygen • Combustion temperature control (e.g., CO_2 recycle increased heat extraction) • Fuel/oxidizer mixing (e.g., to avoid hot spots; high fuel NOx emissions) • Reliable operation: corrosion, deposition of "sticky" particles • Turndown • CO_2 clean-up/ polishing	• Oxygen: see Gas Separation Roadmap • Advanced PFBC concept design studies have been completed • Pilot burner testing completed and on-going • Feasibility and economic studies completed	• Oxygen: see Gas Separation Roadmap • Determine combustion kinetics, emissions with O_2 and various fuels • Develop novel fuel/oxidizer mixing concepts and test at pilot-scale • Develop reliable, cost-effective pumps, ducting, & controls for recycle and test at small pilot-scale • Study ash effect at pilot scale	• Oxygen: see Gas Separation Roadmap • Develop burners/combustion systems & test at pilot-scale • Scale-up tests of recycle systems • PFBC: Utilize CCT project to demonstrate component performance	• Develop full-scale combustion system and component designs

TECHNOLOGY AREA: Combustion and High Temperature Heat Exchange

Technology	Barrier	Current Status	Approach 0-5 years	Approach 5-10 years	Approach 10-15 years
Ultra-low NOx Combustion (Solid fuel combustion)	• Mixing/kinetics limitations • Operational problems (e.g., slagging, corrosion) • Incomplete combustion, high carbon content of ash • Fuel-flexible design makes NOx control more difficult	• Limited data on solid fuel combustion available at elevated pressure and with O_2 enrichment or CO_2 recycle • Corrosion, high carbon in ash issues with current combustion systems • Catalytic combustion explored but catalyst poisoning still an issue • Multi-annular swirl burner development delayed	• Initiate program to apply modeling and experimentation to determine practical limits of NOx emissions from combustion systems • Pilot testing to look at NOx control from char combustion • Develop models to improve NOx agent injection and mixing; validate models • Develop practical NOx reduction designs from modeling studies • Lab- and pilot-scale studies to confirm designs and determine dependence of NOx reduction on fuel properties, residence times, temperature, gas composition, etc. Look at enhanced devolatilization	• Scale-up components of NOx reduction systems to pre-commercial size and test • Test full NOx reduction system at PSDF or similar size facility	

TECHNOLOGY AREA: Combustion and High Temperature Heat Exchange

Technology	Barrier	Current Status	Approach 0-5 years	Approach 5-10 years	Approach 10-15 years
Fuel Flexible Combustion	• Feed preparation and injection • Corrosion, erosion • Emissions • Effect on ash properties	• Up to about 10% biomass has been fed with coal in coal boilers (includes RDF, tires, other wastes) • Significant experience with dedicated combustion of wide range of alternate fuels • Emissions data available from limited number of tests with biomass • Limited experience with such fuels in either gasifiers and Vision 21 combustors	• See Gasification roadmap for pressurized solids feed approach • Pilot-scale combustion tests of “opportunity” feedstocks to characterize combustion , determine emissions and ash properties (Petcoke and biomass) • Initiate long-term corrosion tests using opportunity feedstocks	• Complete long-term corrosion tests • Define emissions, corrosion, ash, or other issues that need attention and integrate with appropriate elements of Vision 21 program	

TECHNOLOGY AREA: Combustion and High Temperature Heat Exchange

Technology	Barrier	Current Status	Approach 0-5 years	Approach 5-10 years	Approach 10-15 years
High Temperature Heat Exchange	• Lack of high-temperature materials with adequate corrosion resistance and strength (see Materials Roadmap) • Poor operability and reliability • High cost relative to alternatives • Poor heat transfer rates as compared to water/steam heat exchangers • Fuel NOx issue with high temperature combustion required to achieve 3000°F air temp.	• Novel high temperature heat exchanger concepts developed and tested under NETL HIPPS program; ODS alloy tube design has been used for over 1000 h with minimal corrosion to heat air to temperatures as high as 2000°F with coal combustion	• Review heat exchanger performance requirements for Vision 21 candidate reference plant concepts. (e.g. 1) HITAF, 2) Hybrid gasifier-combustor, 3) air preheat to O_2 membrane) • Review heat exchange requirements for air preheat to O_2 membrane: requires temperatures of only 1200-1400°F • Simplify design of heat exchanger system with 2000°F capability • Pilot-scale testing of 2000°F "simplified" heat exchanger applicable to Vision 21 plant concepts • Develop conceptual designs for heat exchanger with 3000°F capability • Look at development synergies with high temperature industrial applications	• Build and test pilot-scale 3000°F heat exchanger if supported by systems analysis • Scale up 2000°F heat exchanger; conduct long-term tests to establish reliability	• Continue development and scale-up of 3000°F heat exchanger and conduct long-term tests to establish reliability

TECHNOLOGY AREA: Combustion and High Temperature Heat Exchange

Technology	Barrier	Current Status	Approach 0-5 years	Approach 5-10 years	Approach 10-15 years
Char Combustor (e.g. char from partial gasifier, i.e. Hybrid IGCC)	• Carbon burnout • Flame stability • Low excess air • Low NOx • Hot char handling and feeding	• Atmospheric combustors commercial • Limited data with vitiated air • PCFB pilot starting up (PSDF) • No CO_2 sequestration ready concepts tested	• Continue start-up and testing of PCFB at PSDF • Initiate testing of actual chars and with vitiated air • Initiate pilot testing with O_2 firing and CO_2 recycle for seq. ready • Review combustor performance requirements for Vision 21 candidate reference plant concepts	• Scale-up testing of CO_2 seq. ready char combustors • Demonstration of Hybrid IGCC with char combustor	
Pressurized Solids Feed System	See Gasification roadmap	See Gasification roadmap	See Gasification roadmap	See Gasification roadmap	See Gasification roadmap
Advanced sorbents for PFBC	See Gas Purification roadmap	See Gas Purification roadmap	See Gas Purification roadmap	See Gas Purification roadmap	See Gas Purification roadmap

TECHNOLOGY AREA: Gasification

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Advanced Gasifier (Gasifier concepts or advances beyond commercial gasifiers or gasifiers being demonstrated at commercial scale)	• Fuel feed flexibility: coal + up to 30% alternate fuel (e.g. biomass, petcoke) • Availability, >95% • Cold gas efficiency >82%	• Capital: $150/kW (see note 1) • Syn gas cost <$2.50/10^{6}Btu	Available gasifiers: • Operates on limited range of coals • Efficiency (cold gas) ~78% • Availability: <85% for single train	Available gasifiers: • Capital: $200-250/kW (see note 1) • Syn gas cost ~$4.00/10^{6}Btu
Solids Transport and Removal	• Reduced cost • Increased reliability	• Included with above gasification sub-system cost	• Limited experience with dry solids transfer systems at high-temperature, high-pressure conditions • High unreliability of current lockhopper systems	• Cost included with gasification sub-system costs
Gasifier Feed System (fuel flexible feed)	• Fuel feed flexibility: any coal + up to 30% alternate fuel • Availability, >95+ (gasifier island overall availability greater than 95%) • Operating pressure >400 to 1000 psi • No waste	• Capital: <20% of gasifier cost; est. ~ $30/kW • Minimum additional feed prep cost	• Developmental (available technology has limited fuel flexibility and limited pressure)	• Not available (cost of commercially used feed systems, e.g. coal slurry prep and feed is typically $50-65/kW)

(1) Includes gasifier, syn gas cooling and auxiliaries – does not include air separation, slag handling, feed system

TECHNOLOGY AREA: Gasification

Technology	Barrier	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Advanced Gasifier – Transport Gasifier	• Operability for steady state operation (both air and oxygen operation) • Sulfur removal • Tar production operating envelope • C loss from carryover • Reliability of solids handling • Process Control • Scale-up issues • Controlled feeding at high-pressures • Consistency of feedstock • Need for financial help to demonstrate new technology	• Pilot scale transport reactors built at North Dakota and PSDF (Wilsonville) • Commissioning tests • Syngas HHV limited to 80 Btu/scf • Current experience is 200 psi.	• Operate transport reactor pilot-scale units to develop operating system; develop process models to understand chemical/physical phenomena; modify plant(s) to resolve throughput and efficiency concerns • Demonstrate ability to achieve targeted performance using Wilsonville facility • Conduct systems design and integration studies to identify commercial plant design, cost, and operation concerns; use Wilsonville plant as an initial reference plant. • Identify opportunities to test advanced features for meeting target objectives at operating gasification plants; conduct tests of advanced features	• Demonstrate integrated gasifier/gas cleaning/gas turbine operation; utilize existing plants • Design innovative new demonstration plant concepts utilizing advanced gasifier(s)	• Carryout commercial scale demonstration (privately supported)

TECHNOLOGY AREA: Gasification

Technology	Barrier	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Advanced Gasifier – new innovative gasifier concepts	• Many types of gasifiers already developed over past decades (in-the-box thinking) • Cost competitivenes • Reliability • Key partnerships	• Several innovative gasifiers proposed (use metal oxide oxygen carriers, liquid metal reservoirs, etc.)	• Issue solicitation for advanced gasifier concepts • Assess innovative gasifier concepts that incorporate multiple functions • Technical and economic evaluation of proposed concepts • Implement projects to support attractive concepts	• Scale up concepts that are good candidates for commercial application	• Integrate new gasifiers with Vision 21 plant (use existing facilities where possible)
Advanced Gasifier – Innovative Fixed, Entrained or Fluid Bed Technology	• Component Life (e.g. refractory) • Carbon conversion • Cost	• Commercial plants are operating; innovation required to meet Vision 21 objectives	• Evaluate options that would result in achieving Vision 21 performance and cost goals • Evaluate CO2 removal options • Utilize existing plant sites to demonstrate Vision 21 performance goals	• Continue to implement projects that demonstrate technology advances that have potential to meet Vision 21 goals; utilize existing plant sites	• Demonstrate gasifier concepts that meet Vision 21 goals

TECHNOLOGY AREA: Gasification

Technology	Barrier	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Syn-Gas Cooling	• Materials life (corrosion) • Operability (e.g. deposition) • Cost • Superheat	• Technology available but performance improvements and cost reduction required to meet Vision 21 objectives	• see Materials roadmap • track status of commercial developments		
Solids transport and removal	• reliability (e.g. erosion, plugging, solids seals)	• see current technology performance	• Survey operating plant experience to understand problems and concerns • Identify priority needs to achieve system performance and cost objectives • Define and implement projects to solve key problems identified	• Test selected concepts at PSDF and other appropriate sites	• Demonstrate on commercial plant (privately supported)
Gasifier Feed System (fuel feed flexibility)	• Design for high pressure operation • Reliability • Diverse nature of feedstocks • Feedstock preparation	• Available technology may not meet objectives for co-feeding • Concepts for fuel flexibility have been proposed	• Evaluate fuel flexible feed system concepts versus separate feed systems • Issue solicitation. to develop feed system. • Develop design(s) and test critical components • Evaluate commercial designs	• Test selected concepts at PSDF and other appropriate sites	• Demonstrate on commercial plant (privately supported)

TECHNOLOGY AREA: Gas Purification

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Gas Contaminant Control Technology Syn-Gas/Combustion Turbines 1. High-Temperature Sorbent Systems 2. Novel Concepts 3. Improved cold clean up systems	Composition Alkali 0.1-0.5 ppm (<20 mg/millionBtu) Halides 0.6-3.0 ppm V 0.05-0.2 ppb Sulfur to meet environmental target: <0.01 lb/million Btu Reliability (to be specified) but very high Usable By-Products (no waste)	• Combined gas contaminant and particulate control cost: < $60/kW for oxygen-blown power application	• Cold Gas Cleaning Technology Available • High-temperature technology installed at Pinon Pine plant (focus on sulfur)	• Estimated to be ~ $130/kW for gas and particulate control (for an oxygen-blown system)
Gas Contaminant Control Technology Syn-Gas/Fuel Cells 1. High-Temperature Sorbent Systems 2. Novel Concepts 3. Improved cold gas clean up systems	Molten Carbonate Fuel Cell H_2S <0.5 ppm HCl <0.5 ppm NH_3 <1% vol AsH_3 <1 ppm SOFC H_2S <0.1 ppm HCl <1 ppm NH_3 <5000 ppm Reliability (to be specified) but very high Usable By-Products (no waste)	• Combined gas contaminant and particulate control reference cost: < $60/kW for oxygen-blown power application	• Cold gas cleaning technology available	•
Gas Contaminant Control Technology Syn-Gas/Fuels & Chemicals Production 1. High Temperature Sorbent Systems 2. Novel Concepts 3. Improved cold gas clean-up systems	Composition Total Sulfur <60 ppb Total Halide <10 ppb Acetylene <10 ppb Ammonia <10 ppb NOx <100 ppb HCN <10 ppb Iron Carbonyl <10 ppb Nickel Carbonyl <10 ppb Reliability (to be specified) but very high Usable By-Products (no waste)	• Combined gas contaminant and particulate control reference cost: < $60/kW for oxygen-blown application	• Cold gas cleaning technology available	• Estimated to be ~ $130/kW for gas and particulate control (for an oxygen-blown system)

TECHNOLOGY AREA: Gas Purification

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Gas Contaminant Control Technology PFBC/Power 1. High Temperature Sorbent Systems	Sulfur to meet environmental target: <0.01 lb/million Btu Alkali: < 20 ppb Reliability (to be specified) Usable By-Product (no waste)	• Cost included with PFBC sub-system cost	• Limestone/Dolomite used in commercial PFBC plants to meet current sulfur emission standards • Current NOx emissions met	• Cost of sorbent system integral with PFBC cost
Particulate Control Technology 1. High Temperature Barrier Filters 2. Granular Filters 3. Novel Concepts	<1 ppm (0 ppm > 10μ) Reliability (to be specified)	• Combined gas contaminant and particulate control cost: < $60/kW for oxygen-blown system	1. High –Temperature Barrier Filters Commercial Scale Demonstration <10 ppm: zero ppm>10 microns; Reliability : estimated service life 6 months 2. Granular Filters- Pilot scale 3. Novel Concepts- Developmental	1. High Temperature Barrier Filters Capital ~$40/kW 2. Granular Filters Not Available 3. Novel Concepts Not Available
Combined Particulate/Gas Contaminant Control Technology (Ultra-Clean Synthesis Gas Concepts)	• See above objectives for respective application	• Less than separate particulate plus gas contaminant controls: (< $60/kW)	• Laboratory testing of sorbents and membranes show promise of S capture to <1 ppm	• Not Available

TECHNOLOGY AREA: Gas Purification

Technology	Barrier	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Gas Contaminant Control Technology Syn-Gas/Combustion Turbines 1. High Temperature Sorbent Systems 2. Novel Concepts 3. Improved cold gas clean-up systems	• Attrition resistant sorbents for fluidized bed or transport reactors • High temperature sorbent performance and reactor design to achieve <1 ppm sulfur in product gas and alkali and other trace contaminant control. • Regenerability (adequate activity maintenance)	• Sorbent in full-scale transport reactor ready to be tested at Piñon Pine • Developing pilot-scale hot gas cleanup system at NETL to test sorbent performance and attrition resistance • Alternate sorbent candidates have been evaluated at bench-scale	• Determine trace element speciation and location in gas clean-up system • Long-term testing in full-scale transport reactor at Piñon Pine • Operate pilot-scale hot gas cleanup facility at NETL • Investigate techniques to achieve attrition resistant sorbent • Perform multiple-cycle tests at bench-scale to assess regenerability	• Evaluate long-term test results • Evaluate bench- and pilot-scale results for improved sorbent capabilities • Develop low-cost sorbent manufacturing techniques	• Establish commercial readiness
Gas Contaminant Control Technology Syn-Gas/Fuel Cells 1. High Temperature Sorbent Systems 2. Novel Concepts 3. Improved cold gas clean-up systems	See syn-gas/power application above; the increased performance requirements increase the barrier.	• Refer to Syn-Gas/Power	• Refer to Syn-Gas/Power (Note: There will be need for more than one gas cleaning system design–function of fuel, gaifier and application)	• Refer to Syn-Gas/Power	• Refer to Syn-Gas/Power
Gas Contaminant Control Technology Syn-Gas/Fuels 1. High Temperature Sorbent Systems 2. Novel Concepts 3. Improved cold gas clean-up systems	See syn-gas/power application above; the increased performance requirements increase the barriers.	• Refer to Syn-Gas/Power	• Refer to Syn-Gas/Power (Note: There will be need for more than one gas cleaning system design–function of fuel, gaifier and application)	• Refer to Syn-Gas/Power	• Refer to Syn-Gas/Power

TECHNOLOGY AREA: Gas Purification

Technology	Barrier	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Gas Contaminant Control Technology PFBC/Power 1. High Temperature Sorbent Systems	• Attririton resistant sorbent • Regenerability • Cost	• Sorbents currently in use but need improved performance	• Develop and test new sorbent at PSDF (Wilsonville)	• Utilize PFBC CCT project to demonstrate improved sorbent performance	
Particulate Control Technology 1. High Temperature Barrier Filters	1. Barrier Filters • Filter durability • Ash bridging • Fail-safe filter • Internal structure life • Fuel flexibility	1. Barrier Filters • Demonstration units are being operated • Projects are underway to address barrier issues • Filter operated at 700°F at Wabash IGCC successfully removing particulate	1. Barrier Filters • Utilize existing operating plants to demonstrate ability to meet performance and cost objectives • Utilize planned CCT projects (e.g. Pinon Pine, Lakeland to demonstrate capability.	1. Barrier Filters • Demonstrate on new commercial plant (PRIVATE	1. Barrier Filters
2. Granular Filters	2. Granular Filters – performance, reliability, and cost	2. Granular Filters • Preliminary testing completed at Westinghouse	3. Granular Filters • Select site to demonstrate an advanced concept	2. Granular Filters • Conduct testing at PSDF	3. Granular Filters • Demonstrate at commercial facility
3. Novel Concepts	4. Novel Concepts	3. Novel Concepts	3. Novel Concepts • Explore novel approaches to particulate control technology	3. Novel Concepts	3. Novel Concepts

TECHNOLOGY AREA: Gas Purification

Technology	Barrier	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Combined Particulate/Gas Contaminant Control Technology (Ultra-Clean Synthesis Gas Concepts)	• Low-cost, regenerable sulfur and halide sorbents with characterized performance • Reactor design to reduce cost and improve efficiency • Membranes suitable for high T,P operation • Instrumentation suitable for monitoring and analysis to ppb levels	• Two projects (Siemens-W, RTI) in place to develop hot/warm-gas cleanup technology • Laboratory-scale testing. Screening performance followed by optimization. • Configuration issues: moving bed reactor filtration and sorbent/membrane system.	• Demonstrate ability to meet performance requirements through small-scale tests • Complete process design studies to show integration with gasification system and downstream processes • Design and build integrated pilot-scale control system to test process concept	• Test control system concept with a gasification system	• Design, build and test control system concept in a demonstration plant environment. (PRIVATE)

TECHNOLOGY AREA: Gas Separation

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Air Separation Oxygen membrane Cryogenic Novel concepts	• Purity - For sequestration above 99.5% - For other cases depends on system and economics • Availability: >99% • Energy consumption <100 kWhr/ton O_2	• Capital:$10,000/T/D (separation plant) • Operating cost: $10-12/ton O2 • Flux/Cost of Membrane- scc/cm2/sec/$/cm2> 3.5 will give $2000/T/D of membrane cost	1. Not commercially available: lab-scale testing 2. Commercial systems ~ 390 kWhr/ton (cryogenic)	1. Not available 2. Capital: $16,000/T/D Operating cost: $20/ton O_2 (cryogenic)
Gas Separations – Hydrogen/Carbon Dioxide 1. Hydrogen Membranes (producing hydrogen and CO_2 rich streams from syngas)	1. Hydrogen Membranes • Purity >99% • Permeability: 100 $scm^3/cm^2/min$	1. Hydrogen Membranes • Capital cost $50-100/ft2 membrane • H2 cost $<\$4/10^{6}$Btu • Flux/cost of membrane >12 will give membrane capital $10,000/T/D	1. Hydrogen Membranes • Developmental	1. Hydrogen Membranes • Available H2 process cost $\$5/10^{6}$Btu (PSA) • Capital cost $.25/scf/D or $100,000/T/D (PSA)
2. CO2 Hydrates	2. CO2 Hydrates • >97% H2 recovery when separating CO2 from syngas • >86% CO2 separation	2. CO2 Hydrates • Capital cost ~$100/kW incremental for IGCC plant • Operating cost $10/ton CO2	2. CO2 Hydrates Available technologies for CO2 removal are absorption (MEA), adsorption, and cryogenics	2. CO2 Hydrates • Available process cost $27-30/ton CO2
3. CO_2 Membranes	3. CO_2 Membranes	3. CO_2 Membranes	3. CO_2 Membranes	3. CO_2 Membranes
4. Novel Concepts	4. Novel Concepts	4. Novel Concepts	4. Novel Concepts	4. Novel Concepts

TECHNOLOGY AREA: Gas Separation

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Air Separation 1. Oxygen membrane 2. Cryogenic 3. Novel concepts	1. Oxygen membranes • High-flux materials • Trace contaminant-resistant materials • Leak-proof metal/ceramic seals • Reliable manufacturing techniques for membrane/module production • Thermal integration with plant cycle • Structural integrity • Cost optimization: Temperature/ support hardware tradeoffs; Flux/material cost • Security classification of K-25 technologies	1. Oxygen membranes • Lab-scale development of materials and separation module concepts	1. Oxygen membranes • Develop new high flux and contaminant resistant materials. • Analyze and understand membrane stresses • Thermomechanical modeling and characterization of membrane structures(also applies to H_2 membranes) • Develop membrane fabrication technology and cost optimize • Develop module design technologies and test module at lab scale • Develop process design to resolve thermal integration issues; includes high temperature heat exchange (selected cycle) • Select a V21 plant cycle for O2 system technology demonstration • Consider metal substrates/membrane materials 2. Cryogenics • Rely on commercial market advances	1. Oxygen membranes • Test full-scale modules on simulated gas • Install and integrate O2 system in the selected cycle • Evaluate application of air separation system with alternative Vision 21 cycles and concepts	1. Oxygen membranes • Integrate into operating gasification plant

TECHNOLOGY AREA: Gas Separation

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
			3. Novel Concepts • Evaluate proposed technology advances for alternatives for meeting performance and cost targets.		
Gas Separations – Hydrogen/Carbon Dioxide 1. Hydrogen Membranes (producing hydrogen and CO_2 rich streams from syngas)	1. Hydrogen Membranes • High-flux materials • Trace contaminant resistant materials • Leak-proof metal/ceramic seals • Catalysts and kinetics for high-temperature water-gas shift reaction • Reliable manufacturing techniques for membrane/module production • Systems integration • Access to K-25 technology • Membrane materials consistent with gas clean-up operating temperature	1. Hydrogen Membranes • High-flux material development continuing (current flux ~$5 cm^3/cm^2/min$) • Testing begun to determine material resistance to trace-contaminants • Lab-scale testing of high-pressure components initiated	1. Hydrogen Membranes • Develop high flux, stable membrane materials • Form team to address material seal issues • Develop materials and seals (ANL) • Study potential for H2 membrane separation and integration with high-temperature water gas shift at bench scale (NETL) • Conduct contaminant assessment at bench-scale (NETL) • Establish industrial team to develop membrane/module manufacturing technology • Test module at bench-scale (0.1 ton/day) • Consider metal substrates/membrane materials	1. Hydrogen Membranes • Test full-scale module at 1 ton/day • Demonstrate integrated system with turbines and/or fuel cells (>10 ton/day)	1. Hydrogen Membranes Test pre-commercial membrane unit on slipstream at commercial gasification plant

TECHNOLOGY AREA: Gas Separation

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
2. CO2 Hydrates	2. CO2 Hydrates • Ability to release CO2 from hydrate in energy-efficient manner • Efficient method to capture CO2 • Stable prehydrate • Trace contaminants interfere with hydrate formation	2. CO2 Hydrates • Concept development begun (Simtech, Bechtel, LANL coop. agreement in place) for hydrogen/carbon dioxide	2. CO2 Hydrates • Determine feasibility of CO2 hydrate formation (LANL lab-scale experiments) • Collect bench-scale data for small skid-mounted pilot-plant using coal-derived gas • Conduct engineering and economic assessment • Conduct field test at gasification site	2. CO2 Hydrates To be determined by prior results and application objectives • Evaluate technology for combustion flue gas applications	2. CO2 Hydrates
3. CO_2 Membranes	3. CO_2 Membranes • High flux materials • Resistant to flue gas contaminants, temperature • Selectivity for CO2(separation factor) • Very low cost to treat large volumes • Cannot pressurize the flue gas so little driving force	3. CO_2 Membranes • Lab testing of membranes up to 250°C	2. CO_2 Membranes • Explore concepts using membranes for CO2 separation	3. CO_2 Membranes • Bench-scale testing on simulated gas	4. CO_2 Membranes • Test full-scale modules on simulated gas
4. Novel Concepts	4. Novel Concepts	4. Novel Concepts • Chemical absorption-solid adsorber-RTI for flue gas CO_2 removal	4. Novel Concepts • Determine feasibility of membrane and absorption process • Conduct engineering and economic assessment	5. Novel Concepts • Collect bench-scale data for small skid-mounted pilot-plant using coal-derived gas	3. Novel Concepts • Conduct field test at gasification site

TECHNOLOGY AREA: Turbines

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Fuel Flexible Advance Turbine(s)	• Efficiency – 60% HHV on coal gas (turbine efficiency consistent with this plant efficiency) • CO_2 Removal with Co-Production • Emissions: Single Digit of NOx; 0.02 b/10^6Btu of SOx • RAM excellence	• Capital cost for CT, HRSG, ST energy conversion system of $270 – 300/kW; CT cost of $135/kW	• Efficiency: 41.8%(HHV) combined cycle on coal gas • Emissions: NOx - <25 ppmv/day at 15% oxygen; .02 lb/10^6Btu	• $850 - $935/kW
Turbine(s) for Large Scale Fuel Cell Hybrid Systems	• Efficiency: 80% (LHV, gas) and 60% (HHV, coal) (turbine efficiency consistent with this plant efficiency) with intercooler and reheat • Emissions: Single Digit of NOx; 0.02lb/10^6BTU of SOx • CO_2 Removal with Co-Production • Zero Process Waste • Oil-free compression discharge	• 400-500 $/kW (gas); 1000-1500 $/kW (coal) • 5-7 cents/kWh	• 250 kW SOFC hybrid system either demonstrated or beginning operation • Concept design studies targeting performance objectives of 70 plus for LHV gas • Already demonstrated negligible NOx and SOx emissions on fuel cell systems	• Current cost estimate $5000-$10,000 per kW
Natural Gas/Oxygen /Hydrogen Turbine	• Efficiency – 60% HHV on coal gas (turbine efficiency consistent with this plant efficiency) • CO_2 Removal with Co-Production • Emissions: Single Digit of NOx; 0.02 lb/10^6BTU of SOx • Zero Process Waste	• Capital cost for CT, HRSG, ST energy conversion system of $270 – 300/kW; CT cost of $135/kW	• Not Applicable (Concept studies have projected 71% LHV; 60% HHV)	• Not Applicable (Concept studies have projected cost for various cycles)

TECHNOLOGY AREA: Turbines

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Innovative Concepts - CO_2-based reheat combustion turbine system	• To be determined by reference plant cycle studies.	• To be determined by reference plant cycle studies.	• Not Applicable (Concept studies have projected efficiencies for various cycles)	• Not Applicable (Concept studies have projected cost for various cycles)

TECHNOLOGY AREA: Turbines

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Fuel Flexible Advance Turbine(s)	• Development of a 3000FT gas turbine technology • Integration with high pressure oxygen blown gasification, hot fuel gas treatment, integrated high pressure air separation unit • Development of single digit emissions ultra-high pressure ratio/temperature combustion systems which can operate on high temperature coal gas • Need hot fuel gas treatment • Plant permitting with multi-products • High cost of specialized new turbo machinery (turbine and combustor) coupled with low level of DOE funding • Although fuels vary too much for unified combustion design; rugged turbine needed for alternate fuels	• Advanced Turbine Systems have been developed 2600 FT for natural gas use and will be demonstrated by the year 2002 • Current steam cycles available for 1800 psig/1050°F/1050°F operating conditions • Gas turbine combustors operable at low pressures and 9ppm NOx @15% O_2 using natural gas • Tailored compressions are available	• Carryout market analysis and define performance targets • Perform steady state performance simulation model, plant design performance, and potential cycle performance improvements • Identify turbine re-design for cycle improvement • Simulate and test advanced combustor concepts at subscale for high pressure/temperature coal gas operation/redesign concept to full scale • Identify viable high temperature/ corrosion resistant materials for coatings/advanced high temperature turbines(see materials roadmap) • Develop approval to provide tailored first-time-right turbines • Establish DOE-EPA cooperation • Explore federal type-certification for plant • Assess setting common specs foe alternate fuels to enable combustor commonization	• Redesign (if required) gas and steam turbines (combustor, compressor, turbine section) for integration into selected coal V21 plant(see gasification/ combustion roadmaps) • Field verify full scale combustor concepts on coal gas plant slipstream • Cast full scale turbine components with viable materials/test coatings under actual operating conditions.	• Conduct long term full-scale turbine components tests to establish reliability and validate performance • Redo simulation model predictions with full-scale component validation data • Perform virtual simulation with integrated system components.

TECHNOLOGY AREA: Turbines

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Turbine(s) for Large Scale Fuel Cell Hybrid Systems	• Fuel cell design for high efficiency cost competitiveness for hybrid systems including advanced materials, manufacturing technologies and stack designs • Scalable turbine systems have not been designed to optimize hybrid performance and integration options • Optimal system operation controls and integration components do not exist for highly integrated systems with respect to load following and other process dynamics • Special purpose BOP components or designs: turbines, recuperators, controls • Unproven designs for highly integrated high efficiency systems	• Microturbines exist up to 100kW for integration into a 60% efficient hybrid system – only SOFC system has been operated • Industrial turbines exist for integration into a 20MW SOFC (60%) hybrid system. • Short term integration tests have been performed only on a 250kW SOFC hybrid configuration	• Demonstrate 1MW hybrid SOFC and MCFC systems • Optimize scalable turbine design configuration for the 60% efficient, hybrid system • Conduct system studies for Vision 21 hybrid configurations to define >70% system and configure demonstration power plants for mid-term years	• Scale-up turbine designs for integrated 70% efficient hybrids. • Demonstrate 70% efficient hybrid systems on natural gas fuel • Perform system analysis for coal gas based hybrids and sub scale tests of system components • System studies with advanced fuel cells • Development of long term hybrids	• Resolve any technical issues resulting from integration with gasification • Demonstration of >75% hybrid systems on natural gas • Demonstration of >55% hybrid systems on coal gas

TECHNOLOGY AREA: Turbines

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Natural Gas/Oxygen Fueled-Hydrogen/Steam Turbine Systems	• Oxygen/water mixing technology is significant challenge • Compatible steam turbine (3000°F, 3000 psi) does not exist • Lack of combustor and turbine section ultra-high temperature/ pressure materials with up to 40,000 hours of durable life expectancy • Limited experience with natural gas/oxygen fueled turbine and high temperature/ pressure steam turbines for land-based machines	• Limited lab testing (Clean Energy Systems/Japanese New Sunshine Program) • Single gas generator for the CES concept under test • No power test unit has been built; preliminary design studies underway • Hardware not available for HP & HT turbomachinary	• Prepare scoping document that identifies technical concerns and design options (e.g. address fuel gas injection may call for exceptional gas compressor, hydrogen embrittlement, load shed overspeed, etc) • Fabricate a test article (simulates 10 MW generator) to be used in a test program design to demonstrate non-polluting aspects of gas generator • Operate subscale, state of the art demonstration unit to validate concept • Design to demonstrate stoichiometric combustion of CH_4/O_2 with efficient water quench. • Develop steam turbine materials • Identify alternate hydrogen based cycles	• Build a prototype system with advanced steam turbine sections and multiple gas generators, operate on natural gas and coal gas slipstream • Perform long term testing to evaluate creep, fatigue, heat transfer effectiveness, and overall performance • Evaluate alternate hydrogen based concepts and select candidates for development	• Complete plant design with coal gas • Integrate and demonstrate with gasifier, advanced steam turbine, and carbon sequestration options at subscale output rating(<50MW). • Performa virtual simulation on various configurations with coal gas

TECHNOLOGY AREA: Turbines

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Innovative Concepts (e.g., CO_2-based reheat combustion turbine cycle; - chemical-looping combustion)	- Need for fundamental understanding	• CO_2 based reheat combustion turbine cycle has been studied in other countries; technical issues identified	• Prepare assessment that identifies candidate innovative concepts and presents initial analysis. Submit for external review. • Issue solicitation to investigate the performance and technical barriers for the CO_2 based reheat combustion turbine cycle	• If the CO_2 reheat cycle is attractive, develop components to demonstrate feasibility	• Complete plant design • Virtual simulation with coal gas

TECHNOLOGY AREA: Fuel Cells

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Fuel Cell *(materials, stack, module)*	• 80,000 hour minimum operating life (10 years) • Improved performance consistent with fuel and application requirements - improved cyclic life - increased power density - higher conversion efficiency - more sulfur tolerance	• 100-200 $/kW	• Endurance testing for 100-250 kW stacks in excess of 10,000 to 15,000 hours and cells in excess of 80,000 hours • Limited sulfur tolerance (100s of ppb level) • Limited cyclic life • Conversion efficiency nominally around 50%	• Currently on cost reduction curve to meet cost targets for distributed power stand-alone systems • Order of magnitude capital cost reduction required to meet Vision 21 targets
Gaseous Fuel Processing *(cleanup, conditioning,, reforming)*	• Integrated reformer for gaseous fuels • Gaseous fuel comes from any source (e.g., natural gas, distillates, coal gas, biomass derived syngas) • Limited sulfur removal, and tolerance (bulk sulfur removal in gas purification system) • Hot-gas clean-up (see gas purification roadmap)	• Gaseous processing cost included in fuel cell cost • Gas clean-up NOT included (part of gas purification system)	• Integrated internal reformer in Siemens Westinghouse Power Corporation (tubular) SOFC, demonstrated in 250 kW power plant • Direct internal reforming in Fuel Cell Energy Inc. MCFC, demonstrated in 250 kW power plant • External sulfur polishing	• Included in fuel cell
Power Conditioning *(inversion, interconnect)*	• Industry accepted standard • Specifications must meet system and power quality requirements (including load dynamic response) • Efficiency: 98%	• 50 - 75 $/kW	• Efficiency: 90 –95%	• 150 – 300 $/kW

TECHNOLOGY AREA: Fuel Cells

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Fuel Cell BOP ***(single cycle BOP, combined cycle hybrids, CO_2 sequestration ready, co-generation, fuels production, integrating modules, scale-up)*** NOTE: see Turbine Roadmap section "Turbines for Large Scale Fuel Cell Hybrid Systems" for related fuel cell BOP considerations.	• amenable to hybrid cycle integration and upstream gas conditioning • amenable to CO_2 capture • standard module definition • design for integration of modules into plant • efficient thermal and water management	• 200-300 $/kW	• Integrated fuel cell systems in demonstration include: - One 250 kW SOFC hybrid system - Multiple demonstrations of both MCFC and SOFC simple cycle systems - Vision 21 Concept design studies are currently underway - To-date only single module systems have been demonstrated - Some syn-gas fueled systems have been demonstrated	• Vision 21 Concept design studies are underway • Customized development costs are very high

TECHNOLOGY AREA: Fuel Cells

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Fuel Cell *(materials, stack, module)*	• Use of low cost materials & fabrication techniques • Too high on learning curve and need identification of new technologies for stack cost reduction • Insufficient acceptance and growth of a market for fuel cell modules (establishing an entry market) • Lack of capabilities to meet expanded requirements of Vision 21 (e.g., module integration, sulfur tolerance) • Lack of designs for high efficiency, large scale applications (~300 MW) • Insufficient endurance at full scale - Cyclic operation - Various stack issues (e.g., stability of seals, electrodes, electrolyte, interconnects) - Sulfur intolerance	• Use of low cost materials and fabrication techniques currently under investigation by industry • Manufacturers investing in design and manufacturing plants (to increase from current capability of ~10 MW/year) • Various manufacturers introducing limited number of small fuel cells and micro-turbines in distributed applications • Commercialization groups formed to condition market • Endurance testing for 100-250 kW stacks in excess of 10,000 to 15,000 hours and cells in excess of 80,000 hours • (See Current Technology Performance for other comments)	• Leverage SECA advances as identified in workshop & R&D roadmap: - *materials & manufacturing* - *fuel processing* - *power electronics* - *modeling & simulation* - *thermal systems* (national labs, universities, developers) • Product Development Improvement Objective: commercial entry of Siemens Westinghouse SOFC & Fuel Cell Energy MCFC for 250 kW to 3.0 MW applications • First commercial sales of SOFC and MCFC products (DG applications) • Vision 21 Fuel Cell Materials Program must address sulfur tolerance, cyclic life, power density, thermal management, etc. • Demonstrate Vision 21 concepts at cell level – e.g. next generation stack	• Leverage SECA Phase II program advances • Commercial entry of natural gas fueled hybrid FC/GT systems for 20 MW distributed generation applications • Significant commercial sales of SOFC and MCFC products • Vision 21 enhanced module testing for use with natural gas and syn-gas • Proof of Concept Demonstration at MW scale (cycling, sulfur tolerance, thermal management, power density)	• Leverage SECA Phase III: commercialization of power system module for small stationary and APU applications (cost target $400 /kW) • Significant market share (1000s of MW) for SOFC and MCFC products • Vision 21 operation of integrated 30 MW high efficiency fuel cell and coal gasifier system • Standard design for modular scale up to 100s of MW plant

TECHNOLOGY AREA: Fuel Cells

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Gaseous Fuel Processing (*cleanup, conditioning, reforming)*	• High temperature gas clean-up (see gas purification roadmap) • Conversion efficiency and increased fuel utilization • Sulfur tolerance • Composition of gas – compatibility with Vision 21 plant capability • Ability to handle variations in composition • Currently CO_2 is not captured	• Limited work to address hot gas clean-up and integration with fuel cell system • 70-85% conversion efficiency • limited sulfur tolerance and limited work to address sulfur	• Leverage development and demonstration of reformers for distillates in SECA Phase I • Prove Vision 21 syn-gas operation (Gasification area must address gaseous fuel generation and clean-up) • Need to develop sulfur tolerance • Develop means of separating CO2 • Develop transient performance capability for processor	• Leverage development and demonstration of multi-fuel capability in SECA Phase II • Demonstrate proof of concept gaseous fuel processor integrated with fuel cell subsystem • Define and design the standard module for demonstration in 10-15 year time frame	• Development and demonstration of internal reforming in SECA Phase III • Vision 21 operation of integrated 30 MW, high efficiency fuel cell and coal gasifier system • Standard design for modular scale up to 100s of MW plant
Power Conditioning *(inversion, interconnect)*	• Scale-up to large scale applications above 30 MW • Optimized power electronics for fuel cell and hybrid applications (both turbine and fuel cell)	• Modular, small capacity units adapted for fuel cell applications • Existing high voltage DC and flexible AC Control Technology (FACT)	• Reliance on commercial market through demonstration programs (U.S. Department of Defense Buydown Program, Product Development Improvement awards for SOFC & MCFC) • Power Conditioning Systems and Interconnect Standards (IEEE) • Leverage other federally funded research • Leverage Existing high voltage DC and flexible AC Control Technology (FACT) for central station fuel cell power plant	• Reliance on commercial market for demonstration units	• Reliance on commercial market for demonstration units

TECHNOLOGY AREA: Fuel Cells

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Fuel Cell BOP *(single cycle BOP, combined cycle hybrids*, *CO_2 sequestration ready, co-generation, fuels production)* NOTE: see Turbine Roadmap section "Turbines for Large Scale Fuel Cell Hybrid Systems" for related fuel cell BOP considerations.	• Design of Systems and module compatible with central station plant (e.g. 100-300 MW) • Unproven designs for highly integrated, large scale, high efficiency systems • Understanding of component dynamics • Process control techniques for new, highly integrated systems with respect to load following and other process dynamics • CO_2 sequestration ready designs	• Fuel Cell Energy Inc (FCE) 2.0 MW (Santa Clara), and 250 kW FCE Demonstrations • Siemens-Westinghouse Power Systems (SWPC) 25 kW, 100 kW, and 250 kW SOFC systems demonstrated	• Gas separation technology development • System dynamics investigation and model development • Design of fuel cell unit for module approach	• Demonstrate fuel cell module on natural gas (large systems >30MW) • Design module for coal operation (large systems >30MW) • Demonstrate CO2 sequestration readiness	• Demonstration of a ~30 MW system on coal gas • Demonstrate integrated natural gas system that meets Vision 21 goals

TECHNOLOGY AREA: Synthesis Gas Conversion to Fuels & Chemicals

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives [1/]	Current Technology Performance	Current Technology Cost
Fischer-Tropsch (FT) Reactor System (3-phase slurry)	• Reactor: 10,000 barrels/day - small commercial scale (integrated w/IGCC) • Catalyst: iron or novel catalyst w/ feed synthesis gas H_2:CO capability of 0.6-1.5; • Product: <5% C1-C4 • High yield to diesel >50% C10-C20	• Total Product Value $15-20/bbl • Capital and Operating Cost Criteria for integrated subsystem difficult to specify • Standalone Gas-to-Liquid - Capital: $15K/b/d - Operating:<$5/bbl[2/]	• 2500 barrel/day com'l unit (SASOL) using natural gas - derived synthesis gas probably w/ cobalt catalyst; 15,000 barrel/day planned . • SASOL Coal-to-Liquids complex (SASOL-I, II, and III) • Other companies, domestic and foreign, have tested processes at various scales using cobalt and iron catalysts	• GTL Capital: $25K/barrel (SASOL technology) • Coal-to-Liquid Capital: study planned to revise earlier cost estimates. • Operating: Not available

1/ Costs are based on barrels of installed capacity, expressed as equivalent crude oil price; operating cost includes labor, maintenance and catalyst

2/ Excludes any premium due to superior quality. Doubtful whether product price premium can be expected for high cetane and/or ultra-low sulfur syn-crude. Refiners will absorb higher cost of crude refining.

Note: See gas separations roadmap for hydrogen membranes

TECHNOLOGY AREA: Synthesis Gas Conversion to Fuels & Chemicals

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives 1/	Current Technology Performance	Current Technology Cost
Methanol Synthesis (3 phase slurry reactor)	• Synthesis gas conversion: >50% • Availability: >99% • Catalyst activity: >50% after 6 months • Demonstrate successful fuel performance in variety of applications: -Fuel cells -Turbines -Gasoline? and diesel engines • Optimize use of MeOH as intermediate in integrated energy plant (MeOH as energy storage medium for peak shaving)	• Product: $0.10/gal less than methanol from conventional gas-phase reactor • Low cost integrated option for energy storage • Define cost requirements for acceptability of MeOH in fuel applications.	• 2000 barrel/day Liquid Phase Methanol (LPMEOH™) plant operating as Clean Coal Demonstration • Current feasibility study of integrating LPMEOH™ technology with Wabash River IGCC facility • Some product testing begun for various power/fuel applications	• Approx. $0.60/gal

1/ Based on 4000 barrel/day plant integrated with IGCC

TECHNOLOGY AREA: Synthesis Gas Conversion to Fuels & Chemicals

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Non-Syngas Routes to Fuels and Chemicals - Pyrolytic processes - Extraction Processes - Hydrocarbon Coupling Reactions	• Products Supply and Quality commercially competitive	• Commercially competitive price for products	• No commercial processes (excluding coking)	• NA
Alternative Chemicals and Fuels from Syngas (e.g., DME, olefins, acetic anhydride)	• Products Supply and Quality commercially competitive	• Commercially competitive price for products	• Eastman Chemical Plant • SASOL Plant (see above)	• Cost data not available

TECHNOLOGY AREA: Synthesis Gas Conversion to Fuels & Chemicals

Technology	Barrier	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
F-T Reactor System (3-phase slurry)	• Catalyst performance(e.g, activity, attrition resistance, deactivation resistance, product selectivity) • Catalyst recovery • Reactor efficiency (e.g. gas distribution, fluid dynamics, heat removal) • Feedstock price • Systems engineering to develop optimum strategies for cost reduction and environmental performance	• Promising iron and novel catalysts and separation technologies need to move from lab to evaluation in larger scale test units • Slurry reactor technology under development • Feedstock prices high • Overall economics could be acceptable today (given current oil prices), but too risky for investment without technology improvement	• Continue catalyst and reactor development efforts that culminate in tests at LaPorte, or in similar scale test facility • Complete co-production feasibility studies, R&D and preliminary plant engineering designs • Continue life cycle systems studies to help achieve targeted cost and emissions reductions	• Test co-production of fuels and/or chemicals with electricity at pre-commercial scale • Test fuel production in stand-alone pre-commercial scale facilities • Continue incorporating lab/ bench scale R&D and systems engineering guidance in development and testing of innovative F-T processes	• Deploy commercial co-production and stand-alone F-T fuel plants (PRIVATE)

TECHNOLOGY AREA: Synthesis Gas Conversion to Fuels & Chemicals

Technology	Barrier	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Methanol Synthesis (3 phase slurry reactor)	• Catalyst poisoning due to synthesis gas contaminants, e.g. arsenic and sulfur • Reactor size • Volatile methanol market and phase-out of MTBE requires evaluation of alternative uses for product. Requires developing fuel usage for MeOH	• Base technology demonstrated; all product being used as feedstock for chemical production • Promising results indicate potential for redesigning reactor for lower capital cost	• Complete feasibility study and R&D for coproduction (Wabash IGCC) • Systems analysis for use of MeOH as energy storage or energy transfer medium in integrated energy plant • Select suitable techniques for removing synthesis gas contaminants or develop poison resistant catalysts • Complete end-use testing of methanol product in key applications (fuel cells, turbines)	• Test co-production of methanol with electricity at pre-commercial scale • Test methanol production in stand-alone mode pre-commercial scale facilities • Continue incorporating lab/ bench scale R&D and systems engineering guidance in development and testing of improved methanol synthesis technology	• Deploy commercial co-production and stand-alone methanol fuel plants (PRIVATE)
Non-Syngas Routes to Fuels and Chemicals	• Environmental • Cost • Product acceptability	• Various processes were commercial; No current commercial processes (excluding coking) • Coal extraction projects being implemented	• Expand laboratory work for coal extraction process • Monitor new technology concepts evaluate on merit	• Carry out plant design and cost studies for process concepts that are attractive based on systems analysis • Implement technology development projects for novel approaches based on systems analysis	

TECHNOLOGY AREA: Synthesis Gas Conversion to Fuels & Chemicals

Technology	Barrier	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Alternate Chemicals and Fuels from Syngas	• Cost • Infrastructure compatibility	• Eastman Chemical Plant	• Continue C1 chemistry Program • Monitor new technology options and changes in market that may present future opportunities	• Carry out plant design and cost studies for process concepts that are attractive based on systems analysis • Implement technology development projects for novel approaches based on systems analysis	

TECHNOLOGY AREA: Environmental Control Technology

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives 1)	Current Technology Performance	Current Technology Cost
By-Product Recovery and Utilization	• Minimal waste from processing • Meet environmental and market requirements for product(s) • Minimal energy for processing	• By-product competitive with alternative products	• Technology under development to produce marketable products from coal combustion by-products (CCBs) (e.g., CONSOL, ABB-Alstom) • Technology under development to separate fly ash from unburned coal (UBC) • PC CCBs currently being used as soil amendments, underground mine fill, mine supports, road/trail aggregate, etc. • Technology available for sulfur/acid recovery	• Ash/slag processing cost/credit varies with application • Sulfur/acid recovery – estimate $55/kW • Landfill costs ~$2/ton • New landfill construction $30-$50/ton
Removal/Control of NH_3 from combustion based processes (see also gas purification roadmap)	• Meet regulatory requirements for ground, surface, and drinking water	• Cost of emission control must be comparable with competitive total plant cost	• Cost-competitive technology does not exist for removing NH_3 from fly ash • Technology does exist to remove ammonia from wastewater	• Reference cost applicable for Vision 21 concepts to be determined
NOx Emissions Control	• 0.01 lb/MM Btu (approximately 7ppm for coal-based systems)	• Cost of emission control must be comparable with competitive total plant cost	• Turbine combustor designs – 9-25 ppm • Low temp selective catalytic reduction (SCR) technology – 2 ppm • 0.15 lb NOx/MMBtu or less for PC boilers	• Primary control integrated with energy conversion sub-system cost • SCR - $60-90/kW • SNCR - $15/kW • LNBs - $10-$30/kW

TECHNOLOGY AREA: Environmental Control Technology

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives (1)	Current Technology Performance	Current Technology Cost
SOx Emissions Control	• 0.01 lb/MMBtu (equivalent to 99.95% removed for 3% sulfur coal)	• Cost of emission control must be comparable with competitive total plant cost • See also gas purification roadmap	• Technology (wet FGD) available to achieve > 98% removal • Acid gas (SO3) control more problematic	• \$500 -\$1,000/ton of SO_2 • \$200/kW – combustion process • See also gas purification roadmap
VOC Emissions Control	• Meets or exceeds regulators requirements	• Cost integral with subsystem requiring VOC control – if needed	• VOC control not applied to current coal-based power plants	• N/A
Particulate Emission Control	• PM objectives of 0.005 lb/MMBtu	• Cost of emission control must be comparable with competitive total plant cost • See also gas purification roadmap	• ESPs and baghouses can achieve > 99% control of particulates • NSPS standards for PM is 0.03 lb/MMBtu	• See also gas purification roadmap
Mercury Control	• Greater than 95% reduction	• Cost of emission control must be comparable with competitive total plant cost	• Field demonstration scale testing to achieve 50%-70% reduction • Bench- and pilot-scale development of technology for achieving 90% reduction • EPA has not yet established Hg control standards for power plants	• Preliminary cost estimates in the range of \$50,000 per pound of mercury removed from PC flue gas • Cost target for DOE program 25-50% reduction over current estimates (see above)
Water	• Significantly reduced consumption • Near zero discharge	• Cost of emission control must be comparable with competitive total plant cost • \$10-\$15/kW for dry cooling system	• Technology available to meet current NPDES permit requirements • Waste water treatment technology available to meet existing effluent standards • Wet and dry cooling technology available	• Estimate \$10/kW for waste water treatment • Mechanical draft tower - \$6-8/kW • Natural draft tower - \$10-14/kW • Hybrid (wet/dry) tower - \$12-18/kW • Dry system - \$20-30/kW

(1) Environmental control cost allocation of \$110/kW estimated for a reference Vision 21 oxygen-blown gasification power application includes by-product recovery, waste water treatment, and any additional removal of NOx, Hg or other environmental contaminants. Environmental control technologies for NOx and mercury are in addition to removal that has been accomplished in the gas purification plant sub-system or the energy conversion plant sub-system.

TECHNOLOGY AREA: Environmental Control Technology

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
By-Product Recovery and Utilization	• CCBs must compete on a cost basis with established materials • Improved technologies for treating/separating byproducts from contaminants are needed • Potential implications of more stringent arsenic drinking water standard • C in fly ash adversely affects concrete • Potential regulatory roadblocks, e.g., future RCRA Subtitle C determination • Liability associated with ash/slag that may contain toxic elements or other constituents • CCB variability due to process change and technologies for exploited ash/slag with new properties • Impacts of environmental technologies (e.g., NOx control increases C in ash), particularly multi-pollutant control strategies • CCB processing (e.g., UBC/fly ash separation) costs remain high • Negative public perception of CCBs	• In 2000, ~32% of CCBs being commercially utilized. • CCBs exempt from Subtitle C (hazardous waste) classification • Technologies under development to produce light weight aggregate from coal gasifier slag and from wet FGD sludge. • Characterizing impacts of Hg control technologies on CCBs • CBRC (Combustion By-Products Recycling Consortium coordinated by West Virginia University) funds 18 projects (through early 2002) ranging from basic research to demonstration of utilization • Development of advanced low NOx burner technology that could increase UBC in fly ash	• Implement projects selected from second CBRC solicitation • Increase PC CCB utilization rate to 40%. • Assess by-product recovery needs in a Vision 21 plant (e.g., sorbents, catalysts, used components such as fuel cells, etc.); coordinate with technology areas and industrial ecology task • Evaluate implications of environmental impact for solid waste stream recovery options for reference Vision 21 plant designs • Commercial-scale demonstration of CCB separation and processing technologies • Demonstrate use of CCBs as terrestrial sequestration soil amendment	• Develop largest potential markets for ash/slag products • Increase PC CCB utilization rate to 50% • Assess spent catalyst recycle options • Assess recycle options for advanced regenerable sorbents for sulfur, mercury or other contaminant removal	• Demonstrate commercial product use for Vision 21 plant effluents (Private)

TECHNOLOGY AREA: Environmental Control Technology

Technology	**Barriers**	**Current Status**	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
By-Product Recovery and Utilization (cont'd)			• Identify new technologies that reduce NOx but that don't lead to C in ash • Continue characterization of environmental implications of CCBs.		
Removal/Control of NH_3 from combustion based processes (See also gas purification roadmap)	• Ammonia-based (SCR and SNCR) NOx technologies could impact flyash utilization. • Impacts of NH_3 adsorbed on flyash on water quality and worker health and safety (off-gassing). • On-site aqueous NH_3 storage a safety hazard. • Lack of methods for high T NH_3 from gasification products • Lack of methods for low T NH_3 removal at the <1 ppm level • NH3 emissions create plume opacity problems	• Developing and testing continuous NH_3 analyzers. • Use of a variety of oxidizing agents to produce NO_2 (ozone, methanol) • Gaining operational experience with full-scale SNCR and SCR systems.	• Demonstrate on-line NH3 analyzers and ancillary SCR/SNCR control systems. • Evaluate at bench- and pilot-scale alternative NOx reduction reagents • Pilot-scale testing and development of alternatives to SCR and SNCR • Identify need for additional NH_3 removal in Vision 21 plant concept	• Develop NH_3 control options if additional needs identified for Vision 21 plants	• Demonstrate for Vision 21 plant concept applications

TECHNOLOGY AREA: Environmental Control Technology

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
NOx Emission Control	• See energy conversion technologies for primary control barriers • Impacts of combustion controls on plant efficiency (heat rate) and on UBC. • Impacts of post combustion controls (SNCR/SCR) on balance-of-plant, e.g., NH3 on flyash, ammonium bisulfate pluggage, etc. • Improved catalyst performance and catalyst management plan for final control • Current NOx technologies are relatively expensive	• SCONOX technology available • SCR and SNCR technology currently being employed on PC boilers to meet NOx SIP Call • LNBs a practiced technology • High NOx (>80%) reduction only achieved via SCR • LoTOx, an ozone-based technology • DOE is carrying out pilot-scale development of advanced NOx control systems capable of achieving 0.15 lb/mmBtu NOx, including ULNB, O2-enhanced combustion and methane deNOx	• Reliance on turbine program and commercial market to meet target NOx minimization using SCR technology. • Review Vision 21 plant concepts and technology module performance targets to identify process streams that will require additional NOx control • Identify technology to meet Vision 21 plant requirements *The following initiatives may be required to achieve Vision 21 objectives:* • Develop alternative catalytic materials for SCR • Field demonstration of advanced NOx controls such as Ultra Low NOx burners • Evaluate impact of SCR catalyst on Hg oxidation and capture	• Implement additional control technology projects if needed to meet projected Vision 21 plant requirements • Commercial demonstration of advanced NOx control technologies (Private)	

TECHNOLOGY AREA: Environmental Control Technology

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
NOx Emission Control (cont'd)			• Develop alternative technologies to SCONOX and SCR (i.e., non-catalytic methods) • Evaluate performance of alternate reducing agents such as CO, H2, CH4, hydrocarbons		
VOC Emission Control	• Need for formaldehyde control		• Monitor need for VOC control		
SOx Emission Control	• Low-S eastern coal reserves limited • High capital and operating costs of wet FGD • Wet FGD generates significant volume of byproducts for disposal or reuse • Mercury could impact utilization of scrubber byproducts (e.g., wallboard) • Toxic Release Inventory (TRI) data increasing public's concern of acid gases (SO_3) • Uncertainty about SO_2 reductions to address PM2.5 and visibility issues • Limited industry confidence in dry scrubbing technology	• Field (slipstream) demonstration of sorbent injection for controlling SO_3. • Field demonstration of concept to increase capture of Hg across wet FGD	• Full scale demonstration of acid gas (SO_3, HF, HCl) control technology • Develop and demonstrate lower-cost SO_2 control technology (e.g., duct injection) to address visibility/fine particulate issues • Review Vision 21 plant concepts and technology module performance targets to identify process streams that will require additional sulfur control • Identify technology to meet Vision 21 plant requirements	• Implement additional control technology projects if needed to meet projected Vision 21 plant requirements • Commercial demonstration of advanced SOx control technologies (Private)	

TECHNOLOGY AREA: Environmental Control Technology

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Particulate Emission Control	• TRI data increasing public's concern of metal releases • Implications of control of metals on use/disposal of CCBs • Aging of existing ESP fleet and concomitant decrease in efficiency • Low-S (western) coal impacts on ESP performance (i.e., resistivity impacts)	• Slip-stream testing of advanced hybrid particulate collector capable of 99.99% fine particles • Field testing of non-toxic additives to improve EPS performance with low-S coals • Pilot-scale development of advanced Electro-Core particulate separation technology	• Full scale commercial demonstration of advanced particulate control technology (AHPC, ElectroCore) • Full scale demonstration of ESP additives • Review Vision 21 plant concepts and technology module performance targets to identify process streams that will require additional particulate emission control • Identify technology to meet Vision 21 plant requirements	• Implement additional control technology projects if needed to meet projected Vision 21 plant requirements • Commercial demonstration of advanced particulate control technologies (Private)	

TECHNOLOGY AREA: Environmental Control Technology

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Mercury Removal	• No full-scale commercial operation experience on PC boilers • Context of pending Hg regulations undefined • Hg removal from PC systems sensitive to many factors, including Hg species • Capability to measure ppb level of mercury in the gas stream on a continuous basis • In gasification, Hg removal difficult if done after S (i.e., must be done pre-combustion) • Hg sorbents sensitive to temperature, Hg species, and flue gas moisture • Transfer of Hg from flue gas to solid and liquid byproducts • Hg re-volatilization and leaching from CCBs • Environmental control methods can negatively impact Hg mobility (i.e., Hg is best left as sulfide)	• Selections under Topic Area IV (advanced concepts) of Hg solicitation • EPA makes "positive" regulatory determination • ICR data collected and analyzed by EPA and DOE • Continue bench- and pilot-scale optimization of Hg sorbents • Initiated field scale demonstration of two Hg control concepts • Characterization of Hg in CCBs	• Full-scale demonstration of sorbent injection of wet scrubbing processes • Develop upstream, dry, high temperature removal method for removal of Hg for gasification systems • Develop and field test Hg continuous emission monitors • Develop technology to sequester Hg in solid byproducts • Continue to characterize CCBs/effluents from demonstration projects • Review Vision 21 plant concepts and technology module performance targets to identify process streams that will require additional Hg control • Identify technology to meet Vision 21 plant requirements	• Continue collection of data from full-scale Hg control technology demo projects • Implement additional control technology projects if needed to meet projected Vision 21 plant requirements • Commercial demonstration of advanced Hg control technologies (Private)	

TECHNOLOGY AREA: Environmental Control Technology

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Water	• Availability issues, particularly in western states. • Limitations of use of cooling water due to adverse environmental impacts. • Implications of air emissions on water quality under the CWA 316 (b) cooling water intake rule impact on new and existing plants • Energy penalties associated with wet and dry cooling systems • Increased greenhouse gas emissions from plants impacted by 316(b) • Wetland regulations and siting issues	• Assessing impacts of 316(b) on PC plants	• Develop and test more efficient wet and dry cooling systems • Review Vision 21 plant concepts and technology module performance targets to identify process streams that will require water treatment or where water use can be minimized • Identify technology to meet Vision 21 plant requirements	• Full-scale demonstration of advanced wet cooling systems (Privately funded) • Full-scale demonstration of advanced dry cooling systems (Privately funded) • Implement additional control technology projects if needed to meet projected Vision 21 plant requirements • Commercial demonstration of advanced water treatment technology (Private)	

TECHNOLOGY AREA: Materials

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
High Temperature Heat Exchange Materials (super heaters, reheaters, recuperators)	Advanced Wrought Alloys • 750°C capability in superheaters and reheaters • >650°C capability in gas turbine recuperators • Corrosion resistance for 30 year life • Fabricable and weldable	Advanced Wrought Alloys • Within 20% of current technology	Advanced Wrought Alloys • <600°C capability in superheaters and reheaters • <650°C capability in gas turbine recuperators • Fabricability and weldability reasonably well demonstrated	Advanced Wrought Alloys • < $ 7/lb
High Temperature Heat Exchange Materials (air heaters)	Oxide-dispersion strengthened (ODS) Iron Aluminides and Ferritic Alloys • >1000°C capability with need for fireside corrosion resistance and improved hoop strength Ceramics > 1200 °C	ODS Iron Aluminides and Ferritic Alloys • Equivalent to superalloys Required system analysis given target performance	ODS Iron Aluminides and Ferritic Alloys • 650-750°C performance capability Presently limited to lower temperatures	ODS Iron Aluminides and Ferritic Alloys • Approximately two times the cost of superalloys Present cost excessive
Ultrahigh Temperature Intermetallics for Gasification and Combustion	• ~1200°C performance in combustion and slagging gasification environments	• Requires consideration of material cost, life, and replacement cost	• Developmental; laboratory-scale testing in, for example, molten smelt – results are encouraging	• Not available
Refractory Materials for Gasification and Combustion	• 36-48 month life • Material that can be recycled without hazardous waste disposal • Optimize thermal properties	• Requires system analysis given target performance	• 12-16 month life in gasifiers • 6 month life in combustors	• Cost to reline estimated at >$1 million; 3-6 week time

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TECHNOLOGY AREA: Materials

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Hot-Gas Filters	• Removal of particulates to levels required for inlet to gas turbines or regulatory emissions • Utilization of ceramic, ceramic-composite, and metallic/intermetallic filters • Improved performance, component robustness, operating life • Advanced component design/system packaging • Materials/component capable to withstand higher operating temperatures (i.e., 1800F carbonizer conditions)	• ~$500-800/candle • Life consistent with maintenance cost requirements	1sst Generation Materials - *Oxide/Nonoxide Monoliths* - PFBC/PCFBC – Extended life - IGCC – Extended field testing limited - Commercial production capability 2nd Generation Materials - *CFCC Composites/Filament Wound*: Prototype manufacturing; Limited field testing - FeAl: Commercial manufacturing; Field testing in progress; Transitioning IGCC development to PFBC operational use 3rd Generation Materials – *Advanced metals/ superalloys; Advanced ceramics* - New materials & processing technology being developed; Bench-scale testing & component development to be undertaken	1st Generation: $1000/filter 2nd Generation: <$1500/CFCC filter: app. $800/FeAl filter 3rd Generation: >$1000/filter

TECHNOLOGY AREA: Materials

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Gas Separation Membranes: (1) Hydrogen (2) Oxygen (3) Carbon Dioxide	(1) Hydrogen • Separation of hydrogen from synthesis gas at 99+% purity and high rate. • Simultaneous water-gas-shift (WGS) and hydrogen separation in a membrane reactor.	(1) Hydrogen • Target hydrogen cost <$4/million BTU above feed costs. • Target membrane cost of $50-100/ft^2 that delivers a hydrogen flux of 50-100 scm3/cm2/min	(1) Hydrogen • Membrane separation technology developmental	(1) Hydrogen • Approximate hydrogen cost is $15/million BTU.
	(2) Oxygen • High purity oxygen separation from air more efficiently than PSA and other current technology. • Production of syngas in an oxygen ion-conducting membrane reactor.	(2) Oxygen • Target oxygen cost of $10-12/ton	(2) Oxygen • Non-membrane oxygen separation technologies well-developed; highly competitive • Membrane separation technologies not commercial; lab-scale and pilot-scale testing underway.	(2) Oxygen • Current oxygen production cost is $20-24/ton.
	(3) Carbon Dioxide • Separation of CO_2 from a mixed gas stream at >85% efficiency	(3) Carbon Dioxide • Target carbon dioxide separation cost of $10/ton	(3) Carbon Dioxide • Available technologies are MEA, adsorption, and cryogenics. • Membrane separation demonstrated on lab-scale.	(3) Carbon Dioxide • Current separation costs are $27-30/ton

TECHNOLOGY AREA: Materials

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Turbine Airfoils, Shrouds	• High Temperature rotor inlet temperature of 2900°F • 50,000 hour component life • Failure prediction capability • Performance objectives not yet established for innovative turbine concepts (e.g., H_2, oxygen)	• Cost objective is integral part of turbine cost and comparable to current products	• RIT 2700°F • 48,000 hour component life (1 repair cycle) • No use of ceramics in commercial power plants • Innovative concepts yet to be tested	• Alloys $10-45/lb • $5,000-20,000/part
Turbine Combustors and Transitions	• High Temperature - 3100°F • 50,000 hour component life • Failure prediction capability • Performance objectives not yet established for innovative turbine concepts (e.g., H_2, oxygen)	• Cost objective is integral part of turbine cost and comparable to current products	• 2800°F • 40,000 hour component life (multiple repair cycles) • Limited use of ceramics in commercial power plants • Innovative concepts yet to be tested	• Alloys $10/lb • $3,000-20,000/part (metals) • $20,000-100,000/part (ceramics)
Turbine Combustion Catalysts	• NOx < 5ppm • CO < 10ppm • UHC < 10ppm • 8000 hour life • 5% pressure drop • Operating temp 1300°C	• Cost objective is integral part of turbine cost	• NOx 1-5 ppm (no cat: 9ppm) • CO <5 (no cat: 15) • UHC <5 (no cat: 7) • Life <2000 hr • Operating T 900°C	
Fuel Cells	• See Fuel Cell Roadmap	• See Fuel Cell Roadmap	• See Fuel Cell Roadmap	• See Fuel Cell Roadmap

TECHNOLOGY AREA: Materials

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
High Temperature Heat Exchange Materials (super heaters, reheaters, recuperators)	Advanced Wrought Alloys • Inclusion in ASME Boiler & Pressure Vessel code • Steamside and fireside corrosion resistance • Knowledge of fabrication limits	Advanced Wrought Alloys • Testing panels in operating plants • One vendor is producing foil using commercial methods	Advanced Wrought Alloys • Determine alloy design for property improvement and demonstrate efficacy of the alloy design for a variety alloys and applications	Advanced Wrought Alloys • Demonstrate performance in operating plants • Engage industry to develop a database for ASME code • Demonstrate fabrication using commercial tooling	Advanced Wrought Alloys • Develop, with producers and users, a code case
High Temperature Heat Exchange Materials (air heaters)	ODS Iron Aluminides and Ferritic Alloys • Unequal strength in longitudinal and circumferential directions for alloy tubes • Lack of adequate joining methods • Fireside corrosion resistance	ODS Iron Aluminides and Ferritic Alloys • Dispersion strengthening has shown feasibility • Growth of very large grains are possible in axial direction; control of grain structure in circumferential direction possible but not routine • New joining technologies are being developed • No ASME B&PV code case in sight	ODS Iron Aluminides and Ferritic Alloys • Establish processing parameters – milling, extrusion and heat treating – to obtain desired performance • Demonstrate practicability of fabrication and joining methods • Laboratory and pilot testing of components • Develop data for ASME code case	ODS Iron Aluminides and Ferritic Alloys • Applications testing • Product development and demonstration • Establish industry partnerships	ODS Iron Aluminides and Ferritic Alloys • Commercialization of products
	Ceramics • Corrosion resistance • Reliability • Joining methods • Cost	• Some favorable lab and field testing on composites but limited field demonstration	Same approach as alloys	Same approach as alloys	Same approach as alloys

TECHNOLOGY AREA: Materials

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Ultrahigh Temperature Intermetallics for Gasification and Combustion	• Oxidation/ corrosion resistance • Ductility/ toughness • Cost	• Considerable insight into ductility issues • Potential for coal slags and black liquor smelts	• Alloy design • Laboratory testing to simulate applications	• Laboratory fabrication development • Applications testing	• Industry partnerships to lead to commercial fabrication
Refractory Materials for Gasification and Combustion	• Abrasion and corrosion resistance • Thermal shock and conductivity issues • Reliable repair techniques and materials • Material or processing solution to avoid hazardous waste disposal	• See current technology performance and cost for current status	• Understand failure mechanisms • Initiate development of materials resistant to thermal cycling, abrasion, and slag penetration/ corrosion • Identify critical tests to screen candidate materials based on actual commercial experience • Identify repair techniques including techniques to remove contaminants from refractory surface prior to repairs	• Continue materials development • Perform pilot scale testing to demonstrate new material performance	• Test on production systems

TECHNOLOGY AREA: Materials

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Hot-Gas Filters	• Limited extended field service operation to identify (1) service operating life and (2) field failure mechanisms • Environmental compatibility (Oxidation of nonoxide-based ceramics; Impact of steam/gas phase alkali & chlorides; Potential corrosion of metal media; ash stickiness) • Mechanical properties, (i.e., flange strength/load bearing capabilities) • Low-cost production • Commercial manufacturing capabilities; QA/QC Enhancing Technologies • Bench & in-situ NDE techniques to define life • Integration with alternate modules (i.e., gas separation systems; fuel cells) • Multifunctionality of particulate barrier filters)	1st Generation Materials Oxide/Nonoxide-based Monoliths • Commercially available • Pilot & demonstration plant testing in progress	1st Generation Materials Oxide/Nonoxide-based Monoliths • Extended field testing qualifying life & performance Improvements: • Application of oxidation resistant coatings to non-oxide based monoliths • Development of advanced creep and oxidation resistant nonoxide materials for use at 1800F; Bench & field performance demonstration • Improved thermal fatigue resistance of oxide-based monoliths	1st Generation Materials Oxide/Nonoxide-based Monoliths • Commercial readiness of materials for utilization at process site • Implement improved technology-based materials	

TECHNOLOGY AREA: Materials

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
		2nd Generation Materials CFCC/Filament Wound • Operating temperature >850C • Prototype and bench-scale production • Limited field testing • Pilot-scale testing in progress	2nd Generation Materials CFCC/Filament Wound • Enhanced strengthening of element; Fixturing/sealing improvements • Extended field testing • Scale-up of component manufacturing capabilities	2nd Generation Materials • CFCC/Filament Wound Define life/performance • Commercial readiness of materials for utilization at process site	
		2nd Generation Materials FeAl • 650-700C operating capability • Commercial production • Pilot-scale testing in progress	2nd Generation Materials FeAl • Extended field testing • Optimization; Alloy modification to improve performance	2nd Generation Materials FeAl • Define life/performance • Commercial readiness of materials for utilization at process site	
		3rd Generation Materials Advanced Superalloys for IGCC • Concept and prototype development	3rd Generation Materials Advanced Superalloys for IGCC • Development of materials/components; Expand current PFBC/PCFBC technology; Optimization • Bench-scale and field testing qualification	3rd Generation Materials Advanced Superalloys for IGCC • Demonstration site testing • Scale-up of component manufacturing capabilities • Commercial readiness of materials for utilization at process site	

TECHNOLOGY AREA: Materials

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
		3rd Generation Materials Advanced Ceramics and Composites* • Prototype development	3rd Generation Materials Advanced Ceramics and Composites* • Development of materials and/or component; Optimization • Bench-scale qualification	3rd Generation Materials Advanced Ceramics and Composites* • Pilot-scale field testing	3rd Generation Materials Advanced Ceramics and Composites* • Demonstration site testing • Scale-up of component manufacturing capabilities • Commercial readiness of materials for utilization at process site

* e.g. Mullite-based materials, Pure SiC fibrils (VLS process), Alternate materials (TBD)

TECHNOLOGY AREA: Materials

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Gas Separation Membranes (1) Hydrogen	• Achieving high separation rates at high purity • Membrane stability • Effective seals • Reliable manufacturing methods. • Effective high and low water gas shift catalysts • High cost noble metal membranes • Security classification of K-25 porous membranes • Hydrogen storage materials needed with high capacity, stability, and storage/release kinetics	• Membranes with 0.5 nm pores demonstrated on lab scale yielding high purity hydrogen • Feasibility of water gas shift combined with hydrogen separation demonstrated in a membrane reactor on a lab scale • Small-scale, low flux metal hydrogen separation membranes commercially available • Supported metal membranes being developed • Proton-conducting dense membranes demonstrated on lab-scale	• Declassify K-25 membranes • Develop effective seals • Develop more highly conductive porous membrane structures • Develop more highly conductive dense proton conductors • Develop active, stable high and low temperature water gas shift catalysts • Develop active, stable, sulfur-tolerant reforming catalysts • Develop supported noble metal membrane structures • Develop prototype devices on lab-scale	• Select best applications for industrial testing • Industry partnerships to scale-up and perform system studies	• Continue industry scale-up activities • Fabrication and plant testing of prototypes

TECHNOLOGY AREA: Materials

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Gas Separation Membranes (2) Oxygen	• Achieving high separation rates • Membrane stability, reliability • For syngas production, stable in oxidizing and reducing conditions • Reliable manufacturing methods • Effective seals • Stable interconnect plates in driven planar devices	• Lab-scale demonstration of high purity oxygen separation from air in both driven and passive devices • Pilot scale demonstration of driven and passive oxygen separation devices by industry teams • Pilot scale demonstration of syngas production in membrane reactor	• Membrane composition development to enhance oxygen flux and stability • Develop membrane forms to optimize flux yet remain mechanically robust • Develop active, stable catalysts to produce syngas in a membrane reactor • Develop sealing technology to join ceramic membranes to manifolds • Develop stable electrical interconnects for planar devices	• Pilot and full-scale testing of optimized oxygen separation membrane modules • Pilot and full-scale testing of membrane reactors to produce synthesis gas • Demonstrate integration with a selected cycle • Evaluate application of technology with alternative Vision 21 concepts	• Integrate oxygen separation membrane modules into operating gasification plant • Integrate membrane reactor in a gas to liquids plant

TECHNOLOGY AREA: Materials

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Gas Separation Membranes (3) Carbon Dioxide	• Achieving high separation, concentration rates • Stability, reliability	• Feasibility of carbon dioxide separation by carbon filter composite molecular sieve (CFCMS) demonstrated on laboratory scale • Carbon-coated mesoporous ceramics, treated carbon nanotubes shown effective in adsorbing carbon dioxide in laboratory studies • Polymer membrane strategies shown feasible in carbon dioxide separation on a lab scale	• Demonstrate efficacy of CFCMS approach to separate carbon dioxide from a mixed gas stream • Demonstrate efficacy of mesoporous carbon forms in separating and concentrating carbon dioxide • Develop perm-selective membranes for carbon dioxide	• Prototype devices developed on a laboratory scale for promising separation approaches	• Fabrication and pilot-scale testing of alternative carbon dioxide separation prototypes

TECHNOLOGY AREA: Materials

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Turbine Airfoils and Shrouds	• Material composition to achieve properties and life for SC (early stage) and DS or Eq. (latter stage) blades and for structural ceramics • TBC/EBC temperature capability, resistance to airborne and fuel borne contaminants, and life prediction models • Capability of EBPVD TBC process for coating large parts • Low cost manufacturing methods for single crystal blades and for ceramics • Joining and repair technology for SC alloys • On-line NDE	• Single crystal airfoils made for demonstration engines; temperatures of 2700°F for industrial engines • Ceramic matrix composite shrouds in small engines @ <1100°C • Coatings – TBCs used in aircraft engines and some stationary GTs; EBCs for ceramics are developmental • Surface and X-ray inspection technology established for selected components • Airfoils and shrouds for innovative concepts have been proposed • Refractory metals under development	• Single crystal blades/vanes: - Develop alloy compositions to meet performance requirements (ref. R&D roadmap for next generation turbine systems) - Identify and initiate innovative mfg. technology (e.g. liquid metal cooling) - Develop thermal barrier coatings (TBCs) with higher surface temperature capability and greater temperature drop (includes coating processes, material models, cyclic testing) - Develop coatings for ceramics - Assess test techniques to simulate engine environment - Develop repair techniques for SC alloys and TBCs - Identify materials selection, design and manufacturing techniques to meet innovative turbine designs (e.g., hydrogen, oxygen)	• Single crystal blades/vanes – focus on improved performance and manufacturing: - Apply new processes to improve manufacturing yields to > 80% and reduce manufacturing cost - Continue composition improvements - Develop non-destructive inspection techniques for TBCs - Develop techniques to monitor the condition of TBCs in service/needs input from mechanistic understanding of failure modes, and close linkage to life prediction models • Implement materials programs to meet innovative turbine concept performance requirements (e.g., hydrogen turbines)	• Single crystal blades/vanes: - Develop advanced repair technology and in-field repair • Ceramic matrix composites: transfer combustor and transition component technology to turbine vanes • TBCs: deploy condition monitoring/life prediction technologies • Demonstrate turbine airfoils and shrouds required for innovative turbine concepts (e.g., hydrogen, oxygen)

TECHNOLOGY AREA: Materials

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Turbine Combustors and Transitions	• T-capability of current metal/TBC combustors limits engine efficiency, emissions control • Ceramic life limited by oxidation and volatilization (silicon-based materials) • Ceramic life limited by thermal stability and creep (oxide-based materials) • Ceramic matrix composite cost • Joining technology for ODS alloys and ceramics	• Metal based combustors for large engines • Advanced cooling schemes for SOA metallic combustors • Use of TBCs and ceramic tiles to reduce metal T, and cooling air needs • EBCs for CMC liner materials in early stages of development • Combustors for innovative concepts have been proposed	• Develop structural ceramic compositions to meet stability objectives • Utilize ceramic composites as combustors on small-scale combustors • Explore feasibility of using ODS alloys at metal temperatures ~1100°C • Identify materials selection, design and manufacturing techniques to meet innovative turbine designs (e.g., hydrogen, oxygen)	• Scale-up to large scale combustors • Develop • manufacturing capability • Implement materials programs to achieve combustor performance for innovative turbine concepts (e.g., hydrogen, oxygen)	• "Uncooled" combustor systems for advanced conventional turbines • Demonstrate combustor concepts for innovative turbine systems

TECHNOLOGY AREA: Materials

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Turbine Combustion catalysts	• Catalyst life due to exposure to 1500°C • Acceptable cost	• PdO supported on alumina or zirconia • Precious metal oxides used – temperature, cost, durability trade off	• Redesign application of catalytic combustors for operation at ~900°C • Identify alternate catalysts • Identify catalyst support materials with improved T capability and durability • Carryout rig and engine tests • Identify combustion catalyst needs/requirements for innovative turbine concepts	• Test and model performance • Demonstration combustor testing – integrated combustor/catalyst system • Scale-up methodology • Continue effort to develop higher temperature catalysts	• Integration into engine designs and production
Fuel Cells	• See Fuel Cell Roadmap	• See Fuel Cell Roadmap	• See Fuel Cell Roadmap	• See Fuel Cell Roadmap	• See Fuel Cell Roadmap

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

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

TECHNOLOGY AREA: Computational Modeling And Virtual Simulation

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Modeling and Virtual Simulation Infrastructure (includes physical plant and process visualization equipment and the enabling software, cluster computing capability, information systems, communication architecture)	• Visualization capability that is 3-D (compatible with 2-D), Interactive, Immersive, Real-time, High fidelity, Coupled to other capabilities, and Distributed spatially • Common relational data base for all activities • Capability to support remote collaboration, allow coupling of all Virtual Simulation activities, to be compatible with legacy data, and to be secure • Support remote collaboration	• Cost objective for virtual simulation has not yet been established	• Significant capabilities in commercial software • Not well integrated • Interactivity is limited • Slower than real time • Limited real-time sharing of plant virtualization (between sites) • Relational data bases are commercially available: Oracle, … • Some applications use proprietary data bases • Little applications integration; • Little security software which will allow layers of users • Remote collaboration capabilities exist, but are not widely used	• Virtual simulation hardware systems range from $30K for limited individual visualization to $2 million

TECHNOLOGY AREA: Computational Modeling And Virtual Simulation

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Mechanistic Modeling (Modeling of fundamental phenomena to permit analysis and visualization of the performance of a unit operation)	• Fundamental, science based models of process phenomena that are required to permit the analysis and visualization of the performance of a unit operation. These models would be physics and chemistry based and predictive. They would be consistent with simpler, lower order models that will be used collectively for design and control.	• Not applicable as Vision 21 plant cost	• Extensive steady-state simulations (Reynolds Averaged Navier-Stokes - RANS); capabilities for gas and dilute gas/particle flows • Transient simulations (large eddy simulations - LES) are becoming available • Developing capabilities for dense fluid/particle flows; • Only preliminary results for fuel-cell simulations • Turbomachinery simulations have been developed for aero applications; limited commercial simulations for ground based applications • Detailed kinetics schemes for gas phase chemistry, but limited information for heterogeneous processes • Non-reactive bubble column simulations • Simple models of CO2 storage in nano-tubes	• ~$20K license fee, per seat, for technologies with available models • Estimate $2MM as typical cost to develop models for a unit operation
Sub-System Models (e.g. gasification, turbine, fuel cell subsystems)	• Ability to predict steady-state sub-system performance given in-put feed materials flow, physical characteristics and chemical composition • Ability to simulate dynamic operation of the sub-system	• No cost objective established	• Most sub-system models are proprietary to the equipment supplier • Steady-state performance prediction capability is used commercially • Dynamic modeling capability is limited	• NA

TECHNOLOGY AREA: Computational Modeling And Virtual Simulation

Technology	Vision 21 Performance Objectives	Vision 21 Cost Objectives	Current Technology Performance	Current Technology Cost
Plant Virtual Simulation (includes integrated plant steady-state and dynamic simulation including process control	• Physical visualization: capability to visualize the physical characteristics of an integrated plant (e.g. "walk" through a plant and see each component, piping, valves, etc.) • Operation visualization: capability to see a presentation of the performance of an integrated plant- steady-state heat and material balances throughout the plant and dynamic simulation of plant operation (e.g., start-up, shut down, load follow, change in feed)	• No cost objective established	• ASPEN has been the primary software capability used to perform process simulations for the cycles analyzed.	• Varies with concept and simulation objectives

TECHNOLOGY AREA: Computational Modeling And Virtual Simulation

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Modeling and Virtual Simulation Infrastructure (includes physical plant and process visualization equipment and the enabling software, cluster computing capability, information systems, communication architecture)	• Computational technology (e.g. Speed of visualization, Communication speed, Interactivity, Fidelity) • Integration (e.g. between applications, technologies, model scales) • Cost and run-time • No available standards • Legacy information • Security of shared information • Use of proprietary data bases • Cultural issues	• Complex visualization at a rapid rate (very expensive) • Computational and projection equipment is expensive • Extensive software is available from commercial companies • Massive development is occurring, driven by other markets • Extensive work at national labs and universities • Commercial and proprietary data bases are being used in single applications • Extensive capabilities exist which are being used in other fields	• Utilize available software: commercial, governmental, university, … ; • Demonstrate 3-D, interactive visualization at selected research facilities • Develop high speed linkages between key research facilities • Investigate parallel visualization technology • Collaborate with SC, NASA, and ASCI programs • Create 3-D models of Vision 21 plant components • Integrate common information systems or exchange of information between systems • Upgrade IT to current state of the art in all technologies • Implement common IT between process simulation and CAD applications	• Validate visualization performance • Establish network of visualization capabilities • Link research and development organizations with simultaneous visualization capabilities • 3-D model of Vision21 plants • Extend common IT between process simulation , CAD, and mechanistic modeling activities applications • Develop IT for new Vision 21 technologies • Initiate information system for coupled technologies	• 3-D visualization of energy infrastructure • Extend common IT to all Virtual Demo applications • Complete information for full-scale, coupled technologies

TECHNOLOGY AREA: Computational Modeling And Virtual Simulation

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Mechanistic Modeling (Modeling of fundamental phenomena to permit analysis and visualization of the performance of a unit operation)	• Ability to model complex phenomena (e.g. simulate behavior involving different scales, coupling of multiphysics effects) • Limitations on computation capability • Physical data for model parameters and validation	• Extensively developed for some phenomena (e.g. gas and dilute multiphase combustion • Limited development for coupled phenomena (e.g. fluid-particle hydrodynamics with chemical reaction and physical property changes)	• Identify and assess mechanistic modeling needs; coordinate with technology programs • Identify priorities for model development including level of detail required to meet Vision 21 objectives • Assess state-of the-art of mechanistic models that relate to Vision 21 program needs • Select, define, and Implement priority modeling programs • Test models against laboratory scale data • Initiate simulations of coupled systems at lab scale • Develop a collaboration with commercial vendors, national labs and NASA • Document process performance data from Clean Coal and other applicable projects	• Test phenomena models against pilot scale data • Validate simulations of coupled phenomena at lab scale • Integrate with other virtual simulation applications: process simulation, CAD, control, communications, … • Develop consistent lower order models for process simulation and control • Initiate modeling activities in new Vision 21 technologies • Extend collaboration to power industry	• Test Vision 21 component models against full scale data • Test coupled simulations at pilot scale • Simulate full-scale coupled systems

TECHNOLOGY AREA: Computational Modeling And Virtual Simulation

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Sub-System Models (e.g. gasification, turbine, fuel cell subsystems)	• Model reliability • Validation information • Models for new technologies • Integration of process models with mechanistic models • Economic estimates are not reliable • Limited environmental capability incorporated into models	• Process model software is commercially available • Process models for some existing technologies • Cost estimating software available	• Select processes to simulate; coordinate with respective technologies (e.g., gasifier, turbine, fuel cells) • Define scope of simulation to be carried out; coordinate with systems analysis/integration activities • Develop a portfolio of process models of components proposed for Vision 21 plants • Integrate process simulation, CAD, and mechanistic modeling capabilities • Develop a collaboration with commercial vendors	• Continue development of sub-system component models • Validate simulations at lab/pilot scale • Integrate with other Virtual Simulation applications • Develop consistent lower order models for process simulation and control (i.e. models able to be efficiently run to simulate integrated systems) • Develop life-cycle cost estimate capabilities • Initiate modeling activities foe new Vision 21 technologies • Continue industry collaboration • Utilize models to guide technology development and design • Test models against demonstration plant data	• Test models against available plant data: steady-state and dynamic operation • Utilize model to guide plant design • Refine models to meet integrated plant simulation needs

TECHNOLOGY AREA: Computational Modeling And Virtual Simulation

Technology	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
Plant Virtual Simulation (includes integrated plant steady-state and dynamic simulation including process control	• System complexity (e.g. rapid time scales, coupled processes) • Disparate time scales • Proprietary models for key components • Computation capability to achieve acceptable run-time for simulations	• Process simulation programs for steady-state operation available (e.g. ASPEN) • Tools available (e.g. stochastic methods, neural network methods) • Chemical & Petro-chemical industry applications and experience can serve as resource	• Select processes to simulate; coordinate with respective technologies (e.g., gasifier, turbine, fuel cells) • Define scope of simulation to be carried out; coordinate with systems analysis/integration activities • Laboratory scale coupled systems, using lumped parameter models	• Coupled systems with higher fidelity models	• Full plant

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
1.0 Market Analysis 1.1 Industry Market Forecast (Available in large measure from industry and trade organizations)	• Deregulation and gas pricing are making future market directions uncertain. • Market analyses are of limited value and have a limited life. • Uncertainty over extent to which various possible V21 products (e.g., power, fuels, chemicals) will be demanded by the market • Uncertainty about the need to reduce carbon emissions in the future • Uncertainty over cost/performance for two approaches to reducing carbon emissions (efficiency and sequestration)	• Broad factors affecting power industry have been addressed, but not specific effects on Vision 21 plants • Power industry undergoing rapid change • Distributed generation becoming commercial • Gasification plants being commercialized at petroleum refineries • Have released contracts on market analysis.	• Identify and rank key drivers of emissions, risk and costs. • Carry out an evaluation of the impact of these drivers on the market forecast looking forward five years.	• Update market studies • Revise recommendations as appropriate	• Update market studies.

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
1.1 Industry Market Forecast (continued)	• Quantification of risk is difficult due to limited data at this stage of the program. • Superior environmental performance is of uncertain value to the customer.				

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
1.0 Market Analysis 1.2 Scenario Analysis	• Large number of possible scenarios impact the selection of Vision 21 plant feedstocks, products, technologies, configurations. • Uncertainty of key drivers and constraints such as future environmental regulations, future fuels etc.	• No activity at present. • It is expected that scenario analysis will find most use in analyzing carbon emission issues.	• Carry out study to assess what circumstances may drive selection of different Vision 21 plant options – e.g. consider social choices, possible international events, economics, competing technology options, etc. • Assess the probability of scenarios and prioritize them. • Select the scenarios to provide functional specifications performance analysis. • Use results to assess what Vision 21 plant concepts would best "match" different scenarios	• Review and update.	• Review and update.

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
2.0 Vision 21 Plant Concepts-Process Definition (Putting together flow sheets so that the plants match scenarios)	• *Lack of mechanisms for solicitation and preliminary evaluation of novel ideas that result in performance and cost breakthroughs.* • *Insufficient understanding of impacts of new concepts on the total Vision 21 system.* • Access to intellectual property limits the thorough analyses of new concepts and technologies.	• Key Vision 21 technologies identified. Some plant concepts have been defined that approach efficiency goals. • No intermediate goals defined.	• Identify innovative concepts for Vision 21 components, subsystems, and plants. Provide guidance to enabling/supporting technology areas. • Develop standardized phased propriety data release effort. • Produce plant flow sheets showing how Vision 21 technologies fit market scenarios. • Reassess the goals of the program	• Provide guidance to enabling/ supporting technology areas as needed.	

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
3.0 Vision 21 Plant Concepts – Reference Plants (heat and mass balances)	• Inability to estimate reliability, capital cost, and operating cost of complex Vision 21 systems that involve diverse technologies. • Lack of performance and cost information including availability and operating and maintenance costs. • Undefined integration constraints limit ability to do assessments	• Gross component, subsystem, and system evaluations performed but not on fully consistent basis. • Some concepts exist on paper, some are at small scale and some are unique. • Preliminary cycle analyses have been carried out for selected Vision 21 candidate cycles (e.g. fuel cell/gas turbine, advanced PFBC/fuel cell); additional studies have been initiated as part of Vision 21 procurement	• Develop consistent process evaluation methodology for Vision 21 plant concepts. • Assess innovative concepts for Vision 21 components, subsystems, and plants based on scenarios. • Select reference Vision 21 plant concepts for each of the two application classes consistent with scenario development (power and co-production). • Develop quantitative estimates of efficiency, emissions, cost, and reliability benefits from proposed process innovations including risk uncertainties. • Identify gaps and develop perspective on technology needs.	• Update process evaluation methodology and evaluate new Vision 21 plant concepts selected for further study. • Develop and implement pilot plant scale projects to get data to validate designs performance, reliability and costs.	• Define a demonstration plant and program to get realistic data • Update process evaluation methodology and evaluate new Vision 21 plant concepts selected for further study.

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
3.0 Vision 21 Plant Concepts – Reference Plants (continued) (heat and mass balances)			• Develop conceptual designs including process control diagrams, heat and mass balances, conceptual design and layout of plant and preliminary design of key components. • Evaluate existing tools and develop improved tools for the analysis of plants .		

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
4.0 Systems Integration Analysis	• Company proprietary information will limit lessons learned task • Lack of communication among experts in and out of DOE in diverse technical areas. • Lack of performance and cost information including risk and availability analyses • Systems engineering models are available but they do not treat diverse subsystems with adequate depth. • Improvement needed in dissemination of DOE program data.	• Anecdotal Feedback on selected operating plant systems integration experience has been collected.	• Hold series of systems integration workshops to identify and illuminate issues • Obtain feedback on systems integration experience from operating gasification plants. • Identify systems integration concerns for the reference plants including perspective on plant capacity, fuel flexibility, operating philosophy. • Carry out initial risk / availability analysis on reference plant concepts: module requirements, sensitivity of system design choices. • Update/develop data base of availability for candidate Vision 21 system components	• Revisit lessons learned effort and update understanding based on new commercial plant experience. • Update availability database based on data from existing DOE technology programs. • Identify additional DOE projects that provide opportunity to extend understanding of systems integration issues; pursue project(s) based on assessment of merit. • Update methodology based on results from reference plant studies, availability of new "tools", and prototype plant results.	• Revisit lessons learned effort and update understanding based on new commercial plant experience. • Update availability database based on data from existing DOE technology. programs. • Identify additional DOE projects that provide opportunity to extend understanding of systems integration issues; pursue project(s) based on assessment of merit

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
4.0 Systems Integration Analysis (continued)			• Utilize existing DOE projects to evaluate approaches to understand systems integration issues and to support the existing projects. (e.g. Wilsonville, CCT) • Expand clean coal compendium approach to provide performance and availability information from operating plants and studies relative to all Vision 21technologies • Provide feedback to Enabling and Supporting Technologies program elements.. • Based on the results from the evaluations of the specific reference plant concepts, develop a generalized methodology to identify and analyze systems integration issues		

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
4.0 Systems Integration Analysis (continued)			• Assess application of process synthesis and process integration tools (currently used tools and those being developed for the chemical process industry).		

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
5.0 Vision 21 Plant Operation Analysis	• Vendor intellectual property constraints • Lack of appropriate models for such things as transient analysis for normal operation, abnormal analysis, nonlinear behavior and safety analysis. • Coordination of modeling activities addressing different plant subsystems and components is difficult. • Necessity to negotiate interface conditions of independently developed components to achieve total system requirements.	• On-going projects provide analysis for selected module components e.g. fuel cell hybrid plant projects • Simulation, process and phenomena models have been developed over many years. Current Vision 21 program contracts include work on plant operation analysis. Results of this work will be used to guide this task • Developers of subsystems have set independent performance targets.	• Perform analysis of reference plant concepts to identify module design/operation compatibility (e.g. fuel processing – gas cleaning; fuel cells – gas turbine); objective is to define potential problem areas. • Perform analysis of plant operating philosophy alternatives for reference plants(includes approach for start-up, shut-down, load-following, response to emergencies); use results to identify needs/constraints on system components.	• Carry out tasks for new innovative concepts that may have been identified. • Modify reference plant designs to reflect understanding gained from plant operation analyses on the reference plants. • Review modeling needs and priorities; continue development where appropriate; initiate new programs based on need.	• Review modeling needs and priorities; continue development where appropriate; initiate new programs based on need.

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
5.0 Vision 21 Plant Operation Analysis (continued)			• Extend risk/availability analyses to assess plant operations. • Identify alternate process control strategies; include assessment of "smart" plant opportunities. • Define plant operation modeling needs and priorities for technology modules and for the integrated plant based on systems integration considerations. • Provide feedback to Enabling and Supporting Technology activities.		

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
5.0 Vision 21 Plant Operation Analysis (continued)			• For the priorities selected, initiate development of plant operation models - Basic phenomena models - Dynamic sub-system simulation models - Process control methodology - Plant simulation models • Initiate database of subsystem requirements • Feedback information to subsystem suppliers to support supplier activities to meet revised subsystem requirements.		

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
6.0 Economic Analysis	• Lack of capital, operating, and life cycle costs and reliability for innovative technologies. • Uncertainty in estimating expected cost reductions for 20 year future. • Lack of consistent procedures for estimating and reporting plant life cycle costs. • Costs of potentially high performance Vision 21 systems are unfairly compared to present fossil fuel generating systems. Need for comparison with competitive options for low emission/minimal CO_2 or "no emission" renewable systems.	• Preliminary capital cost targets have been projected for Vision 21 plants.	• Estimate capital and operating costs for the Vision 21 reference plants selected assuming success for the respective technology component objectives. • Evaluate potential of technologies to achieve life cycle cost goals. • Develop standardized basis and tools for estimating life cycle costs. • Identify gaps and critical path technologies.	• Update economic analyses and incorporate new concepts identified, new technology, and new constraints. • Revisit reference plant concepts and revise options to be studied	• Update economic analyses and incorporate new concepts identified, new technology, and new constraints. • Revisit reference plant concepts and revise options to be studied

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
7.0 Commercial Plant Evaluation	• Market needs may be ambiguous and difficult to translate into plant design • Different plants may be advanced by different market sectors, making selection problematic.	• Key Vision 21 technologies identified but not plant configurations for future markets		• A prototype plant will be selected by considering market needs at the time (may not be one of the reference plants) • Project plant performance • Estimate plant cost • Perform system risk/availability analyses • Identify key systems integration issues and revise technology module plans to reflect needs.	• Solicit designs for a commercial-scale Vision 21 plant • Estimate plant performance • Estimate plant cost • Perform system risk/availability analyses.

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
8.0 Industrial Ecology 8.1 Select/Develop Industrial Ecology Model	• Integrating and using models that are appropriate to complex Vision 21 plants • Defining where you draw the boundary for the life cycle analysis. • What factors should be included in the evaluation of Vision 21 plants.	• Life cycle analysis models are currently being used by NETL to evaluate gasification plant concepts.	• Define scope of industrial ecology and what specific factors are to be considered • Identify and review available life cycle assessment models that incorporate economics, resource requirements and environmental emissions for a representative Vision 21 plant. Includes mining, manufacturing, transportation required to produce the product(s). • Identify and review available industrial ecology models that incorporate the integration of industrial activities to address sustainability. • Select a model or approach for evaluating Vision 21 plant concepts. • government) societal planning	• Monitor industrial ecology methodologies and incorporate into Vision 21 plant analyses as appropriate.	• Monitor industrial ecology methodologies and incorporate into Vision 21 plant analyses as appropriate.

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
8.0 Industrial Ecology (continued) 8.1 Select/Develop Industrial Ecology Model			• Develop opportunities for regional planning and cross disciplinary (industry/federal government/ local government societal planning.		

TECHNOLOGY AREA: Systems Analysis and Systems Integration

Technology/ Capability	Barriers	Current Status	Approach 0-5 Years	Approach 5-10 Years	Approach 10-15 Years
8.0 Industrial Ecology 8.2 Plant Assessment	• Availability of process data. • Ability to forecast future regulations create uncertainty • Ability to forecast market needs	• Life cycle analysis models are being used for selected applications. Candidate Vision 21 plants have been identified but specific reference plants have not yet been selected for study.	• Select a reference Vision 21 cycle to perform an initial life cycle analysis and a broader scope industrial ecology analysis. Consider product market demand implications, parts recycle, decommissioning, and economic, resource and environmental life cycle analysis factors.	• Carryout industrial ecology assessment for prototype plant	• Carryout industrial ecology assessment for commercial plant