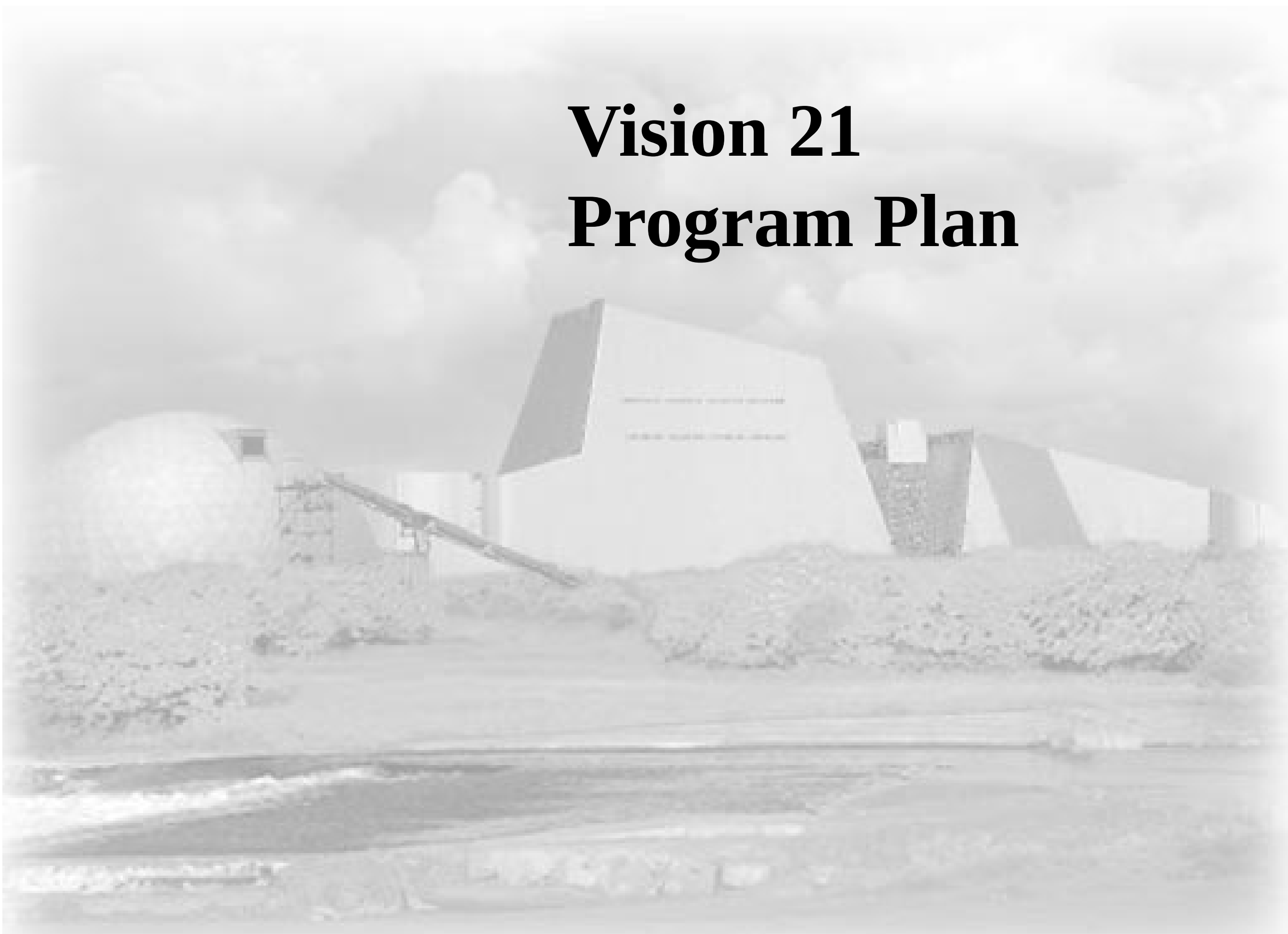
Federal Energy Technology Center
Office of Fossil Energy • U.S. Department of Energy

Vision 21
Program Plan



Clean Energy Plants for the 21st Century

A Message to Our Stakeholders

As the 20th century rapidly draws to a close, the power and fuels research and development community faces a major challenge: to protect the environment while producing a plentiful supply of clean low-cost energy that is essential to maintaining our economic prosperity. We know we will need to depend on fossil fuels for a major share of our electricity and transportation fuels needs well into the 21st century, especially globally. We also believe it makes good sense to rely not on any single energy resource, but rather on a diverse fuel mix that includes coal, gas, oil, nuclear, biomass and other renewables, and "opportunity" resources. The solution lies in developing substantially improved clean and low-cost technology. By taking the lead now and focusing our efforts, we can develop the technology to meet the energy and environmental challenges we face and ensure our continuing economic growth.

This document is the *draft* Program Plan for "Vision 21 - Clean Energy Plants for the 21st Century." It describes what Vision 21 is, sets performance targets for Vision 21 plants, explains how Vision 21 interfaces with and relates to our current power and fuels R&D program, and describes the Vision 21 program elements and activities. A preliminary Roadmap is provided at the end of the Plan.

Much of what is in this Vision 21 Program Plan has come from you, our stakeholders, including what you shared with us at the Vision 21 Workshop held in Pittsburgh in December, 1998. Additional government-industry roadmapping workshops are planned for the future that will focus on intermediate program steps and milestones. We need a program with aggressive but sensible objectives, that is balanced, but gives the appropriate emphasis to the various program elements and activities. We need to respond to key public needs , especially a clean environment, and also to market needs if industry is to build Vision 21 plants in the deregulated, cost-driven arena.

Only with your involvement and support can we succeed. Achieving our goals will not be easy. A cooperative partnership of industry, academia, and government will have the best chance of succeeding.

We welcome your comments and suggestions about the plan. Please respond directly to us or to the contacts listed on the back cover

George Rudins
Deputy Assistant Secretary for Coal and
Power Systems

Rita A. Bajura
Director, Federal Energy Technology Center

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Executive Summary

Introduction

The Department of Energy's Office of Fossil Energy has developed a Vision 21 program — a new approach to producing energy that addresses pollution control as an integral part of high-efficiency energy production — or a "21st Century Energy Plant." It builds on advanced technologies growing out of ongoing research and development programs sponsored by DOE to integrate energy production and pollution control into a new type of facility that could perform a variety of functions.

Today, a typical power plant uses one type of fuel — usually coal — and produces only one thing — electricity. A 21st Century Energy Plant would be fuel-flexible, meaning it could use one or more of several different feedstocks — for example, coal, natural gas, or petroleum coke. Any of these could be mixed with biomass. In turn, the plant could produce one or more of a number of high-value products such as electric power, clean fuels, chemicals, or hydrogen. Secondary products such as heat/steam for industrial use could also be produced.

The 21st Century Energy Plant concept has two unique features. The first unique feature of the 21st Century Energy Plant is its emphasis on eliminating environmental issues associated with the utilization of fossil fuels. Emissions of air pollutants such as sulfur dioxide, nitrogen oxides, and mercury would be reduced to essentially zero levels. Emissions of carbon dioxide, a greenhouse gas, would be dramatically reduced because of the higher efficiency. The plant design would also include the option for capturing and sequestering carbon dioxide. Thus, the plant could produce zero emissions — essentially decoupling the use of carbon-based fuels from the production of greenhouse gases.

The second is "efficiency maximization." The plants would be designed to use as much of the energy in the fuel as possible. This would be done by combining advanced technology modules in new and different ways to meet the needs of a specific site. For example, a 21st Century Energy Plant could provide electric power, as well as industrial steam or heat, to an industrial complex. A different configuration of modules could produce both high-value chemicals and fuel gases for manufacturing plants nearby. Another configuration might be a combination power plant/coal refinery, producing both electricity and transportation-grade liquids fuels.

A number of key core technologies are essential to the realization of the Vision 21 concept. Clean Coal Technology projects have used coal gasification to produce a gas for combustion turbines and have advanced processes for converting gas derived from coal into liquid fuels. These technologies will be integrated in the future with further advances in other key technologies.

Vision 21 represents an exciting new direction in using fossil fuels and other feedstocks efficiently, cleanly, and affordably to produce energy products for the next century. The concept has been endorsed by the President's Committee of Advisors on Science and Technology (". . . it is an appropriate target for DOE . . . ") and supports the President's Climate Change Technology Initiative to reduce the emissions of greenhouse gases. It also supports the National Mining Association's vision — Technology Roadmap for the Mining Industry.

What is a *"21st Century Energy Plant"*?

Existing technologies are being developed, more or less independently, under the Coal and Advanced Power R&D Program. Any one of these technologies cannot individually achieve the efficiency, environmental, and cost goals that will be needed in the early decades of the 21st century. It is time for a new approach that allows us to integrate different power and fuels technologies into systems that do achieve the needed level of performance at costs we can afford.

The current Coal and Advanced Power R&D Program (IGCC, PFB, HIPPS, ATS, Fuel Cells) is the source of base technology for 21st Century Energy Plants. Portions of these programs that contribute to Vision 21 goals will be included. The portions that are not included in Vision 21 will be continued separately to develop near-term products. This base technology is critically important to achieving intermediate milestones and the overall goals of the Vision 21 program.

A 21st Century Energy Plant is not a single configuration — instead it will be a group of plants with different configurations that would be tailored to meet specific market needs.

One plant might serve as the hub of an industrial complex, providing electric power, steam, and heat. While another plant might co-produce high-value chemicals or fuel gases for neighboring manufacturing facilities. Or it mightbe a power plant-coal refinery combination, producing electricity and transportation-grade liquid fuels.

Using some combination of power, fuels, chemicals, and process heat, 21st Century Energy Plants will integrate advanced concepts for high-efficiency power generation and pollution control into a new class of fuel-flexible facilities with virtually no emissions of air pollutants. It will be capable of a variety of configurations that can meet differing market needs, including both distributed and central power generation.

In the past, many of these R&D efforts were carried out independently, each progressing toward a standalone facility. With 21st Century Energy Plants benefits will be realized in the short and intermediate term, i.e., spinoff technologies. While some of these technologies may be introduced into the market as individual facilities, the ultimate, high-efficiency, most economical, and cleanest energy complex in the future will likely be a combination of these advanced technologies integrated into a variety of configurations.

CONCEPT FOR THE "21st CENTURY ENERGY PLANT"

- A future energy facility that would have virtually no environmental impact.
- Conventional pollutants would be captured and either disposed of or converted to marketable co-products.
- There would be no solid or liquid discharges.
- Emissions of carbon dioxide and other greenhouse gases would be reduced by ultra-high efficiency technologies.
- Carbon emissions could be captured at the plant or offset by carbon removal processes applied elsewhere.
- Plant options for zero carbon dioxide emissions would be available by 2015.
- The captured carbon would be sequestered or potentially recycled into useful products.

Why *"21st Century Energy Plants"*?

The 21st Century Energy Plant represents the most effective way to keep fossil fuels, including coal, in the world's energy future.

The U.S. will need to rely on fossil fuels for the major share of its electricity and transportation fuels well into the 21st century. We cannot endanger our economic future by depending on any single fossil energy source. By focusing our activities now and taking the lead on developing the needed technology, we will not only meet the energy and environmental challenges we face but, at the same time, make our economy stronger.

Fossil Fuels → "21st Century ZERO EMISSIONS Energy Plants" → **Electricity Fuels Chemicals**

Who will be involved in the Program?

The Vision 21 program would be industry-driven and cost-shared with DOE, academia, national laboratories, and other government organizations. Ultimately, the research would privately fund first-of-a-kind commercial facilities that coproduce multiple products using some combination of power, fuels, chemicals, and process heat.

When will development of *"21st Century Energy Plants"* begin?

- 1999 — Systems analysis activities will begin that will define the high-performance systems and key components that will be used in 21st Century Energy Plants.
- 2000 — Development of enabling and supporting technologies will commence.
- 2002 — Systems integration issues dealing with the dynamic response and control of the 21st Century Energy Plant will be addressed.
- 2005 — First spinoff technologies introduced.
- 2008 — Industrial ecology analysis will be completed.
- 2010 — Virtual demonstrations of components and subsystems will be conducted.
- 2012 — Development of most enabling and supporting technologies will be completed.
- 2015 — Complete virtual demonstration of a 21st Century Energy Plant.

GOALS FOR THE "21st CENTURY ENERGY PLANT"

Power: Generating efficiencies greater than 60% using coal and greater than 75% using natural gas. [Current coal technology is 33-35% efficiency; current natural gas turbine technology is 45-55% efficient.] Costs of electricity competitive with market clearing prices at the time of deployment.

Combined Heat/Power: Overall thermal efficiencies of 85-90%.

Environmental: Near zero emissions of traditional pollutants, including smog- and acid rain-forming pollutants.

Greenhouse Gas Reduction: Carbon dioxide emissions reduced by 40-50% by efficiency improvements; reduced to zero [net] if coupled with carbon sequestration.

Coproducts: Clean, affordable transportation-quality fuels at costs equivalent to $20 per barrel or less (1998 $); also, industrial-grade heat/steam and potential for fuel-grade gas production.

How will the Program be developed?

Many of the initial building blocks for 21st Century Energy Plants are emerging from DOE's advanced technology programs. Projects in the Clean Coal Technology Program have pioneered the use of coal gasification and pressurized fluidized bed combustion to produce a gas for combustion turbines and advanced processes for converting coal-derived gas into liquid fuels. New types of fuel cells and a revolutionary high-efficiency gas turbine are being developed in the DOE R&D Program.

The Vision 21 program provides a roadmap for integration and further advancement of these technologies to provide progressively cleaner and more efficient energy production. As the program evolves in coming years, this roadmap will guide development efforts in:

Gas-separation technologies: Low-cost oxygen separation is one of the keys to realizing a non-polluting energy facility capable of producing electric power as well as other high value products. Today, the process of extracting oxygen is both expensive and energy intensive, requiring huge refrigeration units capable of cooling air to about 275 degrees below zero Fahrenheit — the temperature at which air becomes a liquid and oxygen can be separated.

KEY TECHNOLOGIES FOR DEVELOPING "21st CENTURY ENERGY PLANTS"

Materials: Higher-strength, corrosion-resistant, and more durable materials will be needed for the 21st Century Energy Plants. Improved ceramics also will be necessary for the high-temperature membranes needed for gas separation.

Catalysts and Sorbents: R&D will be necessary to further improve the effectiveness of catalysts that can lower the costs of coal conversion and sorbents that can remove pollutants from hot gas streams exiting a coal gasifier or combustor.

Instrumentation: To attain peak efficiency, future 21st Century Energy Plant operators will have to fine-tune plant operations to accommodate variations in fuel feedstocks and other variable conditions in plant operations. The use of artificial intelligence and new sensor technology to control plant operations will be a key R&D effort.

"Virtual" Plants: To minimize the cost of progressively larger test facilities, 21st Century Energy Plants will rely on new computer simulation technologies to test processes and verify engineering performance. R&D will be needed to develop advanced computational techniques similar to those used today to design commercial airplanes or to simulate nuclear explosions.

Carbon Sequestration: If the 21st Century Energy Plant concept can be coupled with low-cost carbon sequestration (the capturing and permanent storage of carbon dioxide and other green-house gases), the result would be a future energy facility with virtually no environmental impact outside of its "footprint."

Fuel-Flexible Gasification: Coal gasification is an ideal core technology for 21st Century Energy Plants because it produces a gas stream that can be combusted for electric power, used as a source of hydrogen for a fuel cell or chemical process, or processed as a fuel gas for industrial plants. In order to maximize the fuel flexibility of future plants, research and development will focus on the best ways to gasify fuel mixtures such as coal and biomass or fuel-rich wastes.

Fuel Cell/Turbine Hybrids: Both fuel cells and turbines have great promise as power generating devices; however, combining the two may result in even greater efficiencies and economic benefits. Research on 21st Century Energy Plants will focus on integrating these technologies and adapting them to operate on a variety of feedstocks.

High-Performance Combustion: One configuration of 21st Century Energy Plants might rely on combustion rather than gasification. In this design, future research and development will concentrate on advanced technologies such as pressurized fluidized bed combustion and high-temperature heat exchangers.

Improvements will be needed in materials, catalysts, and instrumentation to make 21st Century Energy Plants a reality, and advanced computation techniques will be necessary to allow for computer simulations for design and testing. Finally, to achieve the goal of an energy facility with virtually no environmental impact, ways must be found to incorporate carbon sequestration (the storage of carbon dioxide and other greenhouse gases) into the 21st Century Energy Plant concept.

Vision 21 planning process (Roadmap)

An analytical hierarchical process using pair-wise comparison techniques was used in developing the Vision 21 Roadmap. Information on existing programs and plans was provided by government personnel. Information on industry needs and trends was ob-tained through a series of continuing contacts with industry representatives and through the Vision 21 Workshop. An analysis was conducted on the effects of the primary energy industry drivers — deregulation, power industry restructuring, and the environment, including concerns about global climate change — and on the roles and impacts of R&D. An extensive list of technologies, program elements, subelements, and activities was developed and value judgments were made on pair-wise comparisons of these items. The items were ranked, taking into account existing levels of R&D effort, degree of maturity of technology, importance to achieving Vision 21 goals, and other factors. The Roadmap that resulted (see the Appendix) is a distillation of the planning process into a coordinated plan that is structured to provide long-range (~15 years) end point objectives and short-medium term (~5-8 years) spinoff benefits.

VISION 21 PROGRAM ELEMENTS

Systems Analysis will be used to develop various system configurations that satisfy the program objectives, define the performance targets for individual subsystems, and identify supporting technology needs.

Enabling Technologies, like gasification and advanced combustion, form the building blocks of 21st Century Energy Plants.

Supporting Technologies are cross-cutting technologies that are necessary for multiple subsystems and components and are important for other applications.

Systems Integration in 21st Century Energy Plants will use “smart” systems integration techniques to combine high-performance subsystems into very clean and efficient low-cost plants.

Designs will be produced for components and subsystems, prototype plants and commercial plants, and a virtual demonstration capability will be developed.

What is the end product of the program in 2015?

At the end of the program in 2015, the American taxpayers will see tangible results:

- Technology basis for ultraclean and efficient low-cost energy plants.
- Improved design and simulation tools that will lower the costs of developing new energy and environmental, and other, technologies.
- Spinoff technologies, available beginning around 2005, that include low-cost oxygen and hydrogen separation technology, improved low-cost manufacturing techniques for high-tech components, and better catalysts for producing fuels from low-valued raw materials.

WHAT’S DIFFERENT ABOUT A “21ST CENTURY ENERGY PLANT”?

- Focuses on flexible components or subsystems rather than on complete plants.
- Integrates multiple technologies.
- Achieves leapfrog improvements in performance and cost.
- Emphasizes market flexibility, multiple feedstocks and products, and industrial ecology.

Vision 21 Clean Energy Plants for the 21st Century

Introduction — The Challenge

The U.S. electric power industry is currently undergoing a period of unprecedented change driven largely by electric utility restructuring, the availability of relatively low-cost natural gas, environmental regulation, and concerns about global climate change.

As the power industry deregulates, utilities which were heretofore protected against competition and guaranteed returns on their investments are now being forced to compete for market share and profits. Deregulation is changing the way the industry operates and invests in new facilities and technology. In a market-driven environment, power plant owners must be concerned about profitability and ability to finance new investments. This may cause owners to avoid technical risk and favor low capital cost alternatives, especially when such alternatives are coupled with a fuel supply contract for a period long enough for the investment to be recovered.

Today's low cost of natural gas is causing power producers to favor low capital cost turbines over relatively high-cost coal-fired boilers for new capacity. The Energy Information Administration projects that in the U.S. about 129 gigawatts (GW) of new, fossil-fuel baseload capacity will be needed in the next twenty years; it is estimated that 81 GW will be natural gas and only 28 GW will be coal (with the remaining 20 GW renewable).

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. Other plants are increasingly being required to cut emissions. 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.

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.

The implications of these drivers for the future economic competitiveness and prosperity of the U.S. cannot be underestimated. Our economic future depends on a supply of affordable electricity to run our factories and heat and light our offices and homes and on clean fuels for transportation. Predictions have been made about the devastating effects that limits on carbon emissions will have on our economy. However, predictions often underestimate the impacts of technological innovation. Indeed technology innovationis the best, and perhaps the only way, to address the coming challenges to our electric power and fuel supply infrastructure.

The bottom line is that the U.S. will need to rely on fossil fuels for the major share of its electricity and transportation fuels well into the 21st century. We cannot endanger our economic future by depending on any single fossil energy source. Although the current situation favors natural gas, for the long-term the wisest policy is to depend on a balanced mixture of energy sources, including gas, coal , biomass, opportunity fuels, "wastes," and oil. Without new and radically better technology, the costs of energy will increase substantially and the predictions of "devastation" may turn out to be correct. On the other hand, by focusing our activities now and taking the lead on developing the needed technology, we will not only meet the energy and environmental challenges we face, but at the same time make our economy stronger.

Vision 21

The current DOE Fossil Energy R&D Program is addressing the development of 1) cost-effective power systems, based on both coal and natural gas individually and in combination, that are substantially cleaner and more efficient than systems in use today, and 2) technology for producing alterna-tive sources of liquid transportation fuels that are cost-competitive with equivalent petroleum products. Different kinds of power systems are being developed more or less independently, each based on a different technology: advanced pulverized coal combustion, gasification combined cycle, pressurized fluidized bed combustion, indirectly fired cycles, advanced turbine systems, and fuel cells. Activities in fuels technology include indirect and direct liquefaction, coprocessing coal with opportunity and “waste” materials to make liquid fuels, and natural gas to liquids processing. Each technology development effort has its own set of objectives and time schedules for development and deployment.

To achieve radical improvements in the performance of fossil fuel-based power systems and to virtually eliminate environmental issues as a barrier to fossil fuel use will require a new paradigm for the development of both technology and systems that incorporate the technology. Any of the technologies under development cannot *individually* achieve the efficiency, environmental, and cost goals that will be needed in the early decades of the 21st century. Rather, we need a new approach that allows us to integrate power and fuel system “modules” into systems that achieve the needed level performance at costs we can afford. *The key difference between Vision 21 and our current R&D portfolio is that Vision 21 focuses on systems that integrate multiple technologies in order to achieve “leapfrog” improvements in performance and cost. Other differences are Vision 21’s emphasis on market flexibility, multiple feedstocks and products, and industrial ecology.*

Vision 21 is a government-industry-academia collaboration to develop technology that will *effectively remove all environmental concerns associated with the use of fossil fuels* for producing electricity and liquid transportation fuels. The approach is to develop and integrate high-performance technology modules to create energy plants that are sufficiently powerful to meet our energy needs in the 21st century, and yet flexible enough to address site-specific market applications. Vision 21 builds on a portfolio of technologies already being developed, including clean coal combustion and gasification, turbines, fuel cells, and fuels synthesis, and adds other critical technologies and system integration techniques. Vision 21 is the Department of Energy’s role in helping to maintain our nation’s economic prosperity by ensuring a future supply of affordable, clean energy.

Objectives/Performance Targets for Vision 21 Plants

The primary objective of the Vision 21 program is to effectively remove all environmental concerns associated with the use of fossil fuels for producing electricity, liquid transportation fuels, and high-value chemicals. The specific performance targets, costs, and timing for Vision 21 plants are shown in the table on the following page.

Other Characteristics of Vision 21 Plants

- Must involve a conversion of energy such as coal or natural gas to high-value products such as electricity or liquid transportation fuels. Steam or heat may be secondary products. Conventional petroleum refineries are excluded, as are coal slurry preparation plants.
- Will likely be large stand-alone energy facilities, generally larger than 30 MWe or with equivalent energy output if other products such as liquid fuels are produced (not including thermal credit for steam or waste heat.)
- May be central station facilities or be located at or near the consumer’s site (e.g., a large industrial consumer.) Small distributed power generation or fuel production is not considered to be part of Vision 21, although near-term spin-off applications for distributed power may occur.
- Will use fossil fuel based feedstocks, either alone or in combination with biomass and/or opportunity feedstocks such as petroleum coke, RDF, MSW, and sewage sludge. Biomass-only plants are excluded.
- Will emphasize market flexibility, including multiple feedstocks and products.
- Will be composed of two or more modules combined with “smart” systems integration techniques.
- That capture and concentrate CO_2 for sequestration purposes may include a theoretical credit for the enthalpy of the pressurized CO_2 “product” in the efficiency calculation.

Efficiency-Electricity Generation	60% for coal-based systems (based on fuel HHV); 75% for natural gas-based systems (LHV) with no credit for cogenerated steam*
Efficiency-Combined Electricity/Heat	overall thermal efficiency above 85%; also meets above efficiency goals for electricity*
Efficiency-Fuels Only Plant	when producing fuels such as H_2 or liquid transportation fuels alone from coal, 75% fuels utilization efficiency (LHV)*
Environmental	near zero emissions of sulfur and nitrogen oxides, particulate matter, trace elements, and organic compounds; 40-50% reduction in CO_2 emissions by efficiency improvement; 100% reduction with sequestration
Costs	aggressive targets for capital and operating costs and RAM; products of Vision 21 plants must be cost-competitive with market clearing prices when they are commercially deployed
Timing	major benefits, e.g. improved gasifiers and combustors, gas separation membranes, begin by 2006 or earlier; designs for most Vision 21 subsystems and modules available by 2012; Vision 21 commercial plant designs available by 2015

* The efficiency goal for a plant cofeeding coal and natural gas will be calculated on a pro-rata basis. Likewise, the efficiency goal for a plant producing both electricity and fuels will be calculated on a pro-rata basis.

Rationale for a Vision 21 Program

An aggressive Government/industry cost-shared Vision 21 program is needed because Vision 21:

- *Removes environmental barriers to fossil fuel use.* Environmental barriers including smog- and acid-rain-forming pollutants, and particulate and hazardous air pollutants, are effectively removed. Solid waste is eliminated by its conversion to useful products. Concerns over global climate change are mitigated by reductions in carbon dioxide emissions of up to 50% resulting from thermal efficiency improvements. Net carbon dioxide emissions can be reduced to zero through sequestration.
- *Keeps energy costs affordable.* Without the technological innovations brought about by a Vision 21 program, use of low-cost fossil fuels is likely to be severely curtailed by environmental pressures, particularly global climate change concerns. This will leave the U.S. with a substantially narrowed range of much higher cost energy options, which may limit the potential for achieving sustained economic growth and prosperity.
- *Produces useful coproducts including liquid transportation fuels.* Vision 21 can produce environmentally superior liquid transportation fuels that are cost-

competitive with equivalent petroleum products. This capability would reduce our reliance on imported oil. Lessened oil imports and stabilized oil prices resulting from the availability of alternative sources of transportation fuels will also improve our international balance of trade.

- *Continues U.S. leadership role in clean energy technology*. By a recently published account, world trade in environmental controls has surpassed trade in armaments. Vision 21 will advance the U.S. technological expertise that will promote the export of fossil energy technology, equipment, and services. U.S. fossil energy/environmental industries will expand, new industries will be created, and there will be local, regional, and national benefits.
- *Provides the most certain route to achieving our energy, environmental, and economic objectives*. None of the power and fuel subsystems currently being developed in the Fossil Energy R&D Program can *individually* meet the energy, environmental, and economic challenges of the future. Although each of these subsystems will be a substantial improvement on today's technology, the rapidly changing domestic and international situation (i.e., climate change, oil security, environmental regulation, electric utility restructuring, aging U.S. energy infrastructure, global trade competition and privatization, and declining R&D budgets) requires that more be done. Vision 21 combines electricity and fuel producing subsystems in a way that seeks to maximize thermal efficiency, minimize emissions of traditional pollutants, minimizes cost, and yet is readily compatible with carbon dioxide sequestration.

Focus

Because no one knows exactly what future energy plants will look like, the focus of the Vision 21 program is on developing flexible components and subsystems that are the building blocks of future Vision 21 plants rather than on the complete plants themselves. Engineers will select these components and subsystems to design and build the energy plants of the 21st century. The feedstocks, products, configuration, environmental controls, and plant size will be site specific and determined by prevailing market and economic conditions. Modular design will be emphasized where practicable in order to offer plant designers maximum flexibility while minimizing design and plant fabrication costs.

There are a number of issues unique to Vision 21 that are being addressed only minimally or not at all in the current power and fuels R&D program. These issues deal primarily with systems integration. Accordingly, several complete Vision 21 systems that are judged to be good candidates for 21st century energy plants will be studied in order to develop the systems integration know-how that will be needed to design Vision 21 plants.

Systems integration addresses the issues of systems engineering, dynamic response and control, and industrial ecology. Systems engineering concerns the configuration of Vision 21 plants, the design of components and subsystems, and subsystem interconnections. Good systems engineering ensures that components and subsystems 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, leading to serious startup, control, and reliability issues. New, advanced 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 handled as waste as input streams for additional processing or recycle. Ideally, the application of industrial ecology principles would eliminate all waste products.

Advanced manufacturing technology will be another focus of the Vision 21 program. Low-cost subsystem modules, e.g., fuel cells, gasifiers, gas separators and purifiers, will require advanced, new manufacturing techniques. Also, advances in modular construction will be required to increase the use of shop-fabricated components and minimize the amount of expensive field fabrication.

Vision 21 will need substantially improved design and simulation tools, including development of a virtual demonstration capability. These tools will be used to aid in the design of individual components and subsystems, to evaluate and compare the performance of different configurations of Vision 21 systems, and to simulate the performance of plant sections and complete Vision 21 plants. Availability of advanced simulation software will reduce the cost of developing Vision 21 systems. Development of this capability will be a key part of the Vision 21 program.

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 the time frame 2005-2015 and beyond. Planning is a cooperative effort of the DOE-Office of Fossil Energy (FE) and the Federal Energy Technology Center (FETC) with input from other DOE organizations, national laboratories, universities, and private industry.

Implementation

To implement Vision 21, partnerships and linkages will be created with industry, universities, private and public R&D laboratories, and federal and state agencies. FETC will issue a series of competitive solicitations, create consortia, and develop CRADAs and other agreements. Systems Analysis (Program Element I) will help to set realistic goals and R&D targets and will be initiated promptly. It is important that stakeholders "buy in" early to the program concepts, R&D targets, approach, and schedule. Existing teams already developing some of the Vision 21 subsystems, e.g., fuel cells, gasification, combustion, etc., would be supplemented if necessary. A board consisting of high-level representatives from key stakeholders, including FETC, would provide overall program guidance and coordination.

Products of the Vision 21 Program

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 applications.

- Technology *basis for Vision 21 plants*. The primary product would be designs for modular components and subsystems. To develop the know-how required to design and build complete plants, including knowledge of systems integration techniques, several designs for prototype plants (small commercial plants used by industry to establish technical and economic viability) and for large commercial plants will also be produced.
- *Improved design and simulation tools.* Software and design tools, including the virtual demonstration computer simulation developed for Vision 21, will be available for application to the design of other energy and environmental systems.
- *Spin-off technologies.* These include low-cost oxygen and hydrogen separation technology, gas purification and cleaning technology, better catalysts for producing fuels and chemicals from low-valued raw materials, more efficient lower cost environmental control technology, improved low-cost manufacturing techniques for high-technology components, and improved materials for service under aggressive high-temperature conditions.

Program Activities

The Vision 21 program includes the development of subsystems, components, and design tools, and the concomitant modeling, analysis, and experimental work. The scale of the latter activities will range from laboratory-, bench-, and pilot-scale, up to and including scales needed to obtain data for demonstrating feasibility for prototype- and commercial-scale plants. However, construction of Vision 21 prototype and commercial-scale plants is not part of the Vision 21 program. These activities, the exact timing of which will depend on 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 data base to industry.

Program Transition

There will be a transition period during which the current power systems and fuels program is restructured into a program that includes Vision 21. Activities in our current programs that are relevant to Vision 21 and necessary to meet Vision 21 goals will be rolled into the Vision 21 program. Other current activities would continue separately or, in a few cases, be phased out. The Transition Plan (table) shows which activities would become part of Vision 21 and which would continue separately. For example, in the advanced pulverized coal program, development of advanced bottoming cycles and systems studies for high-efficiency bottoming cycles would become part of Vision 21; the Low Emission Boiler Systems (LEBS) program would continue separately until its conclusion in FY2000. The advanced environmental control technology portion of the environmental technology program would become part of Vision 21; the portion that concerns control technology for the existing fleet would continue separately from Vision 21. Fuel cell development for long-term 70-80% efficient systems would become part of Vision 21, as would the development of advanced fuel cell-turbine "hybrid" systems.

A rationale has been developed to determine which program activities become part of Vision 21. In general, activities that address longer-term technology development that leads to step-change or "breakthrough" advancements would become part of Vision 21. Current program activities that are shorter-term and result in incremental improvements would continue separately. The program transition is planned to begin in FY99 and be completed within 2-3 years.

Program Management

FETC product managers would continue to have overall responsibility for elements of their programs that lie both within and outside of the Vision 21 program. Product managers and the Vision 21 coordinating team will work together to determine if program objectives, activities, and schedules need to be adjusted in order to be consistent with Vision 21 objectives. The Vision 21 team and product managers will ensure that all Vision 21 program activities (including planning, procurements, schedules, budgets,

V21 Transition Plan

Existing Program	Activities Rolled Into Vision 21	Activities that Continue Separately
Advanced Pulverized Coal	- advanced bottoming cycles - systems studies	- LEBS (ends FY00)
Indirectly Fired Cycles	- pyrolyzer development - high-temp. furnace/heat exchanger dev. - ultra-high efficiency systems/plant design - systems that use O_2 and CO_2 recycle - system integration issues	- complete HIPPS development - repowering - use of O_2-enriched air - ash slagging studies
Integrated Gasification Combined Cycle	- gas stream purification - gas separation (O_2-air, H_2-syngas, CO_2) - advanced gasifiers - fuel flexible gasification - IGCC systems analysis and modeling - early entrance co-production plant	- desulfurization sorbents - Power Systems Dev. Facility (PSDF) activities
Pressurized Fluidized Bed Combustion	- CO_2 recycle - carbonizer development - hot particulate removal - combustion with O_2 - advanced sorbent development - ultra-high efficiency PFBC - isothermal compressor development - PFBC systems analysis and modeling	- feed and ash handling cost reduction - repowering - specific gas turbine development and adaptation of existing turbines - hot particulate filter reliability and adaptation to other markets - PSDF activities
Power Systems Advanced Research	- materials development (high-temp. heat exchangers, refractories, advanced ceramic composites, advanced alloys, hydrogen membrane) - virtual demonstration - advanced instrumentation and controls	- carbon reaction modeling - biomass co-firing - Hg capture mechanisms - biological NOx filters - biological production of fuels - carbon-based sorbents - mineral sequestration - biological sequestration - austenitic alloys - SBIR/STTR programs - UCR/HBCU programs

V21 Transition Plan

Existing Program	Activities Rolled Into Vision 21	Activities that Continue Separately
Environmental Control Technology	- advanced low-NOx combustion - advanced fine particulate controls - management of coal combustion byproducts (CCBs) from advanced power systems - revolutionary CO_2 capture and separation systems - integration of energy systems with terrestrial sinks - modeling of advanced fuel cycles	- $PM_{2.5}$ monitoring & characterization - $PM_{2.5}$ control technology development for existing plants - enhancing fine particulate control of existing equipment - high value/high volume uses of CCBs from existing plants - Hg transport & deposition - evolutionary advances in CO_2 capture and separation - geological sequestration - ocean fertilization - indirect ocean sequestration - advanced CO_2 utilization - CO_2 sequestration failure modes and performance models
Coal Preparation (Solid Fuels and Feedstocks)	- opportunity feedstocks characterization and recovery	- coal preparation
Direct Liquefaction	none	- two-stage liquefaction - co-processing research - systems analysis and modeling
Indirect Liquefaction	- synthesis gas-based products - computational science, virtual reality - advanced (3-phase) reactor design - systems analysis and modeling - early entrance co-production	- proof-of-concept testing - advanced diesel fuels
Fuels Advanced Research	- hydrogen production - hydrogen storage - catalyst development	- advanced diesel fuels
Turbines and Engines	- High Efficiency Engines and Turbines (HEET) (advanced turbines, H_2 and ceramic turbines, fuel flexible turbines; integration testing) - fuel cell/turbine hybrids (turbine and engine development for long-term 70-80% efficient systems)	- distributed generation/fuel cell turbine hybrids (designs for near term 60% efficient systems) - advanced reciprocating engine systems - advanced turbine systems (technology base R&D, utility scale ATS product dev.) - flexible gas turbine systems
Fuel Cells	- fuel cell/turbine hybrids (fuel cell development for long-term 70-80% efficient systems) - 21st century fuel cells (ultra fuel cells) - cascaded fuel cell systems (multiple temperatures, pressures) - low-cost manufacturing	- distributed generation, molten carbonate fuel cells - fuel cell/turbine hybrids - fuel cells advanced research (developer support) - distributed generation interconnects

communications, etc.) are conducted in a consistent and coordinated manner.

Program Elements

The Vision 21 program elements and sub-elements are summarized below. The status of the enabling and supporting technologies are then described, followed by detailed

Program Elements	Program Subelements
I. Systems Analysis Systems analysis is a critical part of the Vision 21 program and serves as the "brain" or guiding force for all activities. The key role of systems analysis is to develop Vision 21 system configurations that satisfy the program objectives, to define the performance targets for individual sub-systems, and identify supporting technology needs.	a. Market Analysis b. Process Definition c. Process Evaluation d. Subsystem Performance Requirements e. Economic Analysis f. Subsystem Data Analysis and Model Development
II. Enabling Technologies Enabling technologies are those upon which the subsystems, or modules, that form the building blocks of a Vision 21 plant depend. Some enabling technologies, like gasification and advanced combustion, are already under development, and some are being demonstrated in the Clean Coal Technology Demonstration Program. Others, such as gas separation, require major improvements to existing technologies.	a. Gas Separation b. High-temperature Heat Exchangers c. Fuel-flexible Gasification d. Gas Stream Purification e. Advanced Combustion Systems f. Fuel-flexible Turbines g. Fuel Cells h. Advanced Fuels and Chemicals Development
III. Supporting Technologies Supporting technologies are cross-cutting technologies that are necessary for multiple Vision 21 subsystems and components and also important in other, non-Vision 21, applications.	a. Materials b. Advanced Computational Modeling and Development of Virtual Demonstration Capability c. Advanced Controls and Sensors d. Environmental Control Technology e. Advanced Manufacturing and Modularization
IV. Systems Integration Vision 21 plants will use "smart" systems integration techniques to combine high-performance subsystems. Systems integration is a principal part of Vision 21 and is necessary to ensure the safe, reliable, and economic operation of Vision 21 plants.	a. Systems Engineering b. Dynamic Response and Control c. Industrial Ecology
V. Plant Designs This program element produces the major products of the Vision 21 program.	a. Designs for Components and Subsystems b. Designs for Prototype Plants c. Designs for Commercial Plants d. Virtual Demonstration Capability

descriptions of the activities and milestones.

Status of Enabling and Supporting Technologies

Enabling Technologies:

- Oxygen Separation Membrane - *Current status*: Membranes are being tested at the laboratory scale. These high-temperature (1500°F) membranes could start to replace conventional energy intensive cryogenic separators by 2007. *Next step*: Test for stability and chemical resistance, scale-up, component integration, verify longevity of membrane. *Long-term Vision 21 needs*: Cost reduction, process integration, verify survivability of membrane system in a commercial application.
- Hydrogen Separation Membrane - *Current status*: Membranes are being tested at the laboratory scale. These membranes, which should be available for testing at commercial scale by 2009, will allow high-temperature separation of hydrogen from syngas for use as a fuel or chemical feedstock. *Next step*: Test for stability and chemical resistance, scale-up, component integration, verify longevity of membrane. *Long-term Vision 21 needs*: Cost reduction, process integration, dependability, verify survivability of membrane system in a commercial application.
- High-Temperature Heat Exchanger - *Current status*: Metal alloy heat exchangers, capable of 2000°F operation, are being tested at process development unit scale and will be available by 2005. Higher temperature (i.e., 3000°F) ceramic heat exchangers are in the materials R&D stage with commercial introduction of large-scale units expected by 2020. High-temperature radiant heat exchangers are required for Vision 21, especially for embodiments that use indirectly fired cycles. Gas exit temperatures above 2700°F are needed to meet Vision 21 efficiency targets. *Next step:* Assess materials and system designs. *Long-term Vision 21 needs:* Develop designs and acceptable-cost fabrication methods for large-scale ceramic heat exchange components; prove system ability to withstand multiple cold starts and temperature spikes.
- Fuel Flexible Gasification - *Current status*: Petcoke has been test fired in industrial- and utility-scale gasifiers and combustors. Biomass, municipal waste, and many other opportunity feedstocks have had only limited or no test experience. Fuel flexibility is needed to allow use of low-cost feedstocks and to take advantage of synergies with other industrial processes (e.g. pulp and paper, oil refining, sewerage treatment plants). *Next step*: Characterize feedstocks, assess handling and chemistry issues. *Long-term Vision 21 needs:* Prove feed system reliability, verify ability to control operating parameters to ensure zero waste discharge with variable feedstocks.
- Gas Stream Purification - *Current status*: Warm gas (700-1000°F) clean-up systems are being tested at utility scale. High-temperature (>1000°F) systems with ultra-pure gas streams will be ready for commercial-scale testing by 2008. These higher temperature systems enable the use of hydrogen membranes and improve efficiency by eliminating the need to cool and then reheat gas streams. *Next step:* Scale up, verify durability of materials for catalysts and filters, improve high-temperature sorbents. *Long-term Vision 21 needs:* Reduce cost of catalyst and filter systems, increase longevity of materials and systems.
- Advanced Combustion Systems - *Current Status:* High-temperature, low-NOx combustors have been developed and tested at pilot-scale under the Low Emission Boiler Systems (LEBS), Advanced Pressurized Fluidized Bed Combustion (APFBC) and High Performance Power Systems (HIPPS) programs. There is no current work on combustion in CO_2/O_2 mixtures, needed to adapt these systems for CO_2 separation and sequestration. *Next step:* Scale-up of low-NOx combustion systems to small commercial scale under LEBS; lab-scale studies to assess combustion of fuels in CO_2/O_2; investigation of isothermal compression. *Long term Vision 21 needs:* Designs for higher temperature combustors that will burn fuels in CO_2/O_2 mixtures and recycle CO_2 exhaust. Goal is to have commercially ready designs by 2015.
- Fuel Flexible Turbines - *Current status*: F class turbines are currently being operated on syngas, the first of the G class turbines are starting operation on conventional fuels and the first advanced turbine systems (ATS) turbines will be tested on natural gas by 2000. *Next step:* Integration studies and technology development to integrate ATS technology into Vision 21 systems. *Long-term Vision 21 needs:* Full-scale test of ATS fuel flexible turbine suitable for Vision 21 applications.
- Fuel Cells - *Current status*: atmospheric pressure fuel cells are currently available in the several kilowatt to several megawatt range (at a cost of about $2000 - 3000/kW). Pressurized, cascaded fuel cells, and fuel cell/turbine systems will be ready for commercial use by 2015. *Next step:* Identify optimal hybrid system, reduce cost by a factor of ten through improved manufacturing techniques and systems integration. *Long-term Vision 21 needs:* Continued cost reduction, verification of commercial scale system stability and reliability.
- Advanced Fuels and Chemicals Development - *Current status*: Catalysts for producing some fuels and chemicals are available for use at pilot- and commercial-scale. Adaptation and evolution of current systems to operate in a Vision 21 plant will be completed by 2005. *Next step:* Identify optimum catalysts and systems, and scale up.

Long-term Vision 21 needs: Cost reduction.

Supporting Technologies:

- Materials - *Current status*: New alloys and ceramics, suitable for use at high temperatures in corrosive environments, are being developed for Vision 21 subsystems and components. *Next step*: Continue to develop advanced alloys and ceramic materials which allow for improved performance. Develop fabrication technology, e.g., joining, welding. *Long-term Vision 21 needs:* Technology for fabricating, at acceptable cost, large-scale ceramic components for Vision 21 applications. Demonstrate reliability of such large-scale ceramic components.
- Advanced Computational Modeling, Virtual Demonstration - *Current status*: The use of virtual demos is already being realized in other industries as a cost-effective way to reduce construction and operational risks and to gain a better understanding of system feedbacks. *Next step*: Develop a computer simulation to “demonstrate” integration of new enabling and enhanced technology modules. *Long-term Vision 21 needs:* Develop computer simulations for complex plants, including co-production plants. To the extent possible, verify that the simulator is accurate by comparing to actual facilities.
- Advanced Controls and Sensors - *Current status*: Gasifiers and other equipment with instrument-hostile environments generally rely on indirect and calculated (measurements estimated based on information at other locations in the process) measurements. Advanced sensors and controls are needed to monitor process conditions directly to increase process efficiency, reliability, availability, and to detect early signs of failure. *Next step*: Develop and test robust sensors and intelligent control systems. *Long-term Vision 21 needs:* Test control systems and sensors in a commercial environment.
- Advanced Environmental Control Technology- *Current status:* Technology improvements for the existing fleet are enabling power generators to meet current and forecasted regulations. *Next Step:* Define control technology requirements for Vision 21 plants and extend performance of existing technologies to meet these requirements, if possible. *Long-term Vision 21 needs:* Develop acceptable cost technologies that effectively control all pollutants from fossil fuels to mitigate any environmental consequences.
- Advanced Manufacturing and Modularization - *Current status*: Most large industrial and utility fossil fuel plants are designed on a site-by-site basis. *Next step*: Design of module packages in several fixed size ranges to reduce design and production costs. *Long-term Vision 21 needs:* Develop methodology for incorporating modular design and construction practices into complex Vision 21 plants.

Activities and Milestones

Activities and Milestones under each program element and subelement are described below.

I. Systems Analysis

a. Market Analysis

1. Conduct market analyses/program reviews. Two market analyses will be conducted: the first in FY01 and the second in FY08. The second study will update developments involving possible restrictions on emission of greenhouse gases and market changes reflecting deregulation of the power industry. These analyses will suggest what features and characteristics of Vision 21 plants are desired by potential purchasers. Variables to be included in the study are plant size, whether fuel and/or chemical co-products are produced and, if so, the identity of the products. The prospects for the use of low-value “opportunity feedstocks” and biomass in combination with fossil fuel feedstocks will be investigated. The effects of deregulation of the power industry and emergence of distributed generation (DG) power systems on the valuation and use of waste heat will be examined. Markets for the heat will be described in terms of size, distribution, and other salient characteristics, e.g., chemical processing, space heating, and space conditioning. The effect of this market on the size of DG power plants will be developed, as will opportunities for designing larger DG plants to enhance the value of byproduct heat. The need for CO_2 collection for sequestration will be treated. The value that the post-regulated power market puts on efficiency, as measured by acceptable capital cost for better performing plants, will be assessed. Adjustments of program emphasis may be made after the market study results are reviewed. FY01-FY02, FY08-FY09

Players: industry (e.g., market research firms), FETC, FE-HQ

Milestones:

- Complete market analyses (FY01, FY08)
- Complete review of program emphasis in light of market study results (FY02, FY09)

b. Process Definition

1. Define high-performance systems and key components. Solicitations will be issued in FY99 and FY06 to tap into industry’s best ideas for high-efficiency, high-environmental performance Vision 21 systems for natural gas, coal, and other solid fuels such as biomass, petroleum coke, and municipal and industrial wastes. Contractors will describe their power systems and use computer models to estimate system performance predicated on assumed performance of one or more subsystems or key components that are not yet commercial, but are in development. Contractors will select the subsystems and components that need further development and develop R&D objectives to bring these subsystems and components to commercial readiness. FY99-FY03 FY06-FY10

Players: industry, national labs, universities, FETC

Milestones:

- Issue solicitations (FY99, FY06)
- Select subsystems and components to be further developed (FY01, FY08)
- Complete process definition reports (FY03, FY10)

c. Process Evaluation

1. Assess state-of-art of Vision 21 systems. At five-year intervals a formal assessment will be conducted of current and near-term capabilities for building Vision 21 systems. Desired efficiency and pollutant emission targets will be specified. Output from the systems integration program element (IV) will be factored into the evaluation in order to help judge the potential reliability, availability, and maintainability of Vision 21 plants. Increasing the simplicity of system configurations will be a goal, i.e., preference will be given to simpler configurations with comparable performance to more complex configurations. FY04, FY09, FY14

Players: industry, national labs, universities, FETC

Milestones:

- Complete first assessment (FY04)
- Complete second assessment (FY09)
- Complete third assessment (FY14)

d. Subsystem Performance Requirements

1. Review component and subsystem performance. A program review exercise will be conducted following each power systems state-of-art assessment. Key process components whose performance must be upgraded to permit significant improvement of overall process efficiency and/or economics will be identified. This information will be used to target subsequent solicitations for component development so that funds are directed to process areas representing critical needs. FY05, FY10

Players: FETC, FE-HQ

Milestones:

- Complete first review (FY05)
- Complete second review (FY10)

e. Economic Analysis

1. Estimate costs of Vision 21 systems. An assessment of capital and operating costs of candidate Vision 21 systems will be performed after the two reviews of Vision 21 systems and subsystem/component performance requirements. A final review will be performed in FY14. Cost estimates will emphasize costs of key components, subsystems, and plant sections. The cost updates will reflect information gained during the development phase of key components and subsystems. FY05, FY10, FY14

Players: industry, universities, FETC

Milestones:

- Complete assessment report (FY05)
- Complete assessment report (FY10)
- Complete assessment report (FY14)

f. Subsystem Data Analysis and Model Development

1. Analyze subsystem data and develop models. Subsystem models will be developed from experimental data and physical principles. State-of-art modeling and graphical display capabilities will be developed. FY02-FY12

Players: industry, universities, national laboratories, FETC, FE-HQ

Milestones:

- Complete description of critical units identified in component and subsystem performance reviews (FY06, FY11)
- Complete development of subsystem models (FY12)

II. Enabling Technologies

a. Gas Separation

1. Develop air separation systems for oxygen-enriched air and high-purity oxygen. Air separation systems for the production of 60-80% oxygen and high-purity oxygen will be developed, including scaleup and integrated testing of dense ceramic ion transport membranes. In an IGCC plant, oxygen production can account for 15-25% of the cost of the plant. Improvements in air separation technology can have a profound impact on the overall economics of IGCC. The availability of low-cost oxygen will also enable the use of oxygen-enriched combustion, leading to the concentration of CO_2. FY00-FY08

Players: industry, national labs, universities, FETC

Milestones:

- Initiate development of promising air enrichment technologies (FY01)
- Initiate scale-up of ITM air separation technology for high-purity oxygen to 5 tons/day (FY02)
- Begin ITM-oxygen/turbine integrated operation at 50 tons/day (FY05)
- Test prototype air enrichment module (FY06)
- Begin integrated testing of air-enrichment module (FY08)
- ITM-oxygen technology commercially ready (FY08)

2. Develop membrane technologies for hydrogen separation. This activity addresses the scaleup, and integrated testing of advanced inorganic membranes for high-temperature hydrogen separation from synthesis gas. Low-cost hydrogen would create significant opportunities in a number of areas, including fuel cell power and fuels and chemicals synthesis. FY00-FY10

Players: industry, national labs, universities, FETC

Milestones:

- Initiate engineering development of high-temperature ceramic membrane technology (FY00)
- Begin development and testing of modules in prototype unit (FY04)
- Demonstrate integrated operation of full-scale modules (FY06)
- Ceramic membrane technology commercially ready (FY10)

3. Develop CO_2 hydrate-based technology for hydrogen separation. This technology offers a low-temperature approach for the production of high-purity hydrogen from a shifted synthesis gas produced by the gasification of carbon-based feedstocks. The focus will be on the development, scaleup, and integrated testing of CO_2 hydrate-based technology for separation of hydrogen from synthesis gas, concentration of CO_2, and sequestration. FY00-FY11

Players: industry, national labs, universities, FETC

Milestones:

- Initiate development of CO_2 hydrate-based technology (FY00)
- Begin testing of small-scale skid-mounted unit at an exiting gasification site (FY03)
- Initiate scale-up for large-scale module demonstration (FY05)
- Begin integration of CO_2 sequestration in aquifers (FY 08)
- Hydrate technology commercially ready (FY11)

4. Produce hydrogen from water dissociation. The dense ceramic proton-transfer membrane developed for separating hydrogen from hot synthesis gas has shown the unique ability to simultaneously decompose water and separate hydrogen. This activity will focus on developing, scaling up, and testing membrane-based technologies for generation and separation of hydrogen from high-temperature steam. FY00-FY15

Players: industry, national labs, universities, FETC

Milestones:

- Initiate concept and materials development (FY00)
- Complete bench-scale testing of sub-scale modules (FY08)
- Complete testing of full-scale module (FY11)
- Integrate technology with Vision 21 system (e.g., a system in which a combustor and fuel cell utilize the products of the water splitting membrane) (FY15)

b. High-temperature Heat Exchangers

1. Develop alloy-tube heat exchangers. This activity concerns the development and pilot-scale testing of high-temperature heat exchangers containing alloy tubes for heating air and other process fluids to temperatures of 2300°F. FY00-FY04

Players: industry, national labs, universities, FETC

Milestones:

- Demonstrate 1000 hours performance of pilot-scale air heater with 2300°F capability (FY04)

2. Develop ceramic-tube heat exchangers. High-temperature heat exchangers using ceramic tubes for heating air and other process fluids to temperatures of 3000°F will be developed and tested. FY03-FY10

Players: industry, national labs, universities, FETC

Milestones:

- Demonstrate 1000 hours performance of pilot-scale air heater with 3000°F capability (FY10)

c. Fuel-flexible Gasification

1. Develop solid fuel feeding technologies. Most gasifiers are designed to process one particular feedstock such as coal or petroleum coke. This limits the gasifier's ability to process low-cost feedstocks that may become available. However, feeding certain feedstocks, including biomass, to a high-pressure gasifier has proved difficult. Because it is unlikely that sufficient crops can be grown in a local area to provide the quantity necessary for a large gasification facility, it is necessary to develop technologies that will permit the use of a wide variety of feedstocks in combination with coal. This activity focuses on the development and testing of advanced technologies for feeding coal and other carbonaceous feedstocks (biomass, MSW) and assessing gasifier performance. FY00-FY06

Players: industry, national labs, universities, FETC

Milestones:

- Begin development of feed system concepts for co-feeding coal and other carbon-based materials (FY00)
- Initiate bench-scale development and testing of promising feed systems (FY02)
- Complete feed system demonstration (FY06)

2. Develop and test advanced gasifiers. The gasifiers currently in operation are expensive, have difficulty processing certain feedstocks, and may not be suitable for many Vision 21 applications. This activity concerns novel gasification concepts including membrane-based gasifiers, advanced gasifiers for processing high-ash coals, transport gasifiers, and catalytic gasifiers. FY00-FY08

Players: industry, national labs, universities, FETC

Milestones:

- Initiate concept development for advanced gasifiers (FY00)
- Begin assessment of catalytic gasification and initiate concept development (FY02)
- Initiate bench-scale development of promising gasification concepts (FY02)
- Complete bench-scale development (FY06)
- Provide industry with advanced gasifier designs (FY08)

3. Scale-up fluidized bed carbonizer (pyrolyzer). A fluidized bed coal carbonizer (pyrolyzer) for second generation fluidized bed combustion and indirectly fired cycles has been tested at the 5 million Btu/h scale. This activity will scale the carbonizer to 50 million Btu/h and test its performance. FY00-FY07

Players: industry, FETC

Milestones:

- Complete construction and shakedown of scaled carbonizer/pyrolyzer (FY02)
- Complete integrated testing with pressurized fluidized bed (PFB) and indirectly fired cycle (FY05)
- Complete higher temperature testing and coproduction assessment (FY07)

d. Gas Stream Purification

1. Develop high-temperature particulate filters. Development of low cost and highly reliable barrier filter systems is necessary to reduce overall power system cost. As currently envisioned, high-temperature hydrogen membrane separation technologies will require filter operation at temperatures over 1300°F. Other Vision 21 concepts will require filters that operate at temperatures as high as 1550°F. This activity focuses on developing and testing to resolve issues related to high-temperature particulate filters for use in advanced gasification and combustion systems. One of the issues facing successful implementation of filter systems under high temperature combustion conditions is ash bridging. Developing designs that are more tolerant of filter ash bridging, thermal shock and hopper overflow will increase reliability and reduce the O&M costs. Ash bridging with different filter designs will be studied at pilot-scale by varying temperatures and particle size along with coal and sorbent types. New configurations such as large sheets made from lightweight composite materials and thinner wall candle filters, designed to resist ash bridging, will be tested in the laboratory to determine if they can be used at high temperatures under gasification conditions. Successful candidates will then be transaudient to pilot-scale testing. Filter element lifetimes will be established by pilot-scale testing over extended periods under combustion and gasification conditions. Ash and char properties will continue to be assessed since it plays a major role in determining the operational performance of filter systems. As testing and evaluation of pilot-scale filter system progresses, inadequacy in components or the need for ancillary equipment will be identified. FY00-FY04

Players: industry, Power Systems Development Facility, FETC

Milestones:

- Develop large oxide ceramic composite sheet filters and large-bore inverted candle filters (FY02)
- Develop and test at bench-scale safeguard devices for PFBC systems (FY02)
- Design and test at bench-scale an advanced, low-cost filter concept (FY03)
- Test at pilot-scale a filter system to further investigate the bridging phenomenon (FY03)
- Test at pilot-scale advanced filter designs for bridging tolerance (FY04)
- Test at pilot-scale metal filters under high-temperature gasification conditions (FY04)

2. Develop contaminant removal technology. This activity concerns development, testing and scale-up of chemical contaminant (H_2S, NH_3, alkalies, chlorides, SOx, NOx, Hg) removal technologies to meet stringent gas quality requirements for advanced combustion systems, synthesis gas conversion, and fuel cell applications. Barrier filter elements offer a tremendous amount of surface area that can be made available for multi-contaminate control. Pilot-scale tests of barrier filter systems integrated with technologies for gas-phase contaminate control will be conducted. The possibility of supporting catalysts or sorbents on the internal porous surface area or internal open area of barrier filter elements will be explored. Injectable sorbents and getters will be assessed for use in barrier filter systems. Sorbents that can be injected upstream of barrier filters systems will be trapped on the dust cake and provide excellent gas and solids contact with long in-system residence time. Disposable sorbents may be considered. New process operations will be required for the integration of gas-phase cleanup and particulate cleanup in the same system or vessel. This effort will assess the need for new equipment and process requirements for the successful integration of gas-phase and particulate cleanup. FY00-FY06

Players: industry, Power Systems Development Facility, FETC

Milestones:

- Develop and test at bench-scale multi-contaminant control filter elements (FY04)
- Develop and test injectable sorbents for use in hybrid, multi-contaminant control systems (FY04)
- Integrate gas-phase and particle cleanup systems (FY05)
- Conduct pilot-scale test of barrier filter systems (FY06)

e. Advanced Combustion Systems

1. Investigate "sequestration-ready" combustion systems. Sequestration-ready systems will be developed that use oxygen enrichment and CO_2 recycle in order to produce concentrated CO_2 exhaust streams. FY02-FY06

Players: industry, national labs, universities, FETC

Milestones:

- Complete construction of pilot-scale system (FY03)
- Measure effects on combustion properties and emissions when burning natural gas, coal, and other fuels (FY06)

2. Test integrated components. This activity concerns testing of integrated components for ultra-high efficiency plants based on combinations of advanced pulverized coal (PC) and PFB combustion technologies combined with high-temperature heat exchangers, sorbents, and particulate removal. FY02-FY08

Players: industry, national labs, universities, FETC

Milestones:

- Complete integration designs (FY05)
- Complete integrated PC and PFB tests (FY08)

3. Develop sulfur sorbents. High-temperature sorbents will be developed for use in in-situ sulfur removal. FY06-FY08

Players: industry, national labs, universities, FETC

Milestones:

- Test sorbents at pilot-scale (FY08)

f. Fuel-flexible Turbines

1. Develop advanced combustion turbine technology. This activity concerns R&D to use advanced heat transfer and aerodynamics, and advanced materials, to develop turbine combustion systems that operate under extremely high-temperatures (3000°F) and corrosive environments. Assessments will include advanced concepts, systems, and components such as the CO_2 Cooperate cycle; hydrogen turbine systems; supercritical steam turbines; ultra-high efficiency simple and combined cycle systems with reheat, intercooling, and optimal integration with gasification; direct combustion and indirect fired power systems; and optimum efficiency thermodynamic concepts. FY00-FY08

Players: industry (especially small business, universities, national laboratories, FETC

Milestones:

- Assess and define concepts for Vision 21 turbine/engine modules (FY03)
- Complete technology development for advanced turbine designs (FY08)

2. Integrate improvements into existing designs. This activity focuses on improvements to existing platforms such as Advanced Turbine Systems (ATS) and Flexible Gas Turbine Systems (FGTS) in order to achieve Vision 21 goals for system performance and cost. Results from the R&D efforts will be incorporated into the designs of existing ATS and other heat engine platforms to make them fuel-flexible, and with enhanced performance to meet Vision 21 goals for system efficiency and cost. Selected platforms/products modules will then be enhanced with the advanced technologies. FY08-FY12

Players: industry (equipment designers), small businesses

Milestones:

- Select engines/turbines platforms from ATS and FGTS programs for integration into Vision 21 systems (FY08)
- Design turbine/engines modules for Vision 21 (FY11)
- Test selected platforms/products modules with advanced technologies developed under activity 1 (FY12)

3. Test/integrate full-scale systems. Advanced turbine/engine modules, developed under activity 2, will be integrated with other systems in Vision 21 configurations. Integrated configurations will be tested through virtual demonstration along with limited testing at a host site to verify the accomplishment of Vision 21 goals. FY13-FY15

Players: FETC, national laboratories, industry (esp. small businesses), suppliers, power generators/marketers, host sites

Milestones:

- Test advanced Vision 21 components under system operating conditions (FY13)
- Integrate the advanced components into host Vision 21 plants with Virtual Demonstration and limited host site turbine/engine test sites (FY15)

g. Fuel Cells

1. Develop fuel cell/turbine hybrids. This activity focuses on development of ultra-clean high- efficiency fuel cell/ turbine electric power plants for the 21st century that can reduce CO_2, SOX, and NOx. The objective is to develop near term (60% efficiency) and intermediate term (70% efficiency) hybrid systems. FY00-FY10

Players: industry (fuel cell developers, turbine manufacturers), FETC

Milestones:

- Issue fuel cell/turbine technology development solicitation for identification, design, and testing of systems of at least 70 percent efficiency (FY00)
- Demonstrate fuel cell/turbine systems of at least 60 percent efficiency under existing fuel cell development projects (FY03)
- Demonstrate fuel cell/turbine systems of at least 70% efficiency (FY10)

2. Develop 21st century fuel cells. This activity is based on vigorous conceptual study development and peer review; the objective is to develop competitively priced ultra-efficient solid-state high-temperature fuel cell power systems capable of operation on natural gas as well as coal-derived fuels. FY00-FY15

Players: FETC, national laboratories, universities, utilities, industry, and other end-users

Milestones:

- Initiate virtual design activities and material and manufacturing/fabrication research (labs/university-lead) (FY00)
- Initiate industry participation in manufacturing/fabrication research (FY01) and begin component fabrication (FY05)
- Initiate small-scale cell testing (FY02) and proof of concept testing (FY05)
- Demonstrate solid state fuel cell system with 70% efficiency (FY10)
- Demonstrate solid state system with at least 80% efficiency (FY15)

h. Advanced Fuels and Chemicals Development

1. Develop technology base for early entry co-production plant. The goal of this activity is to develop the information base upon which to design and build an early commercial plant for co-production of fuels and power. The awardees are to complete research necessary for the design of the early entry co-production plant, including all market and economic analyses necessary to capitalize and construct such a plant with private funds. FY00-FY06

Players: industry-led consortia

Milestones:

- Procurement/award (FY00)
- Complete government funded portion of project (FY04)
- Complete design (FY06)

2. Design co-production fuel module. The goal of this task is to design a full-scale, early commercial, Vision 21 fuels co-production module. The awardees are to complete the feasibility analyses and research necessary for the design, construction and integration of the fuels/chemicals production portion of the Vision 21 facility. FY07-FY13

Players: industry-led consortia

Milestones:

- Procurement (FY09)
- Award (FY10)
- Complete design (FY13)

3. Develop fuels for internal combustion engines. The goal of this activity is to develop non-petroleum based transportation fuel technologies for deployment as part of the Vision 21 concept. These technologies will make environmentally superior transportation fuels from indigenous resources. FY02-FY08

Players: industry, universities, national laboratories, FETC

Milestones:

- Develop iron-based Fischer-Tropsch catalysts that are resistant to attrition (FY03)
- Integrate catalyst-wax separator with reactor design (FY05)
- Demonstrate follow-on processes and products for diesel fuels, jet fuels & additives (FY08)

4. Develop and evaluate advanced fuels for fuel cell-powered vehicles. Fuels suitable for use in fuel cell powered vehicles, including those that may be reformed on-board will be developed, evaluated at the proof-of-concept scale, and tested in prototype fuel cell-powered vehicles. FY05-FY13

Players: industry, universities, national laboratories, FETC

Milestones:

- Complete bench-scale development (FY10)
- Complete POC development (FY12)
- Test fuels in fuel cell powered vehicle (FY13)

5. Design reactor systems for clean fuels. The objective of this activity is to design reactors and reactor systems required for production of advanced clean fuels and fuel additives. The emphasis will be on three-phase reactor systems and the hydrodynamics and kinetics associated with them. FY00-FY12

Players: industry, universities, national laboratories, FETC

Milestones:

- Complete preliminary reactor designs (FY04)
- Complete detailed reactor designs (FY10)
- Integrate with Vision 21 systems (FY12)

III. Supporting Technologies

a. Materials

1. Select high-temperature heat exchanger materials. Alloys are needed for the fabrication of heat exchangers for high-temperature steam bottoming cycles; ceramics are needed for very high-temperature (2500-3000°F) heat exchangers for indirectly fired cycles and other applications. Exposure and durability tests will be conducted of candidate alloys and ceramics for use in high-temperature heat exchangers in aggressive environments. FY02-FY06

Players: national laboratories, FETC

Milestones:

- Evaluate and select alloys suitable for heat exchangers (FY02)
- Evaluate and select ceramic composite tube materials (FY06)

2. Develop advanced refractories. Vision 21 plants will require advanced new erosion and corrosion resistant refractories to serve as vessel liners for gasifiers, pyrolyzers, and combustors, and as pipe liners for the hostile high-temperature environments that will be present in these plants. This work will require a cooperative effort between national laboratories developing the materials and the industrial users where testing will be performed. FY00-FY12

Players: national laboratories, industry, FETC

Milestones:

- Complete initial studies and short-term testing of advanced corrosion/erosion resistant refractories (FY02)
- Initiate long-term testing (FY02)
- Complete long-term testing of coupons (FY08)
- Complete long-term test in a gasifier or pyrolyzer (FY12)

3. Develop hydrogen membrane materials. Vision 21 plants that co-produce fuels and chemicals will require an economical source of hydrogen to convert higher carbon feedstocks to these products. Hydrogen separation membranes are the key to filling this need. New materials which are highly permeable and selective to hydrogen will be developed. FY00-FY03

Players: national laboratories

Milestones:

- Begin large-scale testing of improved membrane material (FY01)
- Complete development and testing of first generation membrane material (FY03)

b. Advanced Computational Modeling and Development of Virtual Demonstration Capability

1. Develop scientific and engineering simulation capability. Computational simulation will provide a new and improved capability for the development of Vision 21 technology. The power of computers is rapidly growing and modeling is becoming more accurate. Simulations can provide a very 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. These transient 3-D simulations will realistically account for all the physically relevant phenomenon such as fluid flow, heat transfer, chemistry, radiation, material stress, *etc*. FY00-FY14

Players: national laboratories, universities, industry (including firms specializing in simulation software), government agencies, FETC

Milestones:

- Complete advanced fuel cell simulations (FY01)
- Complete natural gas-fired internal combustion engine simulations (FY01)
- Complete turbomachinery design simulation (clocking, etc.) (FY02)
- Complete gasifier simulation (FY03)
- Complete natural gas-fired turbine combustor simulation (FY05)
- Complete integrated turbine simulation (turbine and

combustor) (FY06)

- Complete heavy fuel-fired internal combustion engine and turbine simulation (FY08)
- Complete integrated gasifier, clean-up, combustion simulation (FY09)
- Complete membrane separation simulation (FY10)
- Complete integrated Vision 21 plant simulation (FY14)

2. Develop virtual demonstration capability. The concept of the virtual demonstration is to unify all computer related activities of plant design into an integrated suite of codes, which can exchange information easily and accurately. The virtual "demo" will have a visualization "front end" that is based on 3-D solid modeling. This information can be passed to computer aided design (CAD) software to generate drawing, P&IDs, etc. The geometrical and materials information can also be shared with analysis programs for use with computational fluid dynamics (CFD) or structural/stress analysis (computer aided engineering, CAE) software. This will allow "virtual" analysis of the broad details of the simulations to be determined by the process analysis software, which will also be able to communicate within this suite of codes. Another important component of the suite is control analysis. Underlying this capability will be an information management system that will allow the accurate transfer of information between components. These capabilities will be implemented so that they can be accessed over the World Wide Web, to facilitate "virtual" (in another sense of the word) collaboration.

This activity will progress on two tracks. One will be the development of the virtual demonstration capability, the infrastructure of the project. Rapidly advancing computational and internet technologies will be exploited. Commercially developed software capabilities will be tailored to apply to programmatic objectives. A parallel track will be the development of simulation capabilities which will "mirror" the enabling technologies in the Vision 21 program. Each of these components of Vision 21 will be supported by the simulations capabilities of the virtual demo. The two tracks can progress in parallel. However, as the basic capabilities become more completely developed, the fidelity and versatility of the simulations in each technology will improve. FY00-FY15

Players: national laboratories, industrial firms including architect & engineering firms, FETC

Milestones:

- Develop 3-D solid modeling capability (FY00)
- Develop visualization capability (FY01)
- Develop computer-aided design capability (FY01)
- Implement computational/communication resources (FY02)
- Develop structural analysis capability (FY02)
- Introduce concurrent engineering (FY02)
- Complete initial information management system (FY03)
- Complete process analysis models (FY03)
- Complete control analysis models (FY05)
- Integrate virtual demo capability with scientific and engineering simulations (FY05)
- Integration with design and construction management (FY09)
- Develop advanced information management system (FY10)
- Introduce advanced concurrent engineering (FY12)
- Demonstrate virtual operations (FY14)

c. Advanced Controls and Sensors

1. Develop advanced instrumentation and controls: Vision 21 plants will be a highly integrated complexes of advanced subsystems. Control of these plants will require sophisticated new algorithms which utilize advanced computer technology to control and optimize the plant efficiency and emissions performance. New sensors and measurement techniques will be needed to measure contaminants (including regulated pollutants) to ultra-low levels. These sensors will need to withstand very harsh environments (high temperatures and corrosive fluids) that will be present in these plants. FY00-FY10

Players: industry

Milestones:

- Define specifications for advanced instruments (FY00)
- Complete designs and fabrication of prototypes (FY02)
- Complete first generation beta testing (FY05)
- Complete development of sensors and control systems (FY10)

d. Environmental Control Technology

1. Develop advanced low-NOx combustion technologies. The goal is to develop combustion technology capable of meeting projected environmental regulations for advanced power systems. EPA has established a 0.15 lbs/million Btu limit for the eastern U.S. during the summertime ozone season (May-Sept.). In future years, NOx emission limits may tighten further so low emissions from the combustion system are necessary even with use of post-combustion NOx controls like SCR. Of particular interest is using O_2 to stabilize the flame closer to the burner tip. FY00-FY07

Players: industry (equipment suppliers)

Milestones:

- Issue solicitation (FY99)
- Identify low-NOx combustion concepts (FY02)

- Complete pilot-scale tests (FY05)
- Complete designs for commercial systems (FY07)

2. Develop advanced $PM_{2.5}$ control technology. Full implementation of the $PM_{2.5}$ standards is set for the 2008-2012 time frame. Cost effective technology is needed for compliance. This activity will focus on developing technology that will reduce both primary and secondary (from precursors NOx and SOX) $PM_{2.5}$ emissions from Vision 21 plants to negligible levels. FY00-FY07

Players: industry (equipment suppliers, power generators, research organizations)

Milestones:

- Initiate $PM_{2.5}$ control technology development R&D (FY99)
- Complete studies of primary $PM_{2.5}$ formation (FY01)
- Complete R&D on control of NOx precursors (FY03)
- Complete $PM_{2.5}$ control technology development (FY07)

3. Develop coal combustion by-products (CCB) management technology. This activity will develop technology to manage coal combustion by-products from Vision 21 plants that utilize combustion subsystems. Efforts will be made to minimize the volume of CCBs through the use of industrial ecology principles (see program element IVc). FY04-FY08

Players: industry (including construction, cement manufacturers)

Milestones:

- Complete survey of technologies for existing plants (FY04)
- Identify technologies for managing CCBs from advanced plants (FY06)
- Integrate CCB technology into Vision 21 plant design (FY08)

4. Devise revolutionary approaches to CO_2 capture and separation. While evolutionary approaches to CO_2 separation will continue to be explored, Vision 21 will require revolutionary approaches that are more effective and lower in cost. New CO_2 capture and separation concepts will be developed, leading to systems that will produce a CO_2-rich stream suitable for sequestration. FY00-FY10

Players: industry, national laboratories, universities, FETC

Milestones:

- Initiate revolutionary CO_2 capture and separations R&D program (FY00)
- Complete small-scale testing of advanced concepts (FY04)
- Complete integrated testing (FY06)
- Develop Vision 21 design for commercial application (FY10)

5. Integrate energy systems with terrestrial sinks. Coal suppliers and other energy producers can gain carbon offsets by integrating their operations with enhanced terrestrial carbon sink concepts. Non-productive land owned by energy producers can be used to grow biomass which, in turn, can be used as an energy source (e.g., coal biomass co-firing). Special biomass crops can be used to convert poor soils, such as reclaimed coal-stripped lands, into productive energy crops. The focus of this activity is to develop and implement partnerships with energy suppliers and biomass producers. FY00-FY05

Players: industry (including biomass marketers), national laboratories, government agencies, FETC

Milestones:

- Establish partnerships between energy suppliers and biomass producers (FY01)
- Complete assessment of viability of carbon offsets (FY05)

e. Advanced Manufacturing and Modularization

1. Develop improved manufacturing techniques. Improved manufacturing techniques are needed to reduce costs and improve the quality of components. This has already been accomplished in the emission controls industry for flue gas scrubbers and has played a major role in reducing the cost of these systems. Similar improvements are needed in Vision 21 components and subsystems such as fuel cells, heat exchangers, gas separation membranes, and sensors. Modular design will maximize shop fabrication and minimize field construction while maintaining flexibility in the design and deployment of Vision 21 plants. This activity will involve studies to identify ways in which key components can be manufactured more efficiently and cheaply. FY00-FY10

Players: industry (fuel cell developers, turbine manufacturers, equipment vendors)

Milestones:

- Establish a consortium for identifying improved manufacturing techniques (FY00)
- Identify primary components and areas for improvement (FY02)
- Develop improved manufacturing techniques (FY08)
- Complete testing of selected manufacturing techniques (FY10)

IV. Systems Integration

a. Systems Engineering

1. Develop preliminary definition of systems engineering issues. This activity will address component and subsystem compatibility issues. System configurations that achieve Vision 21 efficiency targets will be examined in the context of identifying factors that can affect compatibility, operability, and system cost. Potential issues include linking gasifiers and combustion turbines, turbines and fuel cells, fuel cells and combustion systems, and gas cleanup devices with other subsystems. Early scheduling of this activity will allow necessary subsystem design modifications, including application of industrial ecology principles, to be made early in the development process, when changes can be made more easily and cost effectively. FY00-FY02

Players: industry, universities, national labs, FETC

Milestones:

- Develop system configurations for systems engineering analysis (FY00)
- Complete definition of issues (FY02)

2. Develop preliminary subsystem design modifications and subsystem linkages and interconnects. Designs of subsystems and major components will be examined and modified in order to ensure compatibility. Physical linkages and interconnects will be designed. Modularity and cost minimization will be emphasized. FY03-FY06

Players: industry

Milestones:

- Complete preliminary design modifications for major components and subsystems (FY04)
- Complete preliminary designs for linkages and interconnects (FY06)

3. Define systems engineering issues. The issues identified in activity 1 will be revisited using the most recent Vision 21 system configurations and subsystem designs. FY07-FY09

Players: industry, universities, national labs, FETC

Milestones:

- Complete update of systems engineering issues (FY09)

4. Develop subsystem design modifications and subsystem linkages and interconnects. The design modifications developed in activity 2 will be revisited and updated. FY10-FY12

Players: industry

Milestones:

- Complete design modifications for major components, subsystems, and linkages and interconnects (FY12)

5. Apply virtual demonstration techniques. The virtual demonstration capability developed in program element IIIb will be applied to confirm the viability of Vision 21 system designs. The focus will be on ensuring that Vision 21 key components and subsystems can be fabricated and assembled using accepted manufacturing and construction techniques, including advanced manufacturing technology developed in program element IIIe. FY12-FY14

Players: industry, national labs, universities, FETC

Milestones:

- Complete virtual demonstrations of key components and subsystems (FY13)
- Complete virtual demonstrations of Vision 21 systems (FY14)

b. Dynamic Response and Control

1. Model dynamic response of Vision 21 subsystems. The dynamic response of Vision 21 subsystems to changes in load and other operating parameters will be modeled. Available models (e.g., ProTrax) will be used where appropriate; some subsystems models will need to be developed from first principles. Models will be validated using data from pilot- and full-scale operating subsystems (e.g., gasifiers, fuel cells, turbines). FY02-FY06

Players: industry, national labs, universities, FETC

Milestones:

- Develop dynamic response models for Vision 21 subsystems (FY04)
- Validate subsystem models (FY06)

2. Model dynamic response of Vision 21 systems. Models developed in activity 1 will be combined in order to model combinations of subsystems and complete Vision 21 system configurations. Startup, shutdown, and other system transient events will be modeled and studied. Models will be validated to the extent possible using data from pilot- and full-scale systems. FY06-FY10

Players: industry, national labs, universities, FETC

Milestones:

- Develop dynamic response models for Vision 21 system configurations (FY08)
- Validate system models (FY10)

3. Develop control strategy for Vision 21 plants. This activity will investigate the complex control theory necessary to operate integrated Vision 21 plants. A process control strategy for Vision 21 plants will be developed using the results of activities 1 and 2. Software will be developed that can be used with digital process control systems. FY08-FY12

Players: industry, national labs, universities, FETC

Milestones:

- Develop Vision 21 process control software (FY12)

4. Select and develop process control hardware for Vision 21 plants. State-of-the-art control instrumentation and control hardware will be studied to determine the reliability, availability, and maintainability necessary for operation in the complex, integrated environment of Vision 21 plants. New process control hardware measuring devices and sensors (e.g., flow, temperature, and chemical composition) and control hardware (e.g., valves, pressure controllers) will be developed and tested as needed. FY08-12

Players: industry, national labs, universities, FETC

Milestones:

- Identify existing process control hardware appropriate for Vision 21 (FY08)
- Develop and test new sensors and control hardware (FY12)

c. Industrial Ecology

1. Apply industrial ecology principles to Vision 21 system configurations. Vision 21 system configurations will be evaluated and modified, if necessary, to comply with industrial ecology principles. The goal will be to recycle, or utilize in some other manner, *all* process effluents that would otherwise be regarded as waste streams. Results of this activity will be input to activity IVa3 (systems engineering issues). FY06-08

Players: industry, national labs, universities, FETC

Milestones:

- Complete industrial ecology analysis (FY08)

V. Vision 21 Plant Designs

a. Designs for Components and Subsystems

1. Select components and subsystems. Key components (e.g., heat exchangers, pumps, compressors) and subsystems (e.g., turbines, furnaces, gas separators) will be selected and engineering designs will be prepared. These components and subsystems and will be the key building blocks of Vision 21 systems. Designs modularity will be emphasized. The intent is for designers of future Vision 21 plants to be able to select those modules that would be appropriate for the intended plant configuration. Component sizes and performance requirements will be defined. FY03-FY05

Players: industry, FETC

Milestones:

- Select component and subsystems for design studies (FY04)
- Define performance requirements (FY05)

2. Design modular components and subsystems. Engineering designs will be prepared for modular components and subsystems that can be used in various types of plant configurations. The designs will be reviewed periodically to incorporate new R&D results and updated when necessary. Design and fabrication costs will be estimated. FY05-FY12

Players: industry, universities, national labs, FETC

Milestones:

- Complete initial component and subsystem designs (FY07)
- Review and update designs (FY10)
- Complete component and subsystem designs and cost analysis (FY12)

b. Designs for Prototype Plants

1. Select prototype plant configurations. Several (2-3) configurations for prototype Vision 21 plants will be selected based on the results of market analyses. Updates will be made after the second market study (see activity Ia1). Sites will be selected and the plant feedstocks, products, configuration, and size will be based on market requirements. Systems integration techniques developed in Program Element IV will be used extensively in the final plant designs. FY04-FY09

Players: industry, FETC

Milestones:

- Select initial prototype configurations (FY05)
- Select final prototype plant configurations (FY09)

2. Design prototype plants. Engineering designs will be prepared for the Vision 21 plants selected in activity 1. Prototype plants are small, first-of-a-kind, commercial plants intended to show industry that such plants can be built and operated reliably, safely, and economically. Develop comprehensive equipment lists and prepare cost estimates showing costs for major plant components, subsystems, plant sections, and the complete plant. FY10-FY14

Players: industry, universities, national labs, FETC

Milestones:

- Complete prototype plant designs (FY14)
- Complete cost analyses (FY14)

c. Designs for Commercial Plants

1. Select commercial plant configurations. Several (2-3) configurations for commercial-scale Vision 21 plants will be selected based on the results of market analyses. Sites will be selected and the plant feedstocks, products, configuration, and size will be based on market requirements. Systems integration techniques developed in Program Element IV will be used extensively in the final plant designs. FY05-FY10

Players: industry, FETC

Milestones:

- Select initial commercial plant configurations (FY06)
- Select final commercial plant configurations (FY10)

2. Design commercial plants. Engineering designs will be prepared for the Vision 21 plants selected in activity 1. Comprehensive equipment lists and cost estimates showing costs for major plant components, subsystems, plant sections, and the complete plant will be prepared. FY11-FY15

Players: industry, universities, national labs, FETC

Milestones:

- Complete commercial plant designs (FY15)
- Complete cost analyses (FY15)

d. Virtual Demonstration Capability

1. Simulate component/subsystem performance. The virtual demonstration capability developed in program element IIIb and as part of the enabling technologies (program elements IIa-h.) activities will be used to simulate the performance of components and subsystems of Vision 21 plants. FY08-FY10

Players: industry, universities, national labs, FETC

Milestones:

- Conduct virtual demonstrations of components and subsystems (FY10)

2. Simulate commercial-scale plant performance. Virtual demonstrations of commercial-scale Vision 21 plants will be conducted. These demonstrations will illustrate equipment configuration and orientation and include details of plant operation, including dynamic response to changes in load, variations in feedstock properties, changes in component or subsystem operation, and upset conditions. FY12-FY15

Players: industry, universities, national labs, FETC

Milestones:

- Conduct virtual demonstration of complete Vision 21 plant (FY15)

Preliminary Roadmap

A preliminary Roadmap for Vision 21 is given in the Appendix.

Appendix

Appendix

"Vision 21 - Clean Energy Plants for the 21st Century" - Preliminary Roadmap

Activity Description	FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16
I. SYSTEMS ANALYSIS																			
a. Market Analysis																			
1. Conduct market analysis/program reviews					■							■							
Complete market analysis				◆							◆								
Complete review of program emphasis in light of market study results					◆							◆							
b. Process Definition																			
1. Define high-performance systems and key components		■	■	■	■	■			■	■	■	■	■						
Issue solicitations		◆							◆										
Select subsystems and components to be further developed				◆							◆								
Complete process definition reports						◆							◆						
c. Process Evaluation																			
1. Assess state-of-art Vision 21 systems							■					■					■		
Complete first assessment							◆												
Complete second assessment												◆							
Complete third assessment																	◆		
d. Subsystem Performance Requirements																			
1. Review component and subsystem performance								■					■						
Complete first review								◆											
Complete second review													◆						
e. Economic Analysis																			
1. Estimate costs of Vision 21 systems								■					■				■		
Complete assessment report								◆											
Complete assessment report													◆						
Complete assessment report																	◆		
f. Subsystem Data Analysis and Model Development																			
1. Analyze subsystem data and develop models					■	■	■	■	■	■	■	■	■	■	■				
Complete description of critical units identified in component and subsystem reviews									◆					◆					
Complete development of subsystem models															◆				
II. ENABLING TECHNOLOGIES																			
a. Gas Separation																			
1. Develop air separation systems for oxygen-enriched air and high-purity oxygen			■	■	■	■	■	■	■	■	■								
Initiate development of promising air-enrichment technology				◆															
Initiate scale-up of ITM air separation technology for high purity oxygen to 5 tons/day					◆														
Begin ITM-oxygen/turbine integrated operation at 50 tons/day								◆											
Test prototype air-enrichment module									◆										
Begin integrated testing of air-enrichment module											◆								
ITM-oxygen technology commercially ready											◆								
2. Develop membrane technologies for hydrogen separation			■	■	■	■	■	■	■	■	■	■	■						
Initiate engineering development of high temperature ceramic membrane technology			◆																
Begin development and testing of modules in prototype unit							◆												
Demonstrate integrated operation of full-scale modules									◆										
Ceramic membrane technology commercially ready													◆						
3. Develop CO2 hydrate-based technology for hydrogen separation			■	■	■	■	■	■	■	■	■	■	■	■					
Initiate development of CO2 hydrate-based technology			◆																
Begin testing of small-scale skid-mounted unit at an exiting gasification site						◆													
Initiate scale-up for large-scale module demonstration								◆											
Begin integration of CO2 sequestration in aquifers											◆								
Hydrate technology commercially ready														◆					
4. Produce hydrogen from water dissociation			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Initiate concept and materials development			◆																
Complete bench-scale testing of sub-scale modules											◆								
Complete testing of full-scale module														◆					
Integrate technology with Vision 21 system																		◆	
b. High-temperature Heat Exchangers																			
1. Develop alloy-tube heat exchangers			■	■	■	■	■												
Demonstrate 1,000 hours performance of pilot-scale air heater with 2,300 F capability							◆												
2. Develop ceramic-tube heat exchangers						■	■	■	■	■	■	■	■						
Demonstrate 1,000 hours performance of pilot-scale air heater with 3,000 F capability													◆						
c. Fuel-flexible Gasification																			
1. Develop solid fuel feeding technologies			■	■	■	■	■	■	■										
Begin development of feed system concepts for co-feeding coal and other carbon-based materials			◆																
Initiate bench-scale development and testing of promising feed systems					◆														
Complete feed system demonstration									◆										
2. Develop and test advanced gasifiers			■	■	■	■	■	■	■	■	■								
Initiate concept development for advanced gasifiers			◆																
Begin assessment of catalytic gasification and initiate concept development					◆														
Initiate bench-scale development of promising gasification concepts					◆														
Complete bench-scale development									◆										
Provide industry with advanced gasifier designs											◆								
3. Scale-up fluidized bed carbonizer (pyrolyzer)			■	■	■	■	■	■	■	■									
Complete construction and shakedown of scaled carbonizer/pyrolyzer					◆														
Complete integrated testing with PFB and indirectly fired cycle								◆											
Complete higher temperature testing and co-production assessment										◆									
d. Gas Stream Purification																			
1. Develop high-temperature particulate filters			■	■	■	■	■												
Develop large oxide ceramic composite sheet filters and large-bore inverted candle filters					◆														
Develop and test at bench-scale safeguard devices for PFBC systems					◆														
Design and test at bench-scale an advanced, low-cost filter concept						◆													
Test at pilot-scale filter system to further investigate the bridging phenomenon						◆													
Test at pilot-scale advanced filter designs for bridging tolerance							◆												
Test at pilot-scale metal filters under high-temperature gasification conditions							◆												
2. Develop contaminant removal technology			■	■	■	■	■	■	■										
Develop and test at bench-scale multi-contaminant control filter elements							◆												
Develop and test injectable sorbents for use in hybrid, multi-contaminant control systems							◆												
Integrate gas-phase and particle cleanup systems								◆											
Conduct pilot-scale test of barrier filter systems									◆										
e. Advanced Combustion Systems																			
1. Investigate "sequestration-ready" combustion systems					■	■	■	■	■										
Complete construction of pilot-scale system						◆													
Measure effects on combustion properties and emissions of natural gas, coal and other fuels									◆										
2. Test integrated components					■	■	■	■	■	■	■								
Complete integration designs								◆											
Complete integrated PC and PFB tests											◆								
3. Develop sulfur sorbents									■	■	■								
Test sorbents at pilot-scale											◆								

Appendix
"Vision 21 - Clean Energy Plants for the 21st Century" - Preliminary Roadmap

Activity Description	FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16
f. Fuel-flexible Turbines																			
1. Develop advanced combustion turbine technology			■	■	■	■	■	■	■	■	■								
Assess and define the concepts for Vision 21 turbine/engine modules						◆													
Complete technology development for advanced turbine designs											◆								
2. Integrate improvements into existing designs											■	■	■	■	■				
Select engines/turbines platforms from ATS and FGTS programs for integration into Vision 21 systems											◆								
Design turbine/engines modules for Vision 21														◆					
Test selected platforms/products modules with advanced technologies developed under activity 1															◆				
3. Test/integrate full-scale systems																■	■	■	
Test advanced Vision 21 components under system operating conditions																◆			
Integrate the advanced components into host Vision 21 plants with Virtual Demonstration and limited host site turbine/engine test sites																		◆	
g. Fuel Cells																			
1. Develop fuel cell/turbine hybrids			■	■	■	■	■	■	■	■	■	■	■						
Issue fuel cell / turbine technology development solicitation for identification, design, and testing of systems of at least 70 percent efficiency			◆																
Demonstrate FC/T systems of at least 60 percent efficiency under existing fuel cell development projects						◆													
Demonstrate FC/T systems of at least 70 percent efficiency													◆						
2. Develop 21st century fuel cell			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Initiate virtual design activities and material and manufacturing / fabrication research			◆																
Initiate industry participation in manufacturing / fabrication research and begin component fabrication				◆				◆											
Initiate small scale testing, and proof of concept testing					◆			◆											
Demonstrate solid state fuel cell system with 70% efficiency													◆						
Demonstrate solid state system with at least 80% efficiency																		◆	
h. Advanced Fuels and Chemicals Development																			
1. Develop technology base for early entry co-production plant			■	■	■	■	■	■	■										
Procurement/award			◆																
Complete government funded portion of project							◆												
Complete design									◆										
2. Design co-production fuel module										■	■	■	■	■	■	■			
Procurement												◆							
Award													◆						
Complete design																◆			
3. Develop fuels for internal combustion engines					■	■	■	■	■	■	■								
Develop iron-based Fischer-Tropsch catalysts that are resistant to attrition						◆													
Integrate catalyst-wax separator with reactor design								◆											
Demonstrate follow-on process and products for diesel fuels, jet fuels and additives											◆								
4. Develop and evaluate advanced fuels for fuel cell-powered vehicles								■	■	■	■	■	■	■	■	■			
Complete bench-scale development													◆						
Complete proof of concept development															◆				
Test fuels in fuel cell powered vehicle																◆			
5 Design reactor systems for clean fuels			■	■	■	■	■	■	■	■	■	■	■	■	■				
Complete preliminary reactor designs							◆												
Complete detailed reactor designs													◆						
Integrate with Vision 21 systems															◆				
III. SUPPORTING TECHNOLOGIES																			
a. Materials																			
1. Select high-temperature heat exchanger materials					■	■	■	■	■										
Evaluate and select alloys suitable for heat exchangers					◆														
Evaluate and select ceramic composite tube materials									◆										
2. Develop advanced refractories			■	■	■	■	■	■	■	■	■	■	■	■	■				
Complete initial studies and short-term testing of advanced corrosion/erosion resistant refractories					◆														
Initiate long-term testing					◆														
Complete long-term testing of coupons											◆								
Complete long-term test in a gasifier or pyrolyzer															◆				
3. Develop hydrogen membrane materials			■	■	■	■													
Begin large scale testing of improved membrane material				◆															
Complete development and testing of a first generation membrane material						◆													
b. Advanced Computational Modeling and Development of Virtual Demonstration Capability																			
1. Develop scientific and engineering simulation capability			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
Complete advanced fuel cell simulations				◆															
Complete natural gas-fired internal combustion engine simulations				◆															
Complete turbomachinery design simulation (clocking, etc.)					◆														
Complete gasifier simulation						◆													
Complete natural gas fired turbine combustor simulation								◆											
Complete integrated turbine simulation (turbine and combustor)									◆										
Complete heavy fuel fired IC engine and turbines simulation											◆								
Complete integrated gasifier, clean-up, combustion simulation												◆							
Complete membrane separation simulation													◆						
Complete integrated Vision 21 plant simulation																	◆		
2. Develop Virtual Demonstration capability			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Develop 3-D solid modeling capability			◆																
Develop visualization capabilities				◆															
Develop computer aided design capability				◆															
Implement computational / communication resources					◆														
Develop structural analysis capability					◆														
Introduce concurrent engineering					◆														
Complete initial information management system						◆													
Complete process analysis models						◆													
Complete control analysis models								◆											
Integrate virtual demonstration capability with scientific and engineering simulations								◆											
Integrate with design and construction management												◆							
Develop advanced informational management system													◆						
Introduce advanced concurrent engineering															◆				
Demonstrate virtual operations																	◆		
c. Advanced Controls and Sensors																			
1. Advanced instrumentation and controls			■	■	■	■	■	■	■	■	■	■	■						
Develop advanced instrumentation & control			◆																
Complete designs and fabrication of prototypes					◆														
Complete first generation beta testing								◆											
Complete development of sensor and control systems													◆						

Appendix
"Vision 21 - Clean Energy Plants for the 21st Century" - Preliminary Roadmap

Activity Description	FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16
d. Environmental Control Technologies																			
1. Develop advanced low-Nox combustion technologies			■	■	■	■	■	■	■	■									
Identify low NOx combustion concepts					◆														
Complete pilot-scale tests								◆											
Complete designs for commercial systems										◆									
2. Develop advanced PM2.5 control technology			■	■	■	■	■	■	■	■									
Initiate PM2.5 control technology development R&D		◆																	
Complete studies on primary PM2.5 formation				◆															
Complete R&D on control of NOx precursors						◆													
Complete PM2.5 control technology development										◆									
3. Develop coal combustion by-products (CCB) management technology							■	■	■	■	■								
Complete survey of technologies for existing plants							◆												
Identify technologies for managing CCBs from advanced plants									◆										
Integrate CCB technology into Vision 21 plant design											◆								
4. Devise revolutionary approaches to CO2 capture and separation			■	■	■	■	■	■	■	■	■	■	■						
Initiate revolutionary CO2 capture and separations R&D program			◆																
Complete small-scale testing of advanced concepts							◆												
Complete integrated testing									◆										
Develop Vision 21 design for commercial application													◆						
5. Integrate energy systems with terrestrial sinks			■	■	■	■	■	■											
Establish partnerships between energy suppliers and biomass producers				◆															
Complete assessment of viability of carbon offsets								◆											
e. Advanced Manufacturing and Modularization																			
1. Develop improved manufacturing techniques			■	■	■	■	■	■	■	■	■	■	■						
Establish a consortium for identifying improved manufacturing techniques			◆																
Identify primary components and areas for improvement					◆														
Develop improved manufacturing techniques											◆								
Complete testing of selected manufacturing techniques													◆						
IV. SYSTEMS INTEGRATION																			
a. Systems Engineering																			
1. Develop preliminary definition of systems engineering issues			■	■	■														
Develop system configuations for systems engineering analysis			◆																
Complete definition of issues					◆														
2. Develop preliminary subsystem design modifications and subsystem linkages and interconnects						■	■	■	■										
Complete preliminary design modifications for major components and subsystems							◆												
Complete preliminary designs for linkages and interconnects									◆										
3. Define systems engineering issues											■	■							
Complete update of systems engineering issues												◆							
4. Develop subsystem design modifications and subsystem linkages and interconnects													■	■	■				
Complete design modifications for major components, subsystems, and linkages and interconnects															◆				
5. Apply virtual demonstration techniques															■	■	■		
Complete virtual demonstrations of key components and subsystems																◆			
Complete virtual demonstrations of Vision 21 systems																	◆		
b. Dynamic Response and Control																			
1. Model dynamic response of Vision 21 subsystems					■	■	■	■	■										
Develop dynamic response models for Vision 21 subsystems							◆												
Validate subsystem models									◆										
2. Model dynamic response of Vision 21 systems									■	■	■	■	■						
Develop dynamic response models for Vision 21 system configurations											◆								
Validate system models													◆						
3. Develop control strategy for Vision 21 plants											■	■	■	■	■				
Develop Vision 21 process control software															◆				
4. Select and develop process control hardware for Vision 21 plants											■	■	■	■	■				
Identify existing process control hardware appropriate for Vision 21											◆								
Develop and test new sensors and control hardware															◆				
c. Industrial Ecology																			
1. Apply industrial ecology principals to Vision 21 system configurations									■	■	■								
Complete industrial ecology analysis											◆								
V. VISION 21 PLANT DESIGNS																			
a. Designs for Components and Subsystems																			
1. Select components and subsystems						■	■	■											
Select components and subsystems for design studies							◆												
Define performance requirements								◆											
2. Design modular components and subsystems								■	■	■	■	■	■	■	■				
Complete initial component and subsystem designs										◆									
Review and update designs													◆						
Complete component and sybsystem design and cost analysis															◆				
b. Designs for Prototype Plants																			
1. Select prototype plant configurations							■	■	■	■	■	■							
Select initial prototype plant configurations								◆											
Select final prototype plant configurations												◆							
2. Design prototype plants													■	■	■	■	■		
Complete prototype plant designs																	◆		
Complete cost analyses																	◆		
c. Designs for Commercial Plants																			
1. Select commercial plant configurations								■	■	■	■	■	■						
Select initial commercial plant configurations									◆										
Select final commercial plant configurations													◆						
2. Design commercial plants														■	■	■	■	■	
Complete commercial plant designs																		◆	
Complete cost analyses																		◆	
d. Virtual Demonstration Capability																			
1. Simulate component/subsystem performance											■	■	■						
Conduct virtual demonstrations of components and subsystems													◆						
2. Simulate commercial-scale plant performance															■	■	■	■	
Virtual demonstration of complete Vision 21 plant																		◆	

For more information, contact:

Dr. Lawrence A. Ruth
Senior Management and Technical Advisor
U.S. Department of Energy
Federal Energy Technology Center
P.O. Box 10940
Pittsburgh, PA 15236-0940
Phone: 412/892-4461
Fax: 412/892-4822
Email: ruth@fetc.doe.gov
Visit our web site at: **www.fetc.doe.gov**
Customer Service: **1-800-553-7681**

Dr. Victor K. Der
Director, Power Systems
U.S. Department of Energy
Office of Fossil Energy
19901 Germantown Road
Phone: 301/903-2700
Fax: 301/903-2713
Email: victor.der@hq.doe.gov
Visit our web site at: **www.fe.doe.gov**

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