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U.S. Climate Change Technology Program

TECHNOLOGY OPTIONS

For the Near and Long Term

A Compendium of Technology Profiles and Ongoing Research and Development at Participating Federal Agencies

November 2003

U.S. Climate Change Technology Program

U.S. Department of Energy (Lead Agency)
U.S. Department of Agriculture
U.S. Department of Commerce, including
National Institute of Standards and Technology
U.S. Department of Defense
U.S. Department of Health and Human Services, including
National Institutes of Health
U.S. Department of Interior
U.S. Department of State, including
U.S. Agency for International Development
U.S. Department of Transportation
U.S. Environmental Protection Agency
National Aeronautics and Space Administration
National Science Foundation
Other Participating Research and Development Agencies

Executive Office of the President, including
Council on Environmental Quality
Office of Science and Technology Policy
Office of Management and Budget

November 2003

To the Reader:

We are pleased to present this report titled *U.S. Climate Change Technology Program – Technology Options for the Near and Long Term*. The activities described in this report present a portfolio of Federal R&D investments in climate change technology development and deployment that are believed to offer significant potential for contributing to the President's near and long term climate change goals. A companion report titled *U.S. Climate Change Technology Program – Research and Current Activities* highlights Presidential initiatives and other important research, development, and deployment activities in this area.

Collectively, these technology-related activities form an integral part of a comprehensive U.S. strategy on climate change that rests on three pillars — science, technology, and international cooperation. They also complement the recent Climate Change Science Program (CCSP) strategic plan, which represents an unprecedented effort to advance our knowledge of climate variability, the potential response of the climate system to growing greenhouse gas concentrations and their implications, and management options for natural environments. The scientific information developed under the CCSP will help us better define our technology challenges.

Early in his term, President Bush charged his Administration with identifying a new approach to climate change that is science-based, encourages scientific and technological breakthroughs, harnesses the power of markets, does not hamper economic growth, encourages global participation, and helps achieve the goal of stabilizing atmospheric concentrations of greenhouse gases. As research continues, there is a growing realization that existing technologies, even with substantial refinements, cannot meet the world's increasing demand for energy and achieve the eventual goal of stabilizing greenhouse gas concentrations in the atmosphere. Doing so will require developing low or zero-emission technologies that will fundamentally transform current energy systems.

To achieve this vision, the participating agencies of the U.S. Climate Change Technology Program are pursuing research in carbon sequestration, hydrogen, bio-energy, nuclear fission and fusion, and many other revolutionary technologies. These transformational technologies will put us on a path to stabilizing atmospheric greenhouse gas concentrations and also ensure secure, affordable, and clean energy to power economic growth worldwide.

Through scientific research, technological innovation, and international collaboration, we are working to ensure a bright energy and economic future for our Nation and a healthy planet for future generations. For more information on the U.S. Climate Change Technology Program, please visit our website at http://www.climatetechnology.gov/.

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U.S. Climate Change Technology Program –
Technology Options for the Near and Long Term

Under the leadership of President Bush, the United States is now embarked on a long-term technical challenge – guided and paced by science, and undertaken in partnership with others – to explore, develop, and deploy innovative and advanced technologies that could make a significant contribution to meeting climate change goals. The President directed relevant agencies of the Federal government to apply their resources to this challenge and established a new Cabinet-level management structure to guide and oversee the effort. Under the auspices of this Cabinet-level management structure, the U.S. Climate Change Technology Program (CCTP) is charged with coordinating and focusing these research, development, and deployment activities among the participating agencies.

This report, titled *U.S. Climate Change Technology Program – Technology Options for the Near and Long Term,* presents summary descriptions, or profiles, of technologies or technology areas believed to offer significant potential for contributing to the president's near- and long-term climate change goals. This collection is fairly complete and roughly represents the breadth of Federal R&D in climate change technology development and deployment. Federal investments are further augmented by those of states, local governments, the private sector, and governments abroad. To the extent possible, the CCTP seeks to leverage and coordinate the Federal investments with those of others.

In total, there is a robust portfolio of R&D now underway in the United States and worldwide. From these R&D investments, undertaken together, pragmatic technological opportunities will arise to fundamentally transform and dramatically improve our 21st century energy system, with significantly reduced greenhouse gases emissions as a result.

In this report, more than 80 technology options are identified. They are organized within a series of goals aimed at developing advanced technologies that, if successful, could enable: (i) reduced emissions from energy end use and infrastructure; (ii) reduced emissions from energy supply; (iii) the capture and sequestering of carbon dioxide (CO_2); (iv) reduced emissions of other greenhouse gases; and (v) enhanced capabilities to measure and monitor greenhouse gases emissions. To ease reading and cross-referencing, a standard format for the profiles was adopted (see inset).

Standard Technology Profile Outline

- Technology Description
  - System Concepts
  - Representative Technologies
  - Technology Status/Applications
- Current Research, Development, and Demonstration
  - RD&D Goals
  - RD&D Challenges
  - RD&D Activities
- Recent Progress
- Commercialization and Deployment Activities

Each technology represented here, if successful, could contribute significantly to one or more of the goals outlined above, resulting in climate change-related benefits as compared to a baseline without the technology. Specific estimates of these benefits, however, are uncertain and depend on a number of variables, including marketplace forces, advances in competing technologies, and other factors prevailing at the time. Most of the technologies described require additional R&D investments to improve performance and reduce costs, followed by significant private-sector investment to commercialize and widely diffuse the technologies into the marketplace. Accordingly, such benefits are acknowledged generally by inclusion in this report, but specific estimates are not presented in each profile.

Additional information about the technologies may be obtained by contacting the Federal agency and program office identified as responsible for the R&D or deployment activity. All profiles may be found electronically, in formats suitable for electronic transfer, at the Web site http://www.climatetechnology.gov/.

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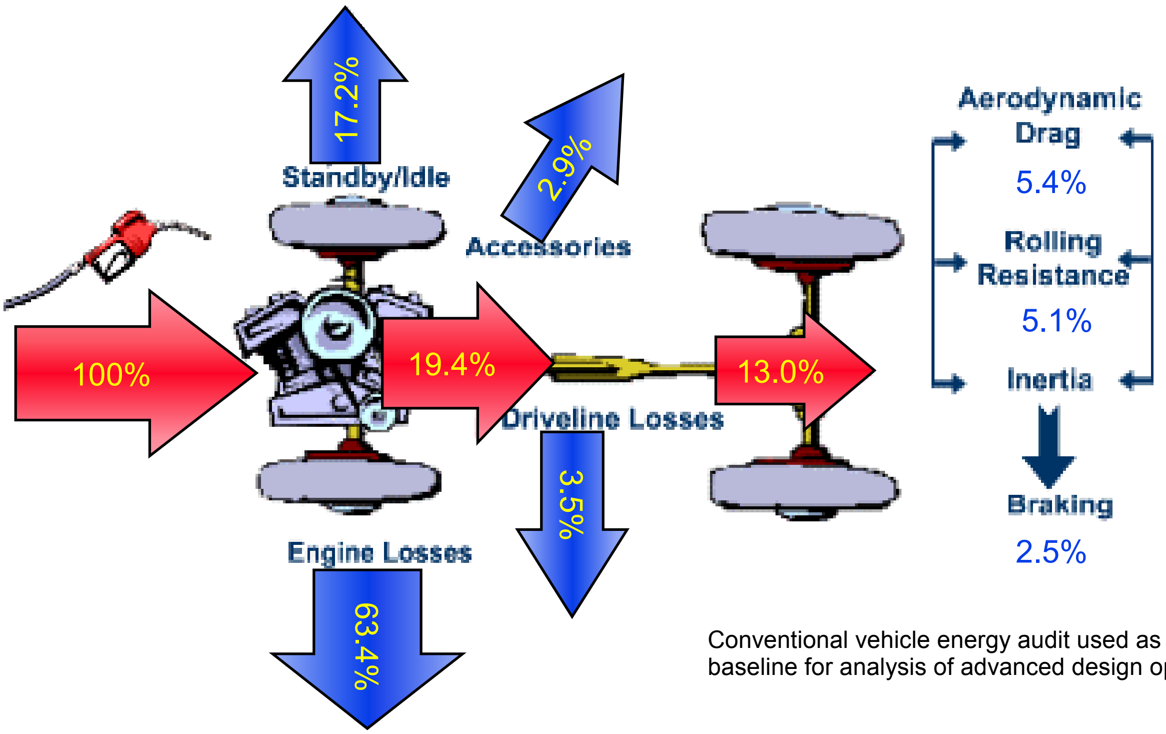
1.0 REDUCING EMISSIONS FROM ENERGY END USE AND INFRASTRUCTURE
1.1 TRANSPORTATION
1.1.1 LIGHT VEHICLES – HYBRIDS, ELECTRIC, AND FUEL CELL VEHICLES

Technology Description



Conventional vehicle energy audit used as baseline for analysis of advanced design options.

Hybrid electric vehicles (HEVs) use a combination of electric and mechanical power. An HEV with a compression ignition, direct-injection (CIDI) engine could offer low carbon emissions and peak energy efficiency more than 70% greater than available from present-day gasoline engines. Advanced combustion engines could reduce fuel consumption by 50%. Fuel cell vehicles (FCVs) directly convert fuels to electricity. Although FCVs may initially run on gasoline or other fuels reformed to produce hydrogen, in the long term they will be powered by hydrogen stored onboard. FCVs using onboard hydrogen produce only water as a tailpipe emission. The fuels used and how they are produced will determine the degree of carbon-emissions reduction compared to conventional vehicles.

System Concepts

- HEVs that provide limited power-assist during acceleration can dramatically reduce peak engine size, resulting in substantial fuel economy benefits.
- HEVs have led to the introduction of "idle-off" strategies using a combined alternator/starter. The engine automatically turns off when the engine is idling or under low-load – such as decelerating or coasting. In such cases, stored energy is required to operate the ancillary loads, such as cabin climate control.
- FCVs can either store a liquid fuel onboard that uses a reformer or other chemical reaction to produce hydrogen, or it can directly store hydrogen in gaseous or liquefied (cryogenic) form.

Representative Technologies

- HEVs and FCVs will require energy storage systems, including some high-power storage that may include electrochemical batteries, ultracapacitors, or other forms of energy storage.
- HEVs also use an internal combustion engine such as CIDI, gasoline direct-injection, as well as efficient electric motors.

Technology Status/Applications

- GM, Ford, and DaimlerChrysler are developing HEVs. Toyota and Honda have sold more than 140,000

HEVs in Japan and the United States since 1997. Some automakers have announced target sales of HEVs of 500,000 in less than 10 years.

- Although several versions of EVs were available, the cost of manufacturer support coupled with limited demand and high battery pack cost has nearly eliminated EVs as an option for consumers.
- Polymer electrolyte membrane fuel cells are being demonstrated on developmental vehicles and buses.
- Sales of vehicles with CIDI engines have exceeded 35% of the new light-duty vehicle sales in Europe and sales are more than 50% in some countries. U.S. sales may be limited due to impending Tier 2 emissions regulations. J.D. Power believes that diesel sales could be 12% of the U.S. market by 2010.

Current Research, Development, and Demonstration

RD&D Goals (by 2010)

- To ensure reliable systems for future fuel cell powertrains, with costs comparable with conventional internal-combustion engine/automatic transmission systems, the goals are:
  - Electric-propulsion system with a 15-year life capable of delivering at least 55 kW for 18 seconds and 30 kW continuous at a system cost of $12/kW peak.
  - 60% peak energy-efficient, durable fuel cell power system (including hydrogen storage) that achieves a 325 W/kg power density and 220 W/L operating on hydrogen. Cost targets are $45/kW by 2010, $30/kW by 2015.
- To enable clean, energy-efficient vehicles operating on clean, hydrocarbon-based fuels – powered by either internal combustion powertrains or fuel cells – the goals are:
  - Internal combustion systems that cost $30/kW, have a peak brake engine efficiency of 45%, and meet or exceed emissions standards.
  - Fuel cell systems, including a fuel reformer, that have a peak brake engine efficiency of 45% and meet or exceed emissions standards with a cost target of $45/kW by 2010 and $30/kW in 2015.[2 3]
- To enable reliable HEVs that are durable and affordable, the goal is:
  - Electric drivetrain energy storage with 15-year life at 300 Wh with discharge power of 25 kW for 18 seconds at a cost of $20/kW.
- To enable the transition to a hydrogen economy, ensure widespread availability of hydrogen fuels, and retain the functional characteristics of current vehicles, the goals are:
  - Demonstrated hydrogen refueling with developed commercial codes and standards and diverse renewable and non-renewable energy sources. Targets: 70% energy efficiency well-to-pump; cost of energy from hydrogen equivalent to gasoline at market price, assumed to be $1.50 per gallon (2001 dollars).[4]
  - Hydrogen storage systems demonstrating an available capacity of 6 wt% hydrogen, specific energy of 2000 Wh/kg, and energy density of 1100 Wh/L at a cost of $5/kWh.[5]
- Internal combustion systems operating on hydrogen that meet cost targets of $45/kW by 2010 and $30/kW in 2015, have a peak brake engine efficiency of 45%, and meet or exceed emissions standards.
- To improve the manufacturing base, the goal is:
  - Material and manufacturing technologies for high-volume production vehicles that enable and support the simultaneous attainment of:
    - 50% reduction in the weight of vehicle structure and subsystems,
    - affordability, and
    - increased use of recyclable/renewable materials.

Notes:

1. Cost references are based on CY 2001 dollar values. Where power (kW) targets are specified, those targets are to ensure that technology challenges that would occur in a range of light-duty vehicle types would have to be addressed.
2. Does not include vehicle traction electronics.
3. Includes fuel cell stack subsystem, fuel-processor subsystem, and auxiliaries; does not include fuel tank.
4. Targets are for hydrogen dispensed to a vehicle assuming a reforming, compressing, and dispensing system capable of dispensing 150 kg/day (assuming 60,000 SCF/day of natural gas is fed for reforming at the retail dispensing station) and servicing a fleet of 300 vehicles per day (assuming 0.5 kg used in each vehicle per day). Targets also are based on several thousand stations, and possibly demonstrated on several hundred stations. Technologies may also include chemical hydrides such as sodium borohydride.
5. Based on lower heating value of hydrogen; allows over a 300-mile range.

RD&D Challenges

- All advanced vehicles face the challenge of achieving competitive cost, reliability, and consumer acceptance.
- HEVs and FCVs need affordable, durable, lighter, and more compact energy storage.
- Power electronics, required by all high-voltage systems, are expensive, need active cooling, and require significant space.
- All energy-efficient vehicles face a severe fuel economy penalty when ancillary loads are applied. Nonpropulsion related loads must be reduced.
- FCVs have no existing infrastructure for refueling or repair.
- Onboard storage of hydrogen in quantities sufficient to meet range requirements is a challenge.
- Significant reductions in catalyst materials or inexpensive substitutes are needed for fuel cells.

RD&D Activities

- DOE, through the FreedomCAR Partnership, is working with industry and other local, state, and Federal government agencies on vehicle-systems analysis, combustion technologies, materials R&D, fuels R&D, and technology introduction through fleet testing and evaluation.
- DOE is working on light vehicles through FreedomCAR that includes component and vehicle simulation, ancillary load reduction, component testing, energy storage, advanced engines, and lightweight materials.

Recent Progress

- GM, Ford, and DaimlerChrysler have developed a variety of hybrid-electric vehicles. The technical feasibility of these concepts has matured, although cost remains an issue.
- Advances in energy storage systems – including hybrid storage consisting of batteries and ultracapacitors – show promise.
- Prototype FCVs are being tested.

Commercialization and Deployment Activities

- HEVs: The biggest competition for gasoline HEVs are advanced combustion conventional vehicles. In Europe, high-efficiency diesel vehicles have demonstrated fuel economies similar to that of gasoline HEVs. Consumer acceptance and willingness to pay a little more for a more fuel-efficient, high-technology vehicle is key. HEVs use conventional fuels, with no refueling infrastructure challenges. Some HEVs have long ranges, appealing to consumers who dislike frequent refueling stops.
- FCVs: FCVs have the zero emissions of an EV but not yet the range of conventional vehicles. Fuel cell vehicles have the potential to require less maintenance due to fewer moving parts and lower operating temperatures. However, cost, hydrogen storage, and infrastructure requirements are substantial barriers.

Market Context

- The market for these technologies is all light vehicles (cars and light trucks). To be successful in the marketplace, these technologies need to be made less expensive and more attractive to new vehicle buyers.

1.1.2 HEAVY VEHICLES

Technology Description

Freight vehicles (Class 7 and 8 trucks and rail) and commercial delivery vehicles (Class 2b through Class 6) are essential to the economic vitality of the nation. Diesel engines are the dominant motive source for these vehicles. Vehicle efficiency could be increased by as much as 100% if all current research such as new generation of ultra-high-efficiency diesel engines (using advanced emissions-control technology), reduced aerodynamic drag, rolling resistance, and parasitic power losses is successful. Development and commercialization of engines with higher efficiency will significantly reduce transportation oil use, emissions (including CO_2), and related costs to the economy. Increased use of lightweight materials will contribute to these goals.

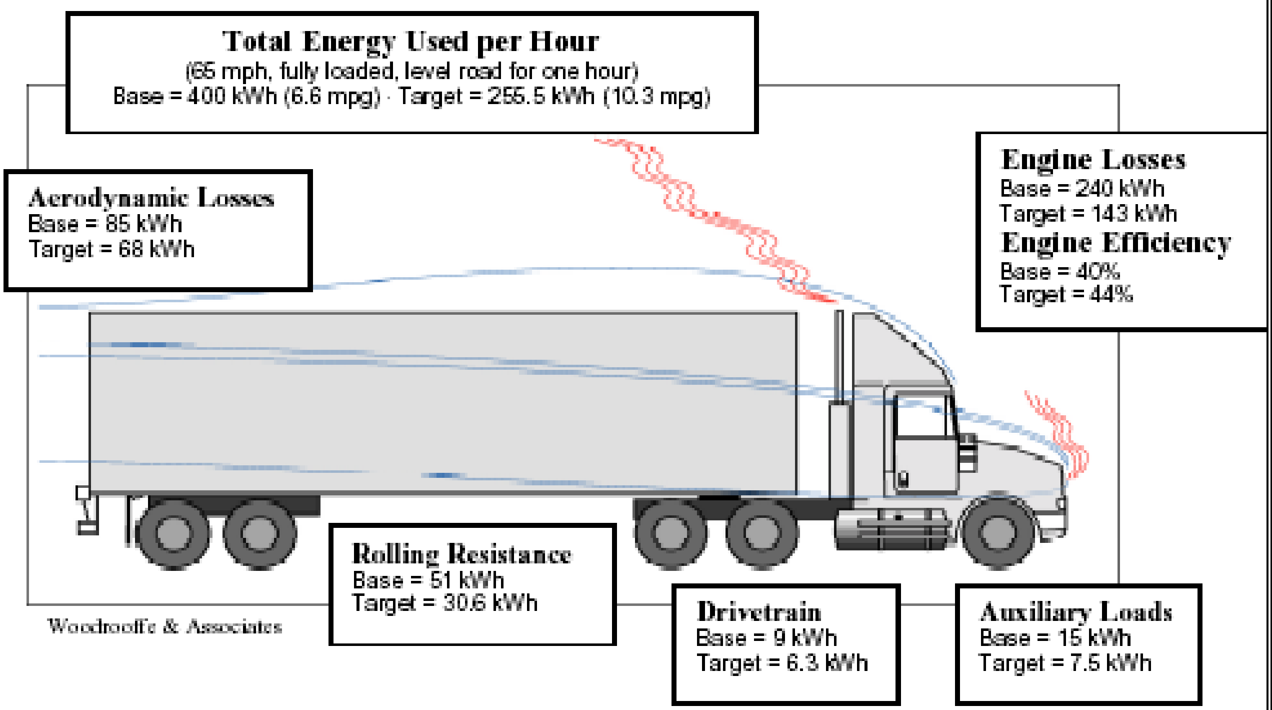


Fig. 4.1. Class 8 truck energy audit.

System Concepts

- Four-stroke, direct-injection diesel engines (with high peak-cylinder pressures, thermal barrier coatings, high-pressure fuel injection systems, and turbocharging) are being developed.
- Lightweight materials, truck aerodynamics, and advanced tires are being developed to improve overall fuel economy.
- Hybrid vehicles with regenerative braking may have application in local delivery vehicles.
- Vehicle electrification can reduce parasitic losses from auxiliary loads and help reduce idling losses.

Representative Technologies

- High-pressure, common-rail fuel injection, bottoming cycles, and friction and wear reduction.
- Software technology to improve vehicle aerodynamics.

Technology Status/Applications

- Virtually all heavy-duty trucks and the entire fleet of locomotives are diesel powered, and there is an increasing trend to convert medium-duty trucks to diesel fuel as well. Advanced combustion concepts – resulting in higher efficiency and lower emissions while maintaining power density – are needed. New advanced technologies for emission controls are required.

- Fuel cells are considered a long-term option. A locomotive fuel cells program is being pursued by industry.
- Software tools are being developed to provide design guidance to reduce aerodynamic drag.

Current Research, Development, and Demonstration

RD&D Goals

- Engine systems including the integration of fuel, engine, and aftertreatment. Specific technology goals are:
  - Development and demonstration of a commercially viable, emissions-compliant engine system for Class 7-8 highway trucks that improves the system efficiency by 20% (from current 42% to 50%) by 2010 and demonstrate 55% efficiency in the laboratory by 2012.
  - Identification of a commercially viable, domestically produced non-petroleum diesel-blending agent that would enable a 5% displacement of diesel fuel by 2012.
- Parasitic losses account for 40% of the total fuel energy used to move a heavy vehicle down the road. These losses arise from aerodynamic resistance, rolling resistances, drivetrain, and auxiliary load losses. Specific 2012 technology goals are:
  - Develop and demonstrate advanced technology concepts that reduce the aerodynamic drag of a Class 8 tractor-trailer combination by 20% (from current 85 kWh to 68 kWh) in a practical, efficient, and commercially viable manner.
  - Develop and demonstrate commercially viable technologies that reduce auxiliary loads by 50% (from current 15 kWh to 7.5 kWh) for Class 8 tractor-trailers.
  - Develop and demonstrate a 10% reduction (from current 51 kWh to 46 kWh) in tire-rolling resistance values vs. existing best-in-class standards without compromising cost or performance.
  - Develop and demonstrate commercially viable lightweight material and manufacturing processes that lead to a 5,000-pound reduction in Class 8 tractor-trailer combinations (a 15-20% weight reduction)
  - Develop and demonstrate commercially viable technologies that increase heat-load rejected by thermal management systems by 20% without increasing radiator size.
- Class 7 and 8 trucks, alone, consume more than 825 million gallons of diesel fuel per year when idling. Technology goals are to reduce fuel use and emissions from idling heavy vehicles by greater than 65%. Specific technology goals are:
  - Development and demonstration of a commercially viable 5 kW, $200/kW, diesel-fueled, internal-combustion engine auxiliary power units by 2007 (0.2 gallons of diesel fuel per hour; 200 lbs. weight; maximum 0.5 cubic-meter size; meeting prevailing emission standards; cooling and fuel systems integrated into vehicle platform, less than 65 dB noise inside cab; noise, vibration, and harshness as good or better than the prime mover engine).
  - Develop and demonstrate a commercially viable fuel cell auxiliary power unit system in the 5-30kW range, capable of operating on diesel fuel at a delivered cost of $400/kW by 2012.

RD&D Challenges

- Technical challenges exist to improving engine efficiency, thus reducing CO_2 emissions, while meeting emission regulations.
- Advanced technology often involves more durable materials, additional components, or additional manufacturing processes, all of which can add cost and weight.
- Meeting tighter emissions regulations can result in an additional load on the engine – such as additional backpressure – which can increase fuel consumption.

RD&D Activities

- DOE is working closely with industry in the 21st Century Truck Partnership.
- The Environmental Protection Agency's National Vehicle Fuel Emissions Laboratory plans to add advanced heavy diesel cycle engines and innovative hybrid drive-train systems for urban delivery trucks to its Advanced Automotive Technology Program.
- Department of Defense Advanced Research Projects Agency, California Energy Commission, and the California Air Resources Board cosponsor R&D projects with DOE.
- DOE sponsors analytical and modeling work.

Recent Progress
• New conceptual model of in-cylinder soot formation has been developed. • Advanced multicylinder engine demonstrated more than 90% reduction in NO_x and particulate matter. • Demonstrated 51% reduction in aerodynamic drag for Class 8 trucks in wind tunnel tests. • Electrification of underhood components – such as air compressors, water pumps, and oil pumps – was shown to reduce fuel consumption by up to 18%.
Commercialization and Deployment Activities
• The diesel engine is the workhorse of all the heavy-duty transport modes that are responsible for most of the nation's intercity freight movement, the lifeblood of the economy. Because of low fuel consumption, high reliability, and long service life, it is widely acknowledged that the diesel engine will continue to dominate heavy-duty transport propulsion for many years. • The strong coupling between efficiency and emissions controls is a significant barrier. Many of the engine design options currently available to manufacturers for emissions reductions involve a fuel economy penalty of 10%-20%. In the absence of significant technology advancements, future emission regulations could detrimentally affect the historical trend toward higher diesel-engine efficiency. • All new technologies must meet high durability requirements. **Market Context** • Stiff domestic and international competition from European and Japanese diesel-engine manufacturers has reduced domestic market share. U.S. manufacturers have limited resources to identify, research, develop, and commercialize many of the promising advanced emission technologies. Effective partnership with national labs is essential for successful completion of advanced automotive research activities.

1.1.3 ALTERNATIVE-FUELED VEHICLES

Technology Description

A school bus in New Jersey runs on biodiesel (right). United Parcel Service maintains a natural gas compressor station and CNG fueling island at several facilities in Connecticut (left).

Alternative fuels that will be important during the transition to hydrogen include electricity, ethanol, biodiesel, liquefied petroleum gas, and compressed natural gas. These fuels offer near-term carbon reductions of 19%-44% for a variety of vehicles.

System Concepts

- Alternative fuel vehicles (AFVs) are similar to today's vehicles, except for certain fuel- and emission-related systems.
- Vehicles operating on gaseous fuels like natural gas or liquefied petroleum gas require specific fuel system components including fuel regulators, an air and fuel-mixing apparatus, and modified fuel injectors. Modifications to the fuel tank and fuel supply and infrastructure are also required.

Representative Technologies

- Compressed natural gas buses are widely used by transit fleets nationwide.
- Automakers offer several models of compressed natural gas, and liquefied petroleum gas, and ethanol flexible-fuel vehicles.
- Heavy-duty alternative fuel engines are offered as options to the commercial market for trucks and buses.

Technology Status/Applications

- Light-duty AFVs have shown good in-service emissions performance and similar levels of fuel economy in Federal fleet demonstrations. AFV purchase costs vary; natural gas vehicles have significant incremental costs over conventional vehicles.
- Heavy-duty AFVs have shown reductions in particulate emissions. Maintenance costs are higher but are likely to decrease with experience. Natural gas is the alternative fuel of choice in these classes of vehicles when considering 100% replacement of fuel.

Current Research, Development, and Demonstration

RD&D Goals
- Develop light- and heavy-duty engine and fuel technologies that utilize transitional alternative fuels and have as good or better performance than conventional engine technologies to meet future emissions standards.
- By 2004, develop two heavy-vehicle engines that use natural gas and achieve emission compliances while being fully competitive with their diesel counterparts.

RD&D Challenges
- AFVs must be developed to meet cost, performance, and future environmental and energy efficiency goals over the lifetimes of the vehicles. Specific areas of concern include cost, range, refueling convenience, cold-start performance, and engine efficiency.
- Some alternative fuels have lower energy content, which can reduce the range of the vehicle – particularly if a gaseous fuel is used.
- Challenges to accelerating the integration of AFV technologies into the marketplace must be addressed by working with industry to eliminate near-term technical barriers and to increase availability, acceptance, and awareness of AFV technology and equipment:
  - Assist with the development of additional vehicle platforms that utilize AFV technologies previously developed in partnership with DOE in order to ensure ongoing viable product availability.
  - Maintain efforts to increase efficiency, reduce costs, and improve emissions performance of AFV engines, technologies, and equipment.
  - Enhance AFV infrastructure and vehicle development by addressing near-term technical problems as they are identified and ensure that appropriate solutions are rapidly communicated and adopted in the marketplace.

RD&D Activities
- DOE, in collaboration with engine and truck manufacturers and fuel suppliers, is conducting the Next-Generation Natural Gas Vehicle project to develop advanced medium- and heavy-duty natural gas vehicles.
- With DOE cofunding, heavy-duty engine manufacturers have major alternative-fuel engine R&D efforts.
- The Environmental Protection Agency is developing unique engine designs utilizing renewable fuels and achieving diesel-cycle efficiency levels while meeting Tier 2 emission standards for light vehicles.
- Component manufacturers, national laboratories and research institutions, universities, and state and local governments have sizable alternative-fuel R&D activities.
- Biomass and hydrogen fuels are discussed in other Technology Profiles; see the Table of Contents.

Recent Progress

- Work on the first-generation, ultra-safe, and ultra-low-emission school bus powered by compressed natural gas has been completed, and the bus is now commercially available. More than 100 have been sold in California, and work on the second generation is underway to improve engine efficiency that reduces carbon emissions. Natural gas transit buses comprise 25% of new bus orders.
- Honda has obtained ultra-low-emission vehicle certification for a dedicated compressed natural gas automobile.
- With DOE assistance, Cummins Engine, John Deere Company, and Mack Trucks have introduced heavy-duty natural gas engines with high efficiency, power ratings, and torque that maintain very low emissions.
- Light-duty alternative-fuel vehicles are currently available from all major automotive manufacturers.

Commercialization and Deployment Activities

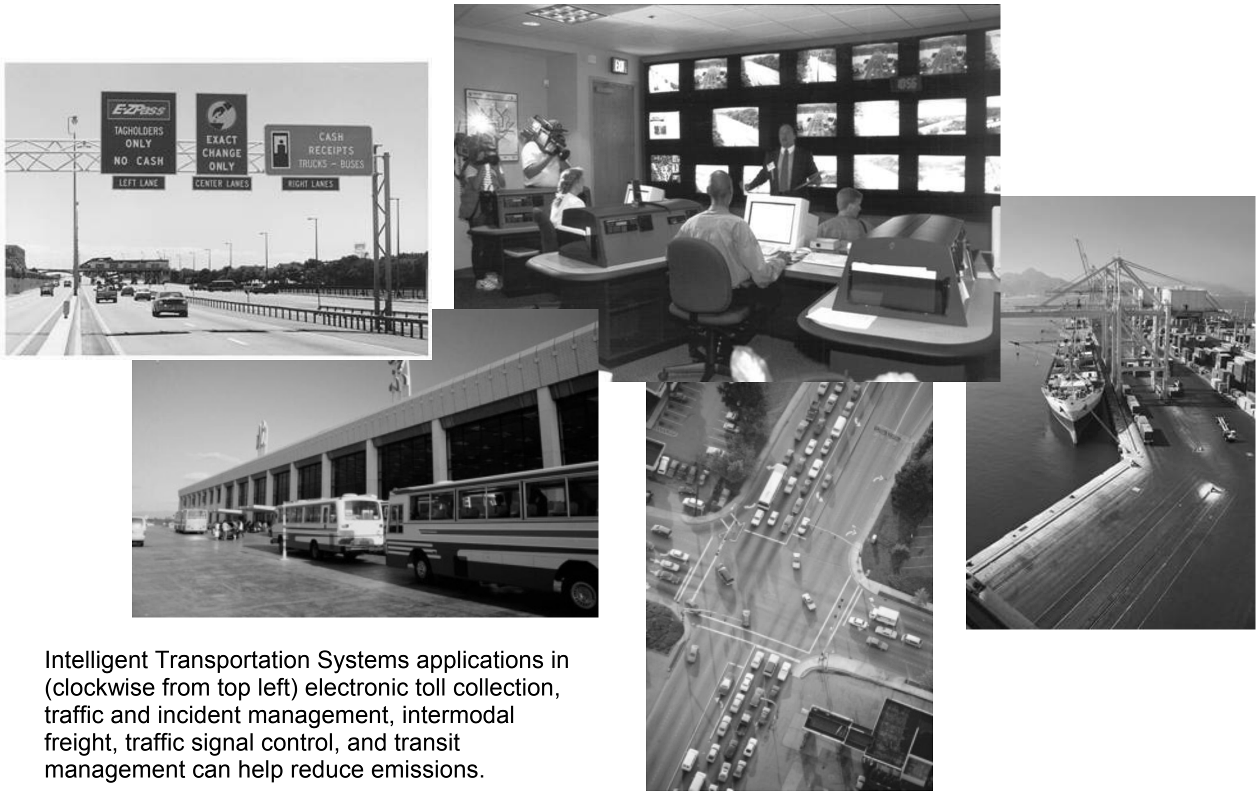
- Domestic automobile manufacturers have been producing AFVs since 1991. Currently, 29 light-duty and 20 medium- and heavy-duty vehicle models are available, powered by a number of alternative fuels. The configurations used include flexible-fuel, dual-fuel, and dedicated fuel. Prices for gasoline-ethanol, flexible-fuel vehicles have decreased to those of their conventional counterparts.
- The Federal government has more than 50,000 AFVs on the road and is expected to lead the deployment of new alternative-fuel vehicles under the direction of DOE, the General Services Administration, and interagency coordinating committees.
- Since its inception in 1991, the DOE-sponsored alternative-fuel, heavy-duty truck demonstration program has assisted in placing more than 600 heavy-duty data collection AFVs. Data collection continues to provide valuable feedback to manufacturers and fleets.
- The DOE Clean Cities Program actively enables deployment of AFVs through its locally based government/industry partnership, with a goal of 1 million light- and heavy-duty vehicles by the end of 2010 in the United States.

Market Context

- The prices of all these fuels need to be made more attractive to vehicle users.

1.1.4 INTELLIGENT TRANSPORTATION SYSTEMS INFRASTRUCTURE

Technology Description



Intelligent Transportation Systems applications in (clockwise from top left) electronic toll collection, traffic and incident management, intermodal freight, traffic signal control, and transit management can help reduce emissions.

Faced with annually increasing demand for travel and transport of goods, the transportation system is reaching the limits of its existing capacity. Intelligent Transportation Systems (ITS) can help ease this strain, and reduce the emissions created and fuel wasted in associated congestion and delays, through the application of modern information technology and communications. Several ITS applications and services offer the potential for reducing fuel use and related carbon emissions associated with travel and freight transportation.

System Concepts

- Intelligent transportation systems (ITS) apply well-established technologies in communications, control, electronics, and computer hardware and software to improve surface transportation system performance.
- ITS are intended to reduce congestion, enhance safety, mitigate the environmental impacts of transportation systems, enhance energy performance, and improve productivity.

Representative Technologies

- Adaptive traffic signal-control systems and freeway management systems smooth the flow of traffic, and reduce stops and delay, which lead to reductions in fuel use and emissions.
- By clearing incidents faster and more efficiently, incident management systems have demonstrated large reductions in energy use associated with the travel delays surrounding the incident.
- ITS applications for intermodal freight include freight and asset tracking, as well as enhancements to freight terminal and international border crossing processes. These enhancements can help create a seamless connection between modes of travel for goods shipments as well as reduce delays and associated emissions at terminals and inspection stations.
- Traveler information/navigation systems help travelers avoid major delays and avoid wasted fuel as a result of navigation errors.
- Electronic screening of commercial vehicles saves fuel and reduces emissions associated with stopping at inspection stations.

- Electronic toll collection – saves fuel consumption and emissions at tollbooths by minimizing delays, queuing, and idling time.

Technology Status/Applications

- Deployment of ITS is underway across the United States. A survey covering 78 of the largest U.S. cities finds that the most widespread deployments are electronic toll collection (ETC) (73% of toll lanes in surveyed cities are ETC capable), emergency management (75% of emergency vehicles are under computer-aided dispatch), and electronic fare payment (EFP) area (52% of fixed route buses accept EFP). Other areas of significant deployment include incident management and signal control systems.
- The Commercial Vehicle Information Systems and Networks (CVISN) is the collection of information systems and communications networks that support commercial vehicle operations in the United States. CVISN is expected to improve commercial vehicle safety, while enhancing productivity, reducing delays and associated emissions. Eight states have been fully funded to achieve Level 1 deployment (i.e., electronic credential administration, safety information exchange, and roadside electronic screening) by September 2003. Of these eight, four states have demonstrated Level 1 capabilities. Forty-nine states have completed a CVISN Business Plan, and 34 states have completed a CVISN Top-Level Design and CVISN Program Plan.

Current Research, Development, and Demonstration

RD&D Goals

- Develop improved analysis capabilities that properly assess the impact of ITS strategies.
- Develop strategies that will improve travel efficiency resulting in lower delays, thereby reducing emissions.

RD&D Challenges

- Develop the next-generation mobile emissions models that assess how reductions in stop-and-go traffic, resulting from effective ITS traffic management, reduce emissions – including those of greenhouse gases. Current models primarily consider vehicle miles traveled, whether that travel occurs at cruising speed (where current vehicles are extremely low-emitters) or under stop-and-go conditions (where vehicular emissions are significantly higher, except for hybrid electrics). Thus, they have the potential of incorrectly penalizing effective strategies.

RD&D Activities

- The Traffic Analysis and Tools Program is developing tools and models for evaluating various ITS strategies and courses of action.
- The Next Generation Simulation Model (NGSIM) program is developing a repository of improved and well-documented algorithms for use by traffic-simulation models.
- The Department of Transportation (DOT) is carrying out evaluations of Field Operational Tests of technologies to reduce commercial vehicle queues and wait times at weigh stations.
- The Electronic Toll Collection/Electronic Screening Interoperability Pilot deployment is being evaluated to determine the impact of using interoperable transponders for toll collection and electronic screening of heavy vehicles. The evaluation hypotheses being tested include the following: "With reduced delays and idle time, fuel consumption and emissions will be reduced."
- EPA is developing the Multiscale Motor Vehicle and Equipment Estimation System (MOVES) mobile source emissions model. This model will provide improved characterization of vehicle emissions from high-emitting and heavy-duty vehicles.
- The Signal Timing Program is being carried out by FHWA to encourage localities to time or retime their traffic signals and optimize their signal systems. This will result in reduced stops and delays, thereby decreasing vehicular emissions.
- The Incident Management Program is developing strategies and providing guidance on clearing traffic incidents sooner. The resulting decrease in vehicle queues and delays result in reduced emissions.

- The Freeway Management Program is developing operational strategies, technologies, and policies for improved efficiency of freeway facilities. Included in the program is research on strategies for sharing HOV lanes with low-emission, energy-efficient vehicles when extra capacity is available; detecting and verifying incidents; and providing en route information to travelers. Reduced delay and travel time, both of which result in reduced emissions and fuel conservation, are the relevant MOEs.
- The ITS Traffic Management Program carries out long-term and applied research toward smoothing traffic flow through management and control technologies. This enhances environmental goals by reducing stopping and starting of traffic, thereby reducing emissions.

Recent Progress

- Developed ITS Deployment Analysis System (IDAS) to determine impacts, benefits, and costs of ITS deployments.
- Completed evaluation of a Field Operational Test to reduce vehicle queues and idling times at land border crossings, including an estimate of the avoided health-related costs resulting from reduced emissions. For the Washington State/British Columbia border along the I-5 corridor alone, the avoided costs were calculated as $1.6M to $2.5M over a 10-year period, depending on the deployment scenario. These reductions are primarily from time savings at the border but include reduced idling at weigh stations.
- There has been a significant increase in the number of Traffic Management Centers (TMCs) implemented nationwide, which are essential for implementing and coordinating traffic-management strategies such as incident management and freeway management. For example, the 2002 Freeway Management Deployment Tracking Survey indicates that 83 agencies had a TMC, of which 41 provide environmental monitoring.
- Increased bus ridership at Acadia National Park, resulting from implementation of ITS technologies, resulted in an estimated reduction of 1.17 tons of emissions in 2002, the first year that ITS was operational.
- ITS deployment tracking in 75 large metropolitan areas indicates that 27 now have high levels of integrated ITS deployment and 30 have medium deployment levels.
- The Comprehensive Mobile Emission Model (CMEM) was developed under the National Cooperative Highway Research Program (NCHRP Project 25-11) to accurately reflect light-duty vehicular emissions, such as those from automobiles.

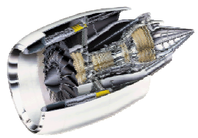
Commercialization and Deployment Activities

- An example of the many commercialization activities underway in ITS is the Center for Commercialization of ITS Technologies recently established in California. Having begun operations on February 7, 2002, the center is a unique partnership among the State DOT, the University of California, and the industry to facilitate and accelerate the deployment and commercialization of ITS Technologies.
- Deployment of electronic toll collection (ETC) systems continues to expand. In a 2002 survey, 73% of toll lanes in 78 of America's largest cities were equipped with ETC.

1.1.5 AVIATION

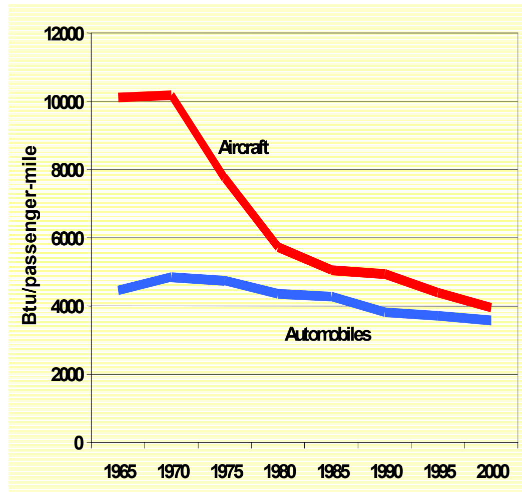
Technology Description

GE90 High Bypass Turbofan



Boeing 777

Today's airplanes are 300 times more energy efficient than early jets.

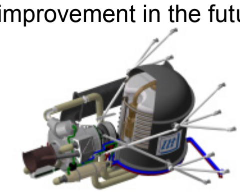


The energy intensity of aircraft and automobiles has improved substantially during the past several decades. Automobile energy intensity has fallen by almost one-fifth, while aircraft energy intensity has fallen by three-fifths during the same period.

LNG Buses at LAX

New technologies reduce ground emissions

…. and revolutionary new concepts offer opportunity for continued improvement in the future.



Humans benefit from the ability to move people and products all over the globe – quickly and safely. Aviation contributes to our quality of life – allowing us to visit friends and relatives, to travel, to experience new places, to shrink the borders of the world. The statistics are impressive. In 1903, Earth's population was 1.6 billion. Today, more than 1.6 billion people use the world's airlines. The Air Transport industry provides 28 million direct, indirect, and induced jobs worldwide. And aircraft carry about 40% of the value of all world trade, providing the "just in time" deliveries critical to productivity improvements. Aircraft use conventional hydrocarbon fuels, and contribute about 10% of greenhouse gas emissions from the transportation sector. Also, emissions from aircraft engines are unique in the aspect that they are deposited directly throughout the upper atmosphere. Subsonic aircrafts emit gases and particles directly into the lower stratosphere and upper troposphere, while emissions from supersonic aircrafts are deposited at higher altitudes. These aircraft emissions perturb the atmosphere by changing the background levels of trace gases and particles, and by forming contrails.

The Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) – together with industry, academia, and other Federal agencies – are pursuing strategies to improve aviation fuel efficiency and reduce its impact on global climate.

System Concepts

- Optimized Operations – more efficient operations to reduce fuel burn.
- Optimize Propulsion – advanced turbine engine technologies to reduce fuel burn.
- Reduce airframe weight and drag – airframe technologies that reduce fuel consumption.
- Alternative vehicles – ground support equipment, airframe concepts, propulsion systems, and fuels that dramatically reduce or completely eliminate emissions from civil aircraft.

Representative Technologies

- Alternate fuel Ground Support Equipment (GSE) and airport ground access vehicles (e.g., electricity, natural gas, propane, fuel cells) reduce ground-based aviation greenhouse emissions.
- Advanced propulsion concepts greatly reduce greenhouse gas and other harmful emissions.
- New materials and design practices continue to reduce aircraft empty weight, enhancing fuel efficiency.
- Information technology and management science advances enable more efficient air traffic management and ground operation procedures.

Technology Status/Applications

- New engine and airframe technologies in today's jets have led to a 70%-80% improvement in fuel burn per seat mile since the early 1960s.
- Airports and airlines are adopting low-emissions technologies available for ground-support equipment and airport access vehicles – substantial progress in replacing gasoline and diesel-powered airport ground vehicles with new vehicles running on cleaner alternative fuels, primarily electricity and compressed natural gas (CNG).
- Enhanced operational procedures offer opportunities for near-term greenhouse gas emissions reductions.
- Continued advances require continued breakthroughs in more efficient engine and airframe technologies; and aircraft technology development and capital turnover follow relatively long cycles, which limits the pace of fundamental changes in design.
- Airborne fuel cells and other alternative-fueled air vehicles have the potential for significant emissions reductions, but are far-term (25 years or more) options.

Current Research, Development, and Demonstration

RD&D Goals

- FAA goal – improve aviation fuel efficiency per revenue plane-mile by 1% per year through 2008, as measured by a three-year moving average, beginning with the three-year average of calendar years 2000-2002.
- NASA technology goals – new technologies with the potential to reduce CO_2 emissions of future aircraft by 25% within 10 years and by 50% within 25 years (using 1997 subsonic aircraft technology as the baseline).

RD&D Challenges

- Developing new technology that reduces emissions while still being affordable.
- Ensuring new concepts do not result in additional system weight, which increases fuel burn substantially.
- Very high premium for safe operation, which constrains the use of unproven new technologies and strategies relative to other transportation modes.

RD&D Activities

- NASA is pursuing research activities on efficient engine technologies, advanced aerodynamic shapes and structures, autonomous robust avionics, and low-emissions alternative power, which could lead to significant emissions reductions.

- FAA has a roadmap for continuing to mitigate the environmental impacts of aviation. This includes research to improve its understanding of the role of aviation emissions on the environment and optimize overall environmental impact mitigation strategies.
- Department of Energy research on alternative-fuel ground vehicles can lead to reduced emissions from airport ground-support equipment and access vehicles.

Recent Progress

- FAA's Inherently Low-Emission Airport Vehicle (ILEAV) Pilot Program seeks to evaluate airport use of alternative-fuel vehicles and infrastructure to determine their reliability, performance, and cost-effectiveness in the airport environment. Under this pilot program, there are 125 project vehicles in operation and at least 150 more vehicles planned for service.
- NASA's primary engine research program, the Ultra-Efficient Engine Technology Program (UEET), has made significant progress toward demonstrating its goals of 15% fuel burn (equivalent to CO_2) reduction and 70% NO_x reduction relative to 1996 standards.
- FAA has developed a unique capability to estimate aircraft emissions ranging from a single flight to regional and worldwide scales. The System for assessing Aviation's Global Emissions (SAGE) will be able to develop aviation emission inventories, both for baseline conditions and forecasted technology, operational, and market-based measures and improvements.
- Airlines have launched new initiatives to reduce fuel burn by limiting the use of auxiliary power units by using ground power whenever possible.
- FAA has established a new Center of Excellence for Noise and Emissions Mitigation, which will identify solutions for existing and anticipated aircraft emissions-related challenges.

Commercialization and Deployment Activities

- Aircraft are dependent on liquid fossil fuels, and potential modifications to fuel type and composition for environmental benefits are limited.
- FAA's Low-Emission Airport Vehicle (ILEAV) Pilot Program is assisting in deploying low-emissions technology to airport operations.
- Fuel costs are a significant portion of operating costs for an airline; hence airlines have great incentives to reduce fuel burn.
- Better meteorological information, yield-management tools, and the hub and spoke system – combined with the growth of low-cost, point-to-point carriers, and a significant increase in the number and reach of regional airlines – is improving the efficiency of the entire aviation network.

1.1.6 TRANSIT BUSES – URBAN DUTY CYCLE, HEAVY VEHICLES

Technology Description

Current transit buses use large-displacement, slow-speed, four-stroke diesel engines as the prime propulsion system. Due to their high efficiency and reliability, diesel engines are the dominant power source for heavy-duty transit buses in the United States, and they are the preferred power source for commercial surface transportation worldwide. In a transit bus, the engine is coupled to a four- or five-speed automatic transmission, which drives through a differential within the solid rear axle that mounts dual rear tires, resulting in a direct (or nearly direct) relationship between wheel speed and engine speed. The engine also directly drives all major vehicle auxiliary systems, through belt, hydraulic, or gear drives or combinations thereof.

Conventional transit bus designs waste substantial energy through braking resulting in poor propulsion system efficiency. The current state of practice simply discards this braking energy as heat during deceleration; none of it is recovered. Past attempts have been made at energy recovery through hydraulic or pneumatic systems. The inherent inefficiency, size, weight, and added complexity of these systems precluded them from production consideration.

The urban duty cycle of transit buses (constant stop and start cycles with as many as 14 cycles every 10 minutes in the case of the CBD-14 driving cycle) means the engine, transmission, and auxiliary systems are most frequently operated in a transient mode. Transient operation in this type of drive system is a condition detrimental to the goals of high efficiency and low emissions.

System Concepts

- Hybrid electric propulsion systems using diesel engines in both parallel and series configuration.
- Lightweight materials including composite body structures and components.
- Clean fuel formulation including bio-gas, synthetic diesel, ultra-low sulfur petroleum diesel.
- Fuel cell systems as standalone propulsion systems and in hybrid configuration.

Representative Technologies

- Compressed natural gas spark-ignited engines.
- Diesel hybrid electric systems with current energy storage technologies.
- Exhaust after-treatment technology for both NO_x and particulates.

Technology Status/Applications

- Diesel buses are still the dominant technology; 20% of all new bus purchases are for natural gas buses.
- Clean fuel formulations continue to be evaluated including bio-diesel, synthetic diesel, and bio-gas.
- Diesel hybrid buses (both parallel and series hybrid) with current energy storage technologies are entering commercial infancy.
- Hydrogen fuel cell buses continue to be demonstrated.

Current Research, Development, and Demonstration

RD&D Goals

- Meet or exceed proposed EPA emissions standard for heavy-duty bus engines of 0.01 g/bhp-hr particulates and 0.20 g/bhp-hr of NO_x plus 0.14 g/bhp-hr of non-methane hydrocarbons (NMHC) by 2007. By 2015, have zero-emission or near zero-emission transit bus commercially available.
  - Advance hybrid electric drive systems in combination with fuel formulation and after-treatment.
  - Continue RD&D for advance energy storage options to enhance commercial viability of hybrid electric and ultimately fuel cell buses.
- Gross load passenger capacity increased from 53-88 to 100 passengers and seated passenger capacity increased from 43 to 50 on a two-axle bus. Transit buses with a maximum single-axle load no greater than 20,000 pounds at the gross vehicle weight with a full passenger capacity of 90-100 people by 2006.
  - Accelerate RD&D of composite body structure bus and bus components.
  - Accelerate broader deployment of composite body structure buses.
- By 2010, transit buses with 10-mpg (128,400 btu/gal equivalent) fuel efficiency at seated load weight on the CBD-14 driving cycle.
  - Advance hybrid electric drive systems with advanced energy storage technology.
  - Advance lightweight bus structures.
- Mean miles between failure (individual components) increased by 50%. Mean time to repair failure (individual components) reduced by 50%.
- By 2015, commercially viable fuel cell transit buses meeting all prevailing standard transit bus operating and maintenance requirements at less than twice the cost of a comparable transit vehicle. Incremental capital cost no greater than 50% compared to standard bus five years after commercial introduction.
  - Continued RD&D for fuel cell propulsion systems specifically designed for heavy-duty transit buses.
  - Continued RD&D for light-duty fuel cell hybrid fuel cell systems for buses.

RD&D Challenges

- Tradeoff between improving vehicle fuel efficiency and vehicle-exhaust emissions.
- Need to consider vehicle systems approach to vehicle fuel efficiency and emissions as opposed to current engine approach.
- Transit bus market volume too low to be technology driver. However, transit bus fleets are ideal platforms for the introduction of new technologies.
- Compact, lightweight, robust, reliable, and durable energy storage technology for hybrid electric and fuel cell buses.
- Cost, reliability, durability, and performance of hydrogen fuel cells need significant improvements for commercialization to be viable.

RD&D Activities

- DOT through FTA continues to be in the forefront of the RD&D of fuel cell buses and is developing a hydrogen and fuel cell bus initiative with key stakeholders.
- DOT through FTA is working in collaboration with DOE, EPA, DOD along with state, regional, and local government agencies (CEC, CARB, SCAQMD, NYSERDA) in the RD&D of advanced bus technologies.

Recent Progress

- Demonstrated 30-foot fuel cell hybrid bus with an automotive fuel cell system that achieved 11 miles per gasoline equivalent fuel efficiency.

Commercialization and Deployment Activities
• New York City Transit has ordered 325 series hybrid electric transit buses that are being delivered. • Long Beach Transit has ordered 27 gasoline hybrid electric transit buses with added-on orders from other agencies potentially totaling 100. • Demonstrations of parallel hybrid electric transit buses are underway and planned in Philadelphia, Seattle, Orange County, Minneapolis, and Austin. • Demonstrations of seven Generation I fuel cell buses with the California Fuel Cell Partnership at AC Transit, Santa Clara VTA, and SunLine Transit. • U.S. Heavy-Duty Fuel Cell Working Group established in 2002 with specific focus on buses. An International Fuel Cell Bus Workshop in Long Beach will facilitate the formation of an International Fuel Cell Bus Working Group. **Market Context** • Electric drive vehicle technology encompassing hybrid electric and fuel cell technologies are global in nature and highly competitive with major European and Asian companies actively pursuing RD&D.

1.2 BUILDINGS

1.2.1 BUILDING EQUIPMENT, APPLIANCES, AND LIGHTING

Technology Description

A school in North Carolina features daylighting, state-of-the-art lighting controls, and an energy management system, allowing individual teachers to select optimum lighting levels for each room.

Energy use in buildings depends on equipment to transform fuel or electricity into end-use services such as delivered heat or cooling, light, fresh air, vertical transport, cleaning of clothes or dishes, and information processing. (The effects of passive and related systems are discussed in other profiles.) There are energy-saving opportunities within individual pieces of equipment – as well as at the system level – through proper sizing, reduced distribution and standby losses, heat recovery and storage, and optimal control. Another promising opportunity lies in multifunction devices ranging from heat pumps, which provide both refrigeration and hot water, to an office appliance that serves as a networked printer, copier, scanner, and paperless fax machine.

System Concepts

- Major categories of end-use equipment include heating, cooling, and hot water; ventilation and thermal distribution; lighting; home appliances; miscellaneous (process equipment and consumer products); and on-site energy and power.
- Key components vary by type of equipment, but some crosscutting opportunities for efficiency include improved materials, efficient low-emissions combustion and heat transfer, advanced refrigerants and cycles, electrodeless and solid-state lighting, smart sensors and controls, improved small-power supplies, variable-capacity systems, reduction of thermal and electrical standby losses, cogeneration based on modular fuel cells and microturbines, and utilization of waste heat from fuel cells and microturbines.

Representative Technologies

- Residential gas-fired absorption heat pumps, centrifugal chillers, desiccant preconditioners for treating ventilation air, heat-pump water heaters, proton exchange membrane fuel cells, heat pump water heaters, solid-state lighting, and lighting controls.
- Specialized HVAC (heating, ventilating, and air-conditioning) systems for research laboratories, server/data systems, and other buildings housing high technology processes.

Technology Status/Applications

- Technology improvements during the past 20 years – through quality engineering, new materials, and better controls – have improved efficiencies in lighting and equipment by 15% to 75%, depending on the type of equipment. Efficiencies of compact fluorescent lamps are 70% better than incandescent lamps; refrigerator energy use has been reduced by more than three-quarters during the past 20 years; H-axis clothes washers are 50% more efficient than current minimum standards. Electronic equipment has achieved order-of-magnitude efficiency gains, at the microchip level, every two to three years.

Current Research, Development, and Demonstration

RD&D Goals

- By 2025, research, develop, and demonstrate marketable and advanced energy systems required to achieve "net-zero" energy use in new residential and commercial buildings through a 70% reduction in building energy use – via high-performance lighting, HVAC, and appliances – with the balance of energy needs met by renewable energy sources.
- By 2010, heat pumps for residential and small commercial applications are 40% more efficient than condensing gas furnaces.
- By 2010, reduced standby losses, improved heat pump water heating, and application of heat-recovery techniques reduce energy use for domestic water heating by 60% over electric storage water heaters.
- By 2020, photovoltaics offer cost-competitive alternatives to grid electricity, enabling the construction of net-zero energy homes/buildings, when combined with ~70% whole building load reductions.
- By 2020, alternative refrigeration equipment with low greenhouse warming potential (e.g., Stirling cycle, Brayton cycle, acoustic, magnetic, thermal electric) will be commercially introduced.
- By 2008, develop a portfolio of distributed generation technologies (including microturbines) that show an average 25% increase in efficiency (compared to 2000 baseline) with NO_x emissions less than 0.15 lb/MWh.
- By 2013, develop solid-state lighting for general illumination applications with luminous efficacy of 90 lumens per watt by 2008, and 160 LPW by 2013.
- By 2030, all aspects of the building envelope, equipment, and appliances will be integrated and combined with on-site microcogeneration and zero-emission technologies.
- The basic RD&D needed ranges from materials science to solid-state electronics, and from a better understanding of combustion fundamentals to advances in control theory. Research is also needed on behavioral and ergonomic dimensions of the user-machine relationship.

RD&D Activities

- Most Federal R&D on building equipment is performed by DOE.
- International funding is less relevant than state activities such as currently ongoing in California, New York, and other states. This research is synergistic with and complements the DOE research.

Recent Progress

- Recent DOE-sponsored R&D, often with industry participation, includes an improved air-conditioning cycle to reduce oversizing and improve efficiency; a replacement for inefficient, high-temperature halogen up-lights (torchieres), which use only 25% of the power, last longer, and eliminate potential fire hazards; ozone-safe refrigerants, where supported R&D was directed toward lubrication materials problems associated with novel refrigerants and ground-source heat pumps.

Commercialization and Deployment Activities

- Building equipment, appliances, and lighting systems currently on the market vary from 20% to 100% efficient (heat pumps can exceed this level by using "free" energy drawn from the environment). This efficiency range is narrower where cost-effective appliance standards have previously eliminated the least-efficient models.
- The stock and energy intensity of homes are growing faster than the building stock itself, as manufacturers introduce – and consumers and businesses eagerly accept – new types of equipment, more sophisticated and automated technologies, and increased levels of end-use services.
- The rapid turnover and growth of many types of building equipment – especially electronics for computing,

control, communications, and entertainment – represent important opportunities to rapidly introduce new, efficient technologies and quickly propagate them throughout the stock.

- The market success of most new equipment and appliance technologies is virtually ensured if the efficiency improvement has a three-year payback or better and amenities are maintained; technologies with payback of four to eight-plus years also can succeed in the market, provided that they offer other customer-valued features (e.g., reliability, longer life, improved comfort or convenience, quiet operation, smaller size, lower pollution levels).
- Applications extend to every segment of the residential and nonresidential sectors. Major government, institutional, and corporate buyers represent a special target group for voluntary early deployment of the best new technologies.

Market Context

- Building equipment and appliances represent an annual market in the United States, alone, of more than $200B, involving thousands of large and small companies. Certain technologies, such as office and home electronics, compete in global markets with little or no change in performance specifications.

1.2.2 BUILDING ENVELOPE (INSULATION, WALLS, ROOF)

Technology Description

National laboratory exhibits show the benefits of energy-efficient building envelope design (left). This home in Atlanta, Georgia, (right) will use 58% less energy for heating and 53% less energy for cooling than a home of comparable size without energy-efficient design.

The building envelope is the interface between the interior of a building and the outdoor environment. In most buildings, the envelope – along with the outdoor weather – is the primary determinant of the amount of energy used to heat, cool, and ventilate. A more energy-efficient envelope means lower energy use in a building and lower greenhouse gas emissions. The envelope concept can be extended to that of the "building fabric," which includes the interior partitions, ceilings, and floors. Interior elements and surfaces can be used to store, release, control, and distribute energy, thereby further increasing the overall efficiency of the buildings.

System Concepts

- Control of envelope characteristics provides control over the flow of heat, air, moisture, and light into the building. These flows and the interior energy and environmental loads determine the size and energy use of HVAC and distribution systems.
- Materials for exterior walls, roofs, foundations, windows, doors, interior partition walls, ceilings, and floors that can impact future energy use include insulation with innovative formula foams and vacuum panels; optical control coatings for windows and roofs; and thermal storage materials, including lightweight heat-storage systems.

Representative Technologies

- *Superinsulation*: Vacuum powder-filled, gas-filled, and vacuum fiber-filled panels; structurally reinforced beaded vacuum panels; and switchable evacuated panels with insulating values more than four times those of the best currently available materials should soon be available for niche markets. High-thermal-resistant foam insulations with acceptable ozone depletion and global warming characteristics should allow for continued use of this highly desirable thermal insulation.
- *Advanced window systems*: Krypton-filled, triple-glazed, low-E windows; electrochromic glazing; and hybrid electrochromic/photovoltaic films and coatings should provide improved lighting and thermal control of fenestration systems. Advanced techniques for integration, control, and distribution of daylight

should significantly reduce the need for electric lighting in buildings. Self-drying wall and roof designs should allow for improved insulation levels and increase the lifetimes for these components. More durable high-reflectance coatings should allow better control of solar heat on building surfaces.

- *Advanced thermal storage materials*: Dry phase-change materials and encapsulated materials should allow significant load distribution over the full diurnal cycle and significant load reduction when used with passive solar systems.

Technology Status/Applications

- Building insulations have progressed from the 2-4 hr ºF ft^2/Btu/in. fibrous materials available before 1970 to foams reaching 7 hr ºF ft^2/Btu/in. Superinsulations of more than 25 ºF ft^2/Btu/in. will be available for niche markets soon. Improvements in window performance have been even more spectacular. In the 1970s, window thermal resistance was 1 to 2 ºF ft^2/Btu. Now, new windows have thermal resistance of up to 6 ºF ft^2/Btu (whole window performance). Windows are now widely available with selective coatings that reduce infrared transmittance without reducing visible transmittance. In addition, variable-transmittance windows under development will allow optimal control to minimize heating, cooling, and lighting loads.

Current Research, Development, and Demonstration

RD&D Goals

- By 2025, research, develop, and demonstrate marketable and advanced energy systems required to achieve "net-zero" energy use in new residential and commercial buildings through a 70% reduction in building energy use – via high-performance walls, windows, roofs and foundations – with the balance of energy needs met by renewable energy sources.
- Commercial-building, low-slope roof options with high insulation qualities (R-30 to R-40) and extended lifetimes (30-plus years).
- By 2008, demonstrate dynamic solar control windows (electrochromics) in commercial buildings.
- By 2010, windows with R10 insulation performance for homes are commercially available.
- Mass-produced (factory-built) customized buildings with integrated envelope and equipment systems designed and sized for specific sites and climates.
- On-site or purchased renewables replacing 15% of purchased energy (see photovoltaics pathway).
- A 30% decrease in the average envelope thermal load of existing residential buildings and a 66% decrease in the average thermal load of new buildings compared to current code requirements.

RD&D Challenges

- Foam insulations that retain high thermal resistance while using blowing agents with zero ozone depletion potential and negligible global warming effect.
- Self-drying wall and roof designs to avoid moisture problems such as materials degradation.
- Electrochromic window films and electrochromic/photovoltaic hybrid window films to control energy flows and generate electricity on site.
- Techniques to distribute and control daylight to reduce electrical energy use for artificial lighting.
- Advanced durable cost-effective superinsulations to reduce heating/cooling loads.
- Self-calibrating multifunction microsensors for monitoring building equipment performance and air-quality monitoring.
- Thermal storage materials: Typically, thermal storage in building components is achieved with heavyweight materials such as masonry. Advanced thermal-storage materials need to be lightweight to integrate with elements similar to drywall, floor, and ceiling panels.
- Scaling electrochromic window technology to commercial-scale window applications.

RD&D Activities

- Key agencies doing building envelope R&D are DOE, National Institute for Standards and Technology, several state agencies, and other institutions such as the Florida Solar Energy Center.

Recent Progress
• A DOE-sponsored RD&D partnership with the Polyisocyanurate Insulation Manufacturers Association, the National Roofing Contractors Association, the Society of the Plastics Industry, and Environmental Protection Agency (EPA) helped the industry find a replacement for chloroflurocarbons (CFCs) in polyisocyanurate foam insulation. This effort enabled the buildings industry to transition from CFC-11 to HCFC-141b by the deadline required by the Montreal protocol. • Spectrally selective window glazings – which reduce solar heat gain and lower cooling loads – and high-performance insulating materials for demanding thermal applications.
Commercialization and Deployment Activities
• A critical challenge is to ensure that new homes and buildings are constructed with good thermal envelopes and windows when the technologies are most cost effective to implement. • The market potential is significant for building owners taking some actions to improve building envelopes. Currently, 40% of residences are well insulated, 40% are adequately insulated, and 20% are poorly insulated. More than 40% of new window sales are of advanced types (low-E and gas-filled). In commercial buildings, more than 17% of all windows are advanced types. More than 70% of commercial buildings have roof insulation; somewhat fewer have insulated walls. • Building products are mostly commodity products. A number of companies produce them; and each has a diverse distribution system, including direct sales, contractors, retailers, and discount stores. • Another critical challenge is improving the efficiency of retrofits of existing buildings. Retrofitting is seldom cost-effective on a stand-alone basis. New materials and techniques are required. • Many advanced envelope products are cost-competitive now, and new technologies will become so on an ongoing basis. There will be modest cost reductions over time as manufacturers compete. **Market Context** • Building structures represent an annual market in the United States of more than $70B/year and involve thousands of large and small product manufacturers and a large, diverse distribution system that plays a crucial role in product marketing. Exporting is not an important factor in the sales of most building structure products.

1.2.3 INTELLIGENT BUILDING SYSTEMS

Technology Description

Energy-management system field tests at the Zion National Park Visitor Center (top) and the Bighorn Home Improvement Center complex in Silverthorne, Colorado (bottom), DOE High Performance Buildings Program.

Intelligent building systems (IBS) use data from design (together with sensed data) to automatically configure controls and commission (i.e., start-up and check out) and operate buildings. Control systems use advanced, robust techniques and are based on smaller, less expensive, and much more abundant sensors. These data ensure optimal building performance by enabling control of building systems in an integrated manner and continuously recommissioning them using automated tools that detect and diagnose performance anomalies and degradation. Intelligent building systems optimize operation across building systems, inform and implement energy purchasing, guide maintenance activities, document and report building performance, and optimally coordinate on-site energy generation with building energy demand and the electric power grid, while ensuring that occupant needs for comfort, health, and safety were met at the lowest possible cost.

System Concepts

- The system consists of design tools, automated diagnostics, interoperable control-system components, abundant wireless sensors and controls, and highly integrated operation of energy-using and producing systems.
- These components would work together to collect data, configure controls, monitor operations, optimize control, and correct out-of-range conditions that contribute to poor building performance.
- Intelligent building systems would ensure that essential information, especially the design intent and construction implementation data, would be preserved and shared across many applications throughout the lifetime of the building.
- Equipment and system performance records would be stored as part of a networked building performance knowledge base, which would grow over time and provide feedback to designers, equipment manufacturers, and building operators and owners.
- Optimally integrate on-site power production with building energy needs and the electric-power grid by applying intelligent control to building cooling, heating, and power.

Representative Technologies

- DOE is developing computer-based building commissioning and operation tools to improve the energy efficiency of "existing" buildings. It is also investing in the next generation of building simulation programs that could be integrated into design tools.
- DOE, in collaboration with industry, also is developing and testing technologies for combined cooling, heating, and power; and wireless sensor and control systems for buildings.

Technology Status/Applications

- Savings from improved operation and maintenance procedures could save more than 30% of the annual energy costs of existing commercial buildings, even in many of those buildings thought to be working properly by their owners/operators. These technologies would have very short paybacks because they would ensure that technologies were performing as promised, for a fraction of the cost of the installed technology.
- Savings for new buildings could exceed 70% using integration of building systems and, with combined cooling, heating and power, buildings could become net electricity producers and distributed suppliers to the electric power grid.

Current Research, Development, and Demonstration

RD&D Goals

- Design environments with fully and seamlessly integrated building design tools that support all aspects of design and provide rapid analysis; design suggestions; quick and easily understood data interpretation; automatic generation of all design documents; and a building electronic-data structure that supports start-up, operation, maintenance, and renovation of the building by intelligent building systems.
- Automatic operation of buildings by automatically sensing installed equipment; checking for proper installation; generating control algorithms; implementing optimal adaptive control; diagnosing and correcting operating episodes that produce inefficient, unhealthy or uncomfortable conditions; managing maintenance; and providing performance data in usable forms for operators of new and existing buildings, facility managers, and owners. Have systems appropriate for homes and other small buildings that require little operator attention.
- Highly efficient combined cooling, heating, and power systems that use waste heat from small-scale, on-site, electricity generation to provide heating and cooling for the buildings, as well as exporting excess electricity to the grid.

RD&D Challenges

- Design tools: enhanced analytical capabilities, integration with the design environment, automated design and analysis capability, design databases, visualization, and high-level monitoring and reporting tools.
- Automated diagnostics: diagnosticians, plug-and-play capabilities, automated real-time purchasing, advanced data visualization, automated identification, and correction of the causes of operation problems.
- System interoperability and controls: integrated control networks; plug-and-play control components; adaptive, optimized, self-generating control algorithms; automatic configuration and commissioning of controls; and advanced control techniques.
- Sensors: wireless data acquisition, detection of materials properties, micro-scale sensors, microelectronic sensors, multiple-sensor arrays, protocols for using new sensors, new sensing technologies, order of magnitude lower-cost sensor systems, and ubiquitous use of sensors.
- Visualization: use of supercomputers, networked personal computer to provide distributed super-computer-level performance, advanced computational methods, and virtual reality systems to permit real-time visualization of designs and design changes, including lighting, thermal flows, and air quality.
- Buildings Combined Cooling, Heating, and Power: Technologies for reusing waste energy to provide net-electricity producing buildings.
- Early priorities include enhancing design-tool integration; developing automated diagnosticians; implementing remote data collection and visualization; developing combined cooling, heating, and power; and developing low-cost, wireless sensor, and control technology.
- Advanced building simulation tools to permit better design, construction, commissioning, and operation.

RD&D Activities

- DOE is funding work with the California Energy Commission, California Institute for Energy Efficiency, Honeywell, Johnson Controls, Siemens, Electric Power Research Institute, Southern California Edison, and Pacific Gas and Electric Company. International efforts include an effort funded by the European Union to develop adaptive control techniques for improving the thermal environment for JOULE IIICSEC.

Recent Progress
• Energy 10: models passive solar systems in buildings. • DOE 2: international standard for whole building energy performance simulation has thousands of users worldwide. • DOE has recently released Energy Plus, the new standard for building energy simulation and successor to DOE-2. • The International Alliance for Interoperability is setting international standards for interoperability of computer tools and components for buildings. • DOE-BESTEST: basis for ANSI/ASHRAE Standard 140, *Method of Test for the Evaluation of Building Energy Simulation Programs.*
Commercialization and Deployment Activities
• Design tools for energy efficiency are used by fewer than 2% of the professionals involved in the design, construction, and operation of commercial buildings in the United States. A larger fraction of commercial buildings have central building-control systems. Few diagnostic tools are available commercially beyond those used for air balancing or integrated into equipment (e.g., Trane Intellipack System) and the recently announced air-conditioning diagnostic hand-held service tool by Honeywell (i.e., Honeywell HVAC Service Assistant). The Department of Energy – in concert with the California Energy Commission – is testing a number of automated diagnostic tools and techniques with commercial building owners, operators, and service providers in an effort to promote commercial use. About 12 software vendors develop, support, and maintain energy design tools; most are small businesses. Another 15 to 20 building automation and control vendors exist in the marketplace – the major players include Johnson Controls, Honeywell, and Siemens. • Deployment involves four major aspects: seamless integration into existing building design and operation practices and platforms, lowering the cost of intelligent-building and enabling technologies, transforming markets to rapidly introduce new energy-efficient technologies, and a focus on conveying benefits that are desired in the marketplace (not only energy efficiency). **Market Context** • These technologies would apply to all buildings, but especially to existing commercial buildings and all new buildings. In addition, new technologies would be integrated into the building design and operation processes.

1.2.4 URBAN HEAT ISLAND TECHNOLOGIES

Technology Description

Heat islands form as cities replace natural vegetation with pavement for roads, buildings, and other structures necessary to accommodate growing populations. These surfaces absorb – rather than reflect – the sun's heat, causing surface temperatures and overall ambient temperatures to rise. The displacement of trees and shrubs eliminates the natural cooling effects of shading and evapotranspiration. Measures to reduce the urban heat island effect include strategically planting shade trees, installing reflective roofs, and installing reflective pavements. Heat island mitigation measures can reduce greenhouse emissions by reducing ambient air temperatures in urban areas, thereby slowing the chemical formation of smog (ozone and precursors) and reducing demand for electricity for air-conditioning in the cooling seasons. In general, the larger the area implementing heat island reduction measures – and the longer, sunnier, and hotter the summer season – the more substantial the impacts on meteorology and air quality. Meteorological modeling can assist in understanding the effects of such measures, as well as the interactions with other factors.

System Concepts

- Reduced temperatures reduce the need for summertime cooling energy. Reduced air-conditioning reduces power plant emissions, including greenhouse gas emissions and ozone precursors.
- Reduced temperatures decrease biogenic volatile organic compounds emissions and evaporative losses.
- Trees sequester carbon (particularly urban or suburban trees, which can sequester about 18 kg of carbon annually) and precipitate particulates and other airborne pollutants.
- Reduced ambient air temperature reduces photochemical reaction rates, which may reduce ozone production.

Representative Technologies

- There are more than 200 Energy Star-labeled roof products, which include coatings and single-ply materials, tiles, shingles, and membranes. Energy savings in buildings with reflective roofs range as high as 32% during peak demand, with a summer average of 15%.
- There are several reflective pavement applications being developed, which include new pavement applications, resurfacing pavement applications, asphalt material type, concrete material type, and other material types. For example, white topping involves covering existing asphalt pavement with a layer of concrete (which has approximately 15% higher albedo than asphalt). Also, chip seals are used for maintenance and resurfacing of low-traffic streets and roads; reflective materials can be used to cover the surface. Higher albedos reduce maximum pavement temperatures by about 10°F per 0.1 increase in albedo. In turn, air temperature is reduced by about 1°F if all pavements have albedo increased by 0.2.
- Placing trees on the west-, south-, and east-facing sides of a building can significantly reduce cooling costs for a home or low-rise building during peak summertime demand. Simulations of energy savings benefits for Sacramento and Phoenix found that three mature trees around homes cut annual air-conditioning demand by 25%-40%.

Technology Status/Applications

- A few states (e.g., California, Georgia, and Florida) have incorporated reflective roofs into their state energy codes. Some states (e.g., California) and communities have reflective roof incentive programs. Reflective roofs are given credit in several environmental rating programs including the U.S. Green Building Council's LEED (Leadership in Energy and Environmental Design) rating system.
- Some communities are installing alternative pavement parking lots and alleys – mainly using porous pavement technologies. White-topping is also becoming increasingly popular.
- Nationally, there are numerous tree-planting programs. Some utilities have partnered with urban forestry groups to encourage residential shade tree planting to reduce air-conditioning energy consumption. Further, several communities have implemented shade tree ordinances (e.g., requiring parking lots shade 50% of paved areas 15 years after development).

Current Research, Development, and Demonstration

RD&D Goals
- Better understand and quantify the impacts heat island reduction measures have on local meteorology, energy use and expenditures, greenhouse gas emissions, and air quality.
- Develop an application based on geographic information systems that predicts heat island outcomes from different development scenarios.
- Better understand the relationship between surface and air temperature.
- Better understand the contribution of radiant emissions from vertical surfaces on the heat island effect.
- Quantify net benefits from large-scale tree planting projects (i.e., volatile organic compound contributions, CO_2 sequestration, and removal of other pollutants).
- Develop cool materials for roofs and pavements.
- Assist the Cool Roof Rating Council with developing procedures to measure and rate the optical properties of the roofing materials.
- Work with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), state and Federal agencies to develop implementation plans.

RD&D Challenges
- Better understand interaction between meteorological, land surface, and emission-specific parameters in baseline and modified modeling scenarios.
- Determine albedo and emissivity levels of city surfaces.

RD&D Activities
- Tulane University and a DOE laboratory are modeling the impacts of heat island reduction measures on local meteorology in seven U.S. domains.
- DOE is modeling the impacts of heat island reduction measures on local meteorology, energy savings, CO_2 reductions, and air quality in several cities including Houston, Chicago, and Baton Rouge.
- DOE is analyzing the urban fabric (surface composition) of several cities including Sacramento, Houston, Chicago, Salt Lake City, and Baton Rouge.
- Several groups in California are examining net benefits from trees.
- DOE is working with granule, pigment, and shingle manufacturers to develop cool-colored shingles.
- DOE is working with the pavement industry on developing cool surfaces.
- The Environmental Protection Agency (EPA) and DOE have lead efforts to organize the Cool Roof Rating Council and develop standards for the American Society for Testing and Materials (ASTM) and ASHRAE.
- USDA Forest Service develops methods and models to quantify carbon storage and sequestration, building energy-use effects, and air pollution removal by urban forests at the local to national scale.
- USDA Forest Service conducts analyses in numerous cities and national assessments to quantify the effects of urban forests on carbon storage and sequestration, building energy use, and air pollution removal.

Recent Progress

- EPA and DOE demonstrated the impact of cool roofs on building energy use; EPA developed the Energy Star Roof Products program.
- ASTM and ASHRAE standards have been developed, and prototype cool-roofing materials have been developed.
- The Cool Roof Rating Council was organized and several state and air-quality management districts have adopted heat-island-reduction measures.

Commercialization and Deployment Activities
• Reflective roofing and paving technologies may be broadly applicable to U.S. cities, but benefits will vary. • Several reflective roof programs (e.g., California's Cool Savings Program) require use of Energy Star Labeled Roof Products, thus increasing the demand and deployment of these products. **Market Context** • Heat island reduction strategies including urban reforestation, rooftop gardens, reflective roofs, and alternative pavements have been implemented in Los Angeles, Sacramento, Salt Lake City, Honolulu, Chicago, Miami, and Atlanta – and other cities are interested. • Nationally, reflective roofing materials still comprise less than 10% of the roofing market; asphalt comprises 95% of urban pavements.

1.3 INFRASTRUCTURE

1.3.1 HIGH-TEMPERATURE SUPERCONDUCTIVITY

Technology Description

America's ongoing appetite for clean, reliable, and affordable electricity has increased at a rate that seriously threatens to exceed current capacity. Demand is estimated to increase by 9% through 2004 – however, only a 3% increase in transmission is planned, and there have been no major new investments in transmission during the past 15 years. Witnessing the regional outages being experienced throughout the country – and those most recently highlighted in the northeast – the inadequacies of the investment in infrastructure investments have, in effect, issued a wake-up call for enhancement of the grid. High-temperature superconducting (HTS) wires can carry many more times the amount of electricity of ordinary aluminum or copper wires. HTS materials were first discovered in the mid-1980s and are brittle oxide, or ceramic-like materials, that can carry electricity with virtually no resistance losses. Through years of Federal research in partnership with companies throughout the nation, technology has developed to bond these HTS materials to various metals, providing the flexibility to fashion these ceramics into wires for use in transmission cables, bearings for flywheels, and coils for power transformers, motors, generators, and the like. Superconducting technologies make possible electric power equipment that is half the size of conventional alternatives, with half the energy losses. When HTS equipment becomes pervasive, up to 50% of the energy now lost in transmission and distribution will become available for customer use. HTS also will reduce the impact of power delivery on the environment and is helping create a new high-tech industry to help meet the challenges due to delays in electric utility restructuring. Other increased performance benefits include improved stability, reliability, power quality, and deferred generation expansion.

System Concepts

- HTS cables have almost no resistance losses and can transport 3-5 times as much power as a conventional cable in the same size conduit.
- HTS power transformers have about 30% reduction in total losses, can be 50% smaller and lighter than conventional units, have a total ownership cost that is about 20% lower, are nonflammable, and do not contain oil or any other potential pollutant. In addition, there are electrical performance benefits associated with current limiting capacity and reduced impedance that will yield cost savings to power companies.
- HTS Fault Current Limiters can provide power companies with surge protection within the local distribution system. They are reusable, require minimal maintenance, and do not need replacement after being activated.
- HTS motors with more than 750 kW would save enough energy over their lifetime to pay for the motor. The motors are 50% smaller and lighter than conventional motors, as well.
- HTS generators with more than 100 MVA will be more energy efficient, compact, and lighter than the conventional generator. The generator has characteristics that may help stabilize the transmission grid.

System Components

- HTS cables consist of large numbers of tapes containing HTS materials operating at 65-77 K, insulated thermally and electrically. A cryogenic refrigerating system maintains the temperature of the cable, extracting heat that manages to leak into the assembly.
- HTS transformers use the same types of HTS materials as cables, formed into coils and mounted on conventional transformer cores. Electrical insulation is accomplished by means other than conventional oil-and-paper, and typically involves a combination of solid materials, liquid cryogens, and vacuum.
- HTS motors, generators, magnetic separators, MRI magnets, and current limiters use HTS wires and tapes in a coil form. Rotating cryogenic seals provide cooling for the rotating machines.
- HTS flywheel systems use nearly frictionless bearings made from superconducting "discs," cooled below the transition temperature of the HTS materials.

Technology Status/Applications

- HTS wires: First generation "BSCCO" wires are available today in kilometer lengths at about $200/kA-m. Second-generation "coated conductors" have been made in 1-10 m lengths in the laboratory and are to be scaled up in 2002-2004 to 100-m lengths. The 1-m tapes carry approximately 50 amperes of current in nitrogen.
- HTS cables: Under the DOE Superconductivity Partnership Initiative, a team led by Pirelli Cable installed a 120-m cable in the city of Detroit, Michigan. Southwire has installed and tested a 30-m prototype cable that has been powering three manufacturing plants in Carrollton, Georgia, since February 2000.
- HTS transformers: Waukesha Electric Systems, with partial DOE funding, demonstrated a 1-MVA prototype transformer in 1999 and is leading a team developing a 5/10-MVA, 26.4-kV/4.2-kV three-phase prototype.
- HTS motors: Rockwell Automation demonstrated a prototype 750-kW motor in 2000 and is designing a motor with five times the rating.

Current Research, Development, and Demonstration

RD&D Goals

- Performance: Develop HTS wires with 100 times the capacity of conventional copper/aluminum wires. Design and demonstrate a broad portfolio of electric equipment based on HTS: 50% reduction in energy losses compared to conventional equipment, and 50% size of conventional equipment with the same rating. Low-cost, high-performance YBCO coated conductors will be available in 2005 in kilometer lengths.
- Cost: Wire cost of $0.01/ampere-meter. Equipment premium cost payback (efficiency savings) will be achieved in 2-5 years of operation. Equipment total cost payback will be achieved during the operating lifetime. Coated conductor goals: For applications in liquid nitrogen, the wire cost will be less than $50/kA-m; while for applications requiring cooling to temperatures of 20-60 K, the cost will be less than $30/kA-m. By 2010, the cost-performance ratio will have improved by at least a factor of four.

RD&D Challenges

- The manufacture of promising HTS materials in long lengths at low cost remains a key program challenge.
- Materials for cryogenic insulation and standardized, high-efficiency refrigerators (approaching 30% of Carnot efficiency) are required.
- Scale-up of national laboratory discoveries for "coated conductors" requires the use of film industry or semiconductor industry processing expertise and equipment to make electric wires and is a key activity for the labs and their industry partners.

RD&D Activities

- DOE funding is used for three key program activities: the Accelerated Coated Conductor Initiative, the Superconductivity Partnership Initiative, and Strategic Research. Performers include national laboratories, industry, academia, and other Federal agencies.

Recent Progress

- The development at the national laboratories of ion-beam assisted deposition and rolling-assisted, biaxially textured substrate (RABiTS™) technologies for producing high-performance HTS film conductors suitable for cables and transformers, and the involvement of four unique industry-led teams to capitalize on it, was a major success story for FY 1997.

- The world's first HTS cable to power industrial plants exceeded 13,000 hours of trouble-free operation in Carrollton, Georgia (Southwire Company). The 30-m cable system has been operating unattended since June 2001.
- During the summer of 2001, Detroit Edison installed a 120-m HTS cable system in an urban substation that serves 14,000 customers.
- Rockwell Automation demonstrated a prototype 1000-HP synchronous motor that exceeded design specifications by 60%, and is now designing a 5000-HP motor.

Commercialization and Deployment Activities

- High-temperature superconducting cables and equipment: Commercialization and market introduction requires development of inexpensive wires for transmission and distribution, and end uses such as electric motors. These wires are now under development under a government-industry partnership but are still years from wide-scale use. Using high-temperature superconductivity wires to replace existing electric wires and cables may be analogous to the market penetration that occurred when the United States moved from copper wire to fiber optics in communications. Some pre-commercial demonstrations have begun, but the Superconductivity Partnership Initiative could be expanded.

1.3.2 TRANSMISSION AND DISTRIBUTION TECHNOLOGIES

Technology Description

The electric utility industry is restructuring itself from a regulated environment to operation under competitive wholesale electricity markets. However, the electric transmission and distribution (T&D) systems remain regulated entities that connect deregulated generation to the end-use customer. Construction of U.S. transmission above 230 kV is expected to increase by only 6% (in line-miles) during the next 10 years, while demand is expected to increase more than 20%. The resulting increase in the intensity of use of existing facilities will increase energy losses and transmission congestion, and is likely to cause grid reliability problems and threaten the continued growth of wholesale electricity trade. Energy losses in the U.S. T&D system were 7.2% in 1995, accounting for 2.5 quads of primary energy and 36.5 MtC. Losses are divided such that about 60% are from lines and 40% are from transformers (most of which are for distribution). Technologies that can improve efficiency and reduce carbon emissions are high-voltage DC (HVDC) transmission, high-strength composite overhead conductors, and power transformers and underground cables that use high-temperature superconductors (see related technology profile). High-efficiency conventional transformers also could have significant impacts on distribution system losses. In addition, energy storage and real-time system monitoring and control systems could improve system reliability and customer access to competitive generation, including renewable power producers. There is no active U.S. program for HVDC development or improved distribution transformer technologies.

System Concepts

- Composite-core, low-sag transmission conductors can transport two to three times as much power as conventional conductors over the same rights-of-way and with no tower modifications.
- Energy storage will facilitate more optimal use of existing infrastructure and increase the dispatchability of renewable resources.
- Real-time grid operations using measured data and automatic, intelligent controllers can improve T&D reliability – and lead to a smart, switchable future network that can anticipate and respond automatically to system contingencies.

System Components

- One advanced composite overhead conductor consists of an aluminum metal matrix composite core (replacing the steel core of a conventional cable) surrounded by temperature-resistant aluminum alloy wires.
- Several large- and medium-scale energy-storage systems, using different electrochemistries, have been developed.
- Real-time control uses wide-area measurement systems, synchronized by global positioning system (GPS) satellite clocks that feed system information to artificial neural net controllers. The controllers reconfigure the system in real time, preventing outages and allowing maximum use of available transmission capacity.

Technology Status/Applications

- Aluminum composite-core conductors, terminations, and suspensions have been developed by 3M Company and demonstrated in the field by leading U.S. and European utilities. Additional field trials in the United States and accelerated thermal cycling tests are planned in 2003-2005. This extensive mechanical and electrical testing is required to predict the 40-year life responses of this new conductor technology. Niche applications including long-span river crossings and short lead-time reconductoring over congested existing rights-of-way are now cost-effective. In addition, the conductor's core has 25% lower electrical resistances than steel, enabling higher transmission efficiencies.

- Large-scale energy-storage systems are entering field demonstrations.
- Wide-area measurement systems used for monitoring, event analysis, and system model studies have been deployed in the Western United States power grid to help analyze system disturbances.

Current Research, Development, and Demonstration

RD&D Goals

- Accelerated thermal-cycle testing for 3M's composite conductor in 2003-2005. Field-testing of this conductor began in 2002 on a 230kV transmission line on DOE's Western Area Power Administration grid. Other advanced conductors are expected to undergo similar high-current and field tests in 2003-2006.
- Demonstration of the reliability of energy-storage systems, and reduction of the cost of such systems by 30%.
- Operation of a prototype smart, switchable grid on a region on the U.S. transmission grid by 2010. The market for conventional utility-control systems approaches $300 M/year.

RD&D Challenges

- Development of large-diameter composite conductors for high-voltage transmission lines that are both low-cost and high capacity, so as to yield the highest payoffs in grid reliability and competitive market efficiency.
- Energy-storage systems with reduced costs that can meet several applications while using a single system.
- Neural net networks that can be trained in parallel to perform control functions in real-time control systems.
- A regulatory framework that will allow investors to make credible projections of the return on investment in new transmission capacity.

RD&D Activities

- For composite conductors, 3M Company cost-shared on a DOE effort in FY2002 and FY2003 to perform field tests and accelerated, controlled thermal tests on several conductor sizes.
- DOE is cost-sharing an energy-storage effort with industry. EPRI has a newly reformed energy storage target.

Recent Successes

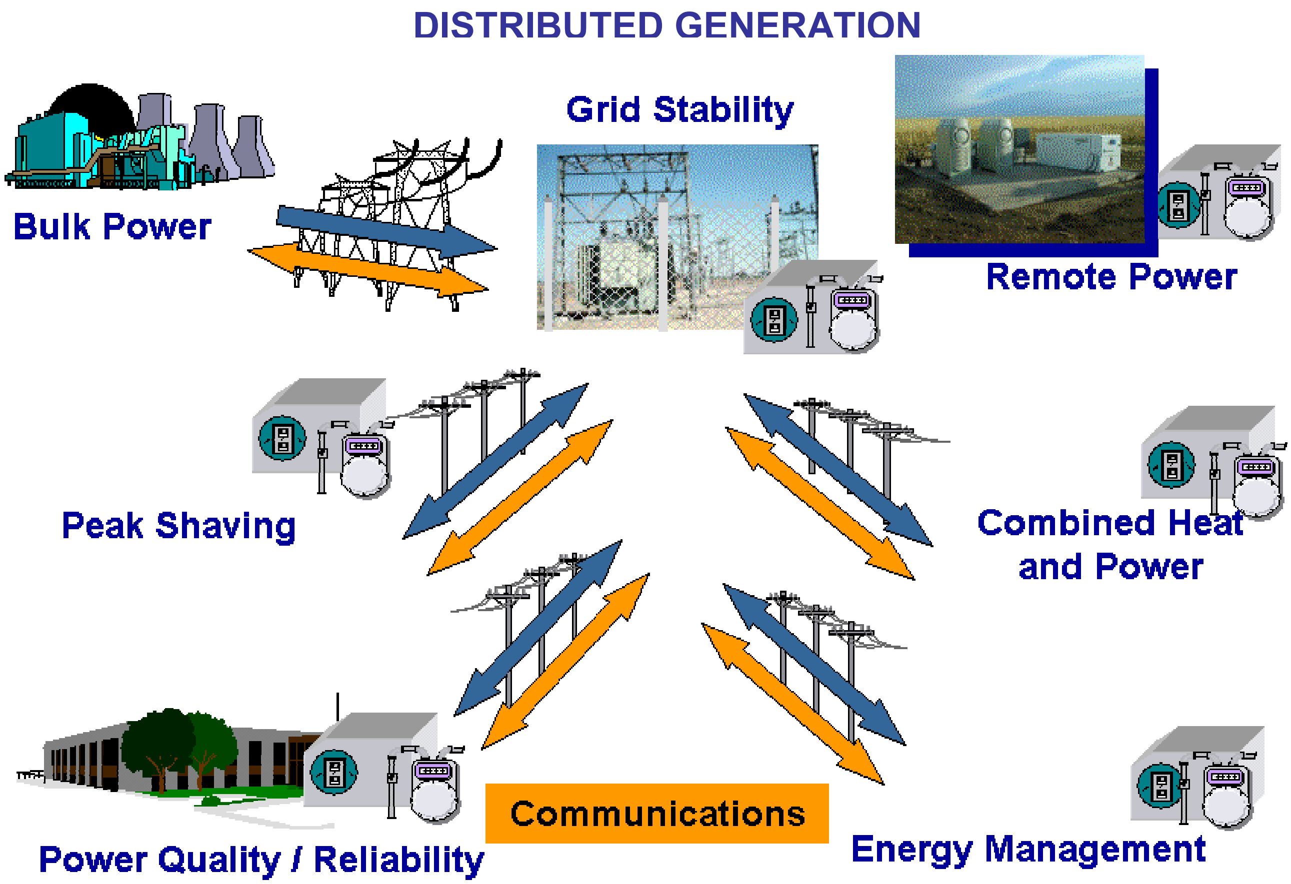
- DOE's *National Transmission Grid Study*, released in May 2002, examined issues surrounding U.S. transmission system upgrades and expansion, and contains 51 recommendations for actions to remove constraints on the U.S. transmission grid.
- Real-time monitoring tools have been developed by DOE and installed in California with funding by the California Energy Commission, and at the North American Electric Reliability Council (NERC) to monitor and display voltage and frequency over wide areas.
- Demand response (DR) projects are assisting independent transmission system operators (ISOs) with DR program design, and identifying DR capabilities to respond to markets for energy and contingency reserves.

Commercialization and Deployment Activities

- Commercial deployment of high-current composite conductors awaits U.S. field trial results, and manufacturing cost reductions for all but high-value niche applications.

1.3.3 DISTRIBUTED GENERATION AND COMBINED HEAT AND POWER

Technology Description



Distributed generation, including combined heat and power (CHP), can be distinguished from central energy resources in several respects. These distributed energy resources are small, modular, and come in a range of capacities from kilowatts to megawatts. They comprise a portfolio of technologies that can be located onsite or nearby the location where the energy is used. They provide the consumer with a greater choice, local control, and more efficient waste utilization to boost efficiency and lower emissions.

System Concepts

- The portfolio of distributed generation technologies includes, for example, photovoltaic systems, fuel cells, natural gas engines, industrial turbines, microturbines, energy-storage devices, wind turbines, and concentrating solar power collectors. These technologies can meet a variety of consumer energy needs including continuous power, backup power, remote power, and peak shaving. They can be installed directly on the consumer's premise or located nearby in district energy systems, power parks, and mini-grids.
- CHP technologies have the potential to take all of the distributed generation technologies one step further in pollution prevention by utilizing the waste heat from the generation of electricity for the making of steam, heating of water, or for the production of cooling energy. The average power plant in the United States converts approximately one-third of the input energy into output electricity and then discards the remaining two-thirds of the energy as waste heat. CHP systems similarly produce electricity, but then capture up to half or more of this waste heat to make steam, heat or cool water, or meet other thermal needs, thus making use of two-thirds or more of the input energy. CHP technologies make greater use of the fuel input by producing multiple products – electricity and reusable thermal energy, reaching efficiency levels of 70% or greater.

System Components

- Advanced industrial turbines and microturbines – combustion turbines are a class of electric-generation devices that produce high temperature, high-pressure gas to induce shaft rotation by impingement of the gas on a series of specially designed blades. Simple cycle efficiencies range from 21% to 40%. Turbines produce high-quality heat and can be used for CHP production. Microturbines are small combustion turbines with outputs of 25-1,000 kW. Microturbines evolved from automotive and truck turbochargers.
- Energy-storage systems – the combination of an energy-storage device (e.g., a battery or a flywheel) and a power-conversion system to connect the storage device with the local grid.
- Concentrating solar power – concentrating solar power systems use suntracking mirrors to reflect and concentrate sunlight into receivers where it is converted to high-temperature thermal energy, which can then be used to drive turbines to generate electricity.
- Fuel cells – power is produced in fuel cells electrochemically by passing a hydrogen-rich fuel over an anode and air over a cathode and separating the two by an electrolyte in producing electricity. The only byproducts are heat, water, and carbon dioxide.
- Natural Gas Engines – the reciprocating engine is widespread and well-known technology. Spark ignition gas-fired units (the focus here) typically use natural gas or propane. Capacities are typically in the 0.5- to 5-megawatt range.
- Photovoltaic Systems – photovoltaic systems use semiconductor-based cells to convert sunlight directly to electricity.
- Hybrid Systems – hybrid systems consist of two or more types of distributed energy technologies.
- Wind Energy Systems – wind turbines convert the kinetic energy of wind into electricity.

Technology Status/Applications

- Industrial gas turbines and natural gas reciprocating engines are existing technologies that are being utilized and have a great deal of potential.
- Microturbines, concentrating solar power, fuel cells, wind energy, photovoltaic systems, and hybrid systems are currently under development.
- CHP is a proven technology, responsible for 8% of U.S. electricity generation. The potential for expanding the use of CHP in the United States is enormous – the Department of Energy and the Environmental Protection Agency have a goal of doubling CHP capacity to 92 GW by 2010.

Current Research, Development, and Demonstration

RD&D Goals

- Near-term goals are to develop next-generation distributed energy technologies and address the institutional regulatory barriers that interfere with siting, permitting, and interconnection of distributed energy. The long-term goal for 2020 is to reduce the cost and emissions and increase the efficiency of distributed energy technologies to achieve 20% of the new electric generation capacity in the United States.

RD&D Challenges

- Provide lower cost and more efficient systems.
- Improve the reliability.
- Solve the institutional and regulatory barriers such as a lack of widely used technical interconnection standards.
- Enhance the implementation of CHP with technologies such as microturbines, fuel cells, gas turbines and reciprocating engines.

RD&D Activities

- Direct and coordinate a diverse portfolio of research development and demonstration investments in distributed natural gas technologies.
- Conduct supporting RD&D and enabling technologies.
- Direct and coordinate a diverse portfolio of RD&D energy generation and delivery systems architecture for distributed energy.
- Coordinate activities with RD&D and renewable energy technologies.

• Conduct system integration, implementation, and outreach activities aimed at addressing infrastructure, institutional, and regulatory needs.
Recent Progress
• DOE's advanced turbine system program has developed an industrial gas turbine with Solar Turbines, Inc., for a 48%-efficient simple-cycle machine. CHP is currently at 50 GW of installed capacity. • Wind energy systems have been installed in various western and eastern United States locations. • Microturbines have achieved more than 10,000 hours of operations and preliminary tests. • The Southern Company recently accepted a SAFT/SatCon LiIon System developed by the DOE ESS program that provided three times the 100kW/1 minute rated performance. Southern agreed to test the battery system at no cost, because it can supplement a distributed energy resource (in this case a microturbine) and provide load-following capability.
Commercialization and Deployment Activities
• Advanced industrial gas turbines in the range of 1 to 50 MW are starting to be deployed. • Natural gas reciprocating engines of 0.5-5 MW with efficiencies of 30%-40% are now being deployed. • The DOE and EPA CHP programs are cooperating to actively promote the use of CHP to add about 46 GW of new CHP capacity by 2010. **Markets** • Distributed generation, including CHP, is currently helping the U.S. economy and has the potential to enhance the electric infrastructure. These technologies could produce more than 100 GW of generated capacity for the U.S. electric system..

1.3.4 ENERGY STORAGE

Technology Description

A 5-MVA battery energy-storage system for power quality and peak shaving.

Advanced storage technologies under active development include processes that are mechanical (flywheels, pneumatic), electrochemical (advanced batteries, reversible fuel cells, hydrogen, ultracapacitors), and purely electrical (superconducting magnetic storage). Energy storage devices are added to the utility grid to improve productivity, increase reliability or defer equipment upgrades. Energy storage devices must be charged and recharged with electricity generated elsewhere. Because the storage efficiency (output compared to input energy) is less than 100%, on a kilowatt-per-kilowatt basis, energy storage does not directly decrease CO_2 production. The exception to this rule is the use of advanced energy storage in conjunction with intermittent renewable energy sources, such as photovoltaics and wind, that produce no direct CO_2. Energy storage allows these intermittent resources to be dispatchable.

Energy-storage devices do positively affect CO_2 production on an industrial output basis by providing high-quality power, maximizing industrial productivity. New battery technologies, including sodium sulfur and flow batteries, significantly improve the energy and power densities for stationary battery storage as compared to traditional flooded lead-acid batteries.

System Concepts

- *Utilities:* The efficiency of a typical steam plant falls from about 38% at peak load to 28%-31% at night. Utilities and customers could store electrical energy at off-peak times, allowing power plants to operate near peak efficiency. The stored energy could be used during high-demand periods displacing low-efficiency peaking generators. CO_2 emissions would be reduced if the efficiency of the energy storage were greater than 85%. Energy storage also can be used to alleviate the pressure on highly loaded components in the grid (transmission lines, transformers, etc.) These components are typically only loaded heavily for a small portion of the day. The storage system is placed downstream from the heavily loaded component. This reduces electrical losses of overloaded systems. Equipment upgrades also are postponed, allowing the most efficient use of capital by utility companies.
- *Industrial:* The operation of modern, computerized manufacturing depends directly on the quality of power the plant receives. Any voltage sag or momentary interruption can trip off a manufacturing line and electronic equipment. Industries that are particularly sensitive are semiconductor manufacturing, plastics and paper manufacturing, electronic retailers, and financial services such as banking, stock brokerages, and credit card-processing centers. If an interruption occurs that disrupts these processes, product is often lost, plant cleanup can be required, equipment can be damaged, and transactions can be lost. Any loss must be made up decreasing the overall efficiency of the operation, thereby increasing the amount of CO_2 production required for each unit of output. Energy-storage value is usually measured economically with the cost of power-quality losses, which is estimated in excess of $1.5 B/year in the United States alone.

Industry is also installing energy-storage systems to purchase relatively cheap off-peak power for use during on-peak times. This use dovetails very nicely with the utilities' interest in minimizing the load on highly loaded sections of the electric grid. Many energy-storage systems offer multiple benefits. (An example is shown in the photo.) This 5-MVA, 3.5-MWh valve-regulated lead-acid battery system is installed at a lead recycling plant in the Los Angeles, California, area. The system provides power-quality protection for the plant's pollution-control equipment, preventing an environmental release in the event of a loss of power. The system carries the critical plant loads while an orderly shutdown occurs. The battery system also in discharged daily during the afternoon peak (and recharged nightly), reducing the plant's energy costs.

Representative Technologies

For utilities, the most mature storage technology is pumped hydro; however, it requires topography with significant differences in elevation, so it's only practical in certain locations. Compressed-air energy storage uses off-peak electricity to force air into underground caverns or dedicated tanks, and releases the air to drive turbines to generate on-peak electricity; this, too, is location specific. Batteries, both conventional and advanced, are commonly used for energy-storage systems. Advanced flowing electrolyte batteries offer the promise of longer lifetimes and easier scalability to large, multi-MW systems. Superconducting magnetic energy storage (SMES) is largely focused on high-power, short-duration applications such as power quality and transmission system stability. Ultracapacitors have very high power density but currently have relatively low total energy capacity and are also applicable for high-power, short-duration applications. Flywheels are now commercially viable in power quality and UPS applications, and emerging for high power, high-energy applications.

Technology Status - Utilities

Technology	Efficiency [%]	Energy density [W-h/kg]	Power density [kW/kg]	Sizes [MW-h]	Comments
Pumped hydro	75	0.27/100 m	low	5,000-20,000	37 existing in U.S.
Compressed gas	70	0	low	250-2,200	1 U.S., 1 German
SMES	90+	0	high	20 MW	high-power applications
Batteries	70–84	30-50	0.2-0.4	17-40	Most common device
Flywheels	90+	15-30	1-3	0.1-20 kWh	US & foreign development
Ultracapacitors	90+	2-10	high	0.1-0.5 kWh	High-power density

System Components

Each energy-storage system consists of four major components: the storage device (battery, flywheel, etc.); a power-conversion system; a control system for the storage system, possibly tied in with a utility SCADA (Supervisory Control And Data Acquisition) system or industrial facility control system; and interconnection hardware connecting the storage system to the grid. All common energy-storage devices are DC devices (battery) or produce a varying output (flywheels) requiring a power conversion system to connect it to the AC grid. The control system must manage the charging and discharging of the system, monitor the state of health of the various components and interface with the local environment at a minimum to receive on/off signals. Interconnection hardware allows for the safe connection between the storage system and the local grid.

Current Research, Development, and Demonstration

RD&D Goals

- Utilities require high reliability, and costs less than or equal to those of new power generation ($400–$600/kW). Compressed gas energy storage can cost as little as $1-$5/kWh, while pumped hydro ranges from $10-$45/kWh. Battery storage systems range from $300-$2000/kW.

RD&D Challenges

- The major hurdles for all storage technologies are cost reduction and developing methods of accurately identifying all the potential value streams from a given installation. Advanced batteries need field experience and manufacturing increases to bring down costs. Flywheels need further development of fail-safe designs and/or lightweight containment. Magnetic bearings could reduce parasitic loads and make flywheels attractive for small uninterruptible power supplies and possibly larger systems using multiple individual units. Ultracapacitor development requires improved large modules to deliver the required larger energies. Advanced higher-power batteries with greater energy storage and longer cycle life are necessary for economic large-scale utility and industrial applications.

RD&D Activities

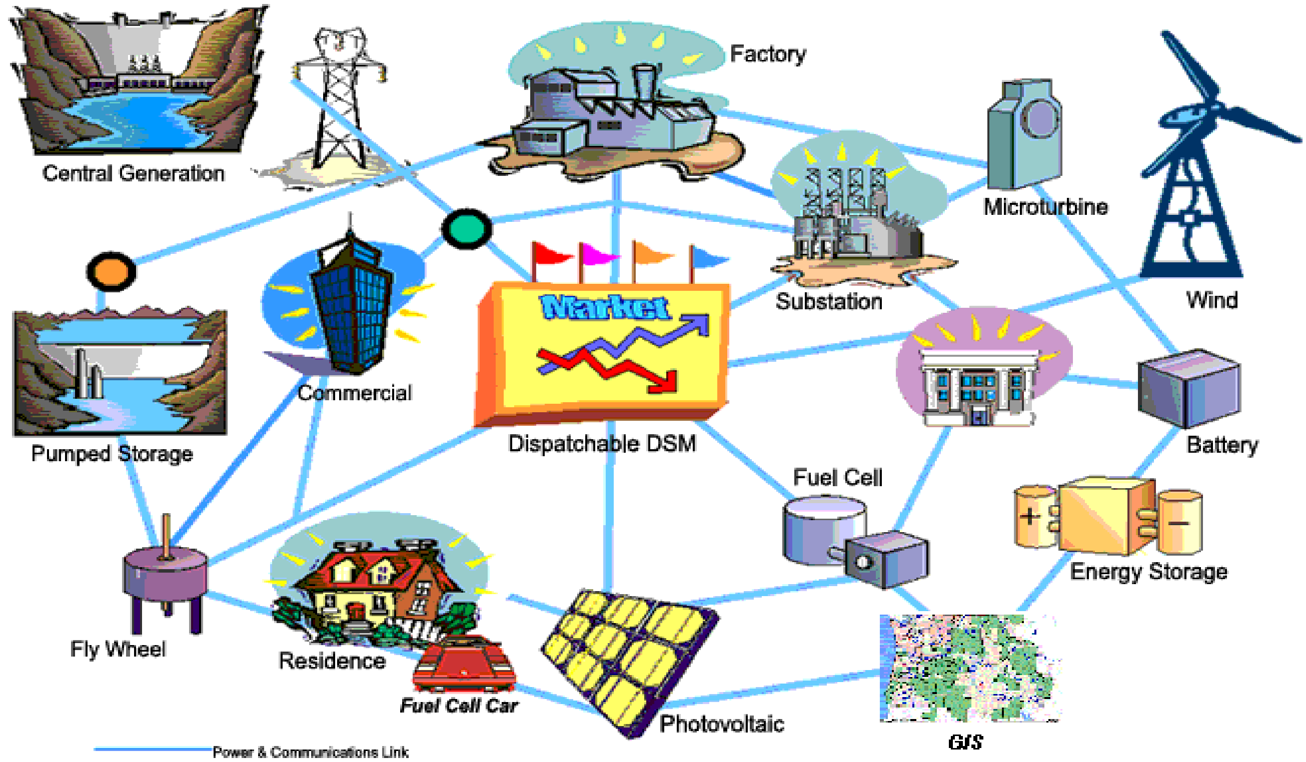
- The Japanese are investing heavily in high-temperature, sodium-sulfur batteries for utility load-leveling applications. They also are pursuing large-scale vanadium reduction-oxidation battery chemistries. The British are developing a utility-scale flow battery system based on sodium bromine/sodium bromide chemistry. DOE's Energy Storage Systems Program works on improved and advanced electrical energy storage for stationary (utility, customer-side, and renewables) applications. It focuses on three areas: system integration using near-term components including field evaluations, advanced component development, and systems analysis. This work is being done in collaboration with a number of universities and industrial partners.

Commercialization and Deployment Activities

- For utilities, only pumped hydro has made a significant penetration with approximately 37 GW.
- Approximately 150 MW of utility peak-shaving batteries are in service in Japan.
- Two 10-MW flow battery systems are under construction – one in the United Kingdom and the other in the United States.
- Megawatt-scale power quality systems are cost effective and entering the marketplace today.

1.3.5 SENSORS, CONTROLS, AND COMMUNICATIONS

Technology Description



Improved sensors and controls, as part of the next-generation electricity transmission and distribution system, could significantly increase the efficiency of electricity generation and delivery, thereby reducing the greenhouse gas emissions intensity associated with the electric grid. Sensors and controls will play a key role in the development of the nation's next-generation electric T&D system. In the grid of the future, distributed energy resources will be fully integrated into grid operations, providing a robust energy infrastructure enhanced by local protection and control measures. The communication and control challenges associated with this evolution are significant. Local system conditions will be sensed, and local intelligent agents will process the data and communicate decision commands to local controllers for problem rectification and performance optimization. These local sensors and distributed software agents will assess adequacy and security with only high-level oversight from the central control authority. Distribution system and transmission grid reliability will be significantly improved by higher levels of local distributed energy generation using power electronics to control and manage two-way power flow as directed by local sensors and intelligent agents.

System Concepts

- In the future, there must be a rapid, widespread measurement and control system that enables distributed energy generation to provide highly reliable services under all disturbance scenarios. Local control of such highly reliable services will improve local power quality and improve the efficiency of the distribution system. This will be done with local sensors and "intelligent agents" that monitor local conditions and provide local responses.
- Conventional utility sensors, while robust and reliable, are quite expensive. Low-cost, reliable and robust sensors must be developed that can monitor current flow, voltage, and phase angle throughout the distribution system. These sensors would provide the intelligent agents with the information they need to make rapid, correct decisions.

Representative Technologies

- Low-cost physical sensors will be used to measure voltage, current, temperature, phase angle, and for other electric distribution and grid system characterization applications.
- The system architecture will be dependent on the ability of intelligent agents to diagnose and forecast local faults. This will involve placing a number of sensors, intelligent agents, and controllers at strategic locations.
- The sensing, communication, and information analysis required for intelligent decision making must happen in real time or near real time (in seconds), sufficiently faster than the time required to affect coordination, control, and protection schemes.
- Communications must take place to advise the central controller of the local system status, perform critical nonrepudiating functions to manage the electricity commerce, and enable real-time markets for energy and ancillary services.

Technology Status/Applications

- The variety of transduction methods and the capability to fabricate small, rugged sensor devices has advanced tremendously during the past five years. Modern techniques for fabricating electronic devices allow unprecedented miniaturization of sensors and electronic controls.
- Rapid analysis of sensor data and feedback control is also advancing, often enabled by microprocessor technology.
- Rapid, low-cost communications methods are also undergoing fast-paced advancement in wireless and fiber-optic technologies.

Current Research, Development, and Demonstration

RD&D Goals

- The first step in the research plan will be to develop computer simulation models of the distribution system to assess the alternative situations. To validate these models, prototype sensors and communication systems, as well as assessment methods for the intelligent agents, will be required. The simulation models will be tested in the laboratory and then in the field. When the models have been validated on a sufficiently large scale, the functional requirements and architecture specifications can be completed, and final technology solutions that conform to the established architecture can be explored.

RD&D Challenges

- A challenge will be the development of cost-effective fault detection and control systems that can be readily implemented in the nation's power grid. The electricity market with an ever-increasing demand for highly reliable services is a key factor in the development of the new control system.
- In response to market communications, distributed energy generation must be capable of supplying the highly reliable services presently provided by large turbine generators, such as spinning reserves, reactive power supply, and voltage and frequency regulation. The entire control scheme is now based on the response of the large generation stations to supply these services. Traditionally, it has been considered to be too difficult to use distributed energy generation to supply these services because there are simply too many units to control reliably and quickly.

RD&D Activities

- Within DOE, sensor and control programs are being developed to focus on issues related to system architecture, distributed intelligence, interconnection technologies and standards, simulation and modeling of the distribution system, load/demand management, and aggregation testing and control of a suite of distributed energy resources.
- Workshops have been held with utilities; energy service companies; and providers of communications, sensor, control, and information technologies to plan strategies and develop roadmaps.

Recent Progress

- A Grid-Friendly™ appliance controller, based on the gate array chip, is being developed to monitor the power grid while controlling on-off operations of household appliances (refrigerators, air conditioners, water heaters, etc.) in response to power grid overload. This device has been tested in a laboratory environment and is ready for installation in the next generation of appliances.

- A wireless end-device controller is being installed at more than 200 facilities in southwest Connecticut, with the goal of controlling 2-3 megawatts of electricity on a real-time dispatchable basis. The controller collects real-time energy-use information and controls end-use loads (lighting, vending machines, etc.) to manage system peak demand.

Commercialization and Deployment Activities

- There are more than 4,200 sensor and control companies in the United States. Commercialization of sensor technology depends on demonstrating economic viability at a level commensurate with the risks small businesses can assume.

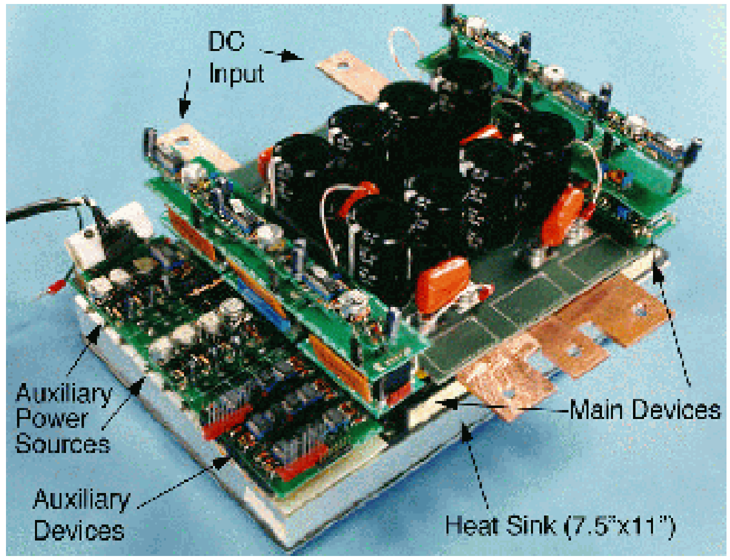
Market Context

- The market for improved sensors and controls cuts across all industrial and transportation sectors. Nuclear, fossil, and end-use efficiency technologies would all benefit.

1.3.6 POWER ELECTRONICS

Technology Description

Improved power electronics, as part of the next-generation electricity T&D system, could significantly increase the efficiency of electricity generation and delivery, thereby reducing the greenhouse gas emissions intensity associated with the electric grid. Power electronics is the technology that is used to provide the interface between different types of electrical power, such as DC and 60-Hz AC. Power electronics equipment transforms frequency, voltage, and power factor. Power levels and voltages from a few kilowatts and 120 volts – all the way up to transmission-level powers and voltages – are now possible with today's technology. Power electronics can enable the simple connection of various types of electrical infrastructure links like distributed energy resources. It can help to regulate voltage in the distribution system and transmission grid, and can solve power-quality and voltage-dip problems. Most important, power electronics can provide for an integrated approach to reliability, where all the components – energy conversion, energy storage, control, and power electronics – work together.



About 60%-70% of the nation's electrical power is used to drive motors and motors are reasonably efficient at their designed or rated speed and load. However, efficiencies can be tremendously improved by operating motors at variable speeds that match the system requirements. Motors driven by power electronics to achieve variable speed capability are increasing dramatically in numbers as the technologies become available. Continued development of power electronic devices with higher power-handling capability and reliability will offer an unprecedented opportunity for U.S. industry and utilities to reduce energy consumption and improve competitiveness.

Power electronic structures have been developed to overcome shortcomings in solid-state switching device ratings so that they can be applied to high-voltage electrical systems. The unique structure of multilevel voltage source power electronics allows them to reach high voltages with low harmonics without the use of transformers. This makes these power electronics suitable for flexible AC transmission systems (FACTS) and custom power applications. The use of power electronics to control the frequency, voltage output (including phase angle), and real and reactive power flow at a DC/AC interface provides significant opportunities in the control of distributed power systems.

As distributed power sources become increasingly prevalent in the near future, power electronics will be able to provide significant advantages in processing power from renewable energy sources using fast response and autonomous control. Additionally, power electronics can control real and reactive power flow from a utility-connected renewable energy source. These power electronic topologies are attractive for continuous control of system dynamic behavior and to reduce problems such as voltage harmonics, voltage imbalance, or sags.

System Concepts

- Advanced inverter topologies: Inverter circuitry that accommodates and takes advantage of advanced solid-state devices while further improving the overall efficiency, packaging, and performance of the inverter.

Representative Technologies

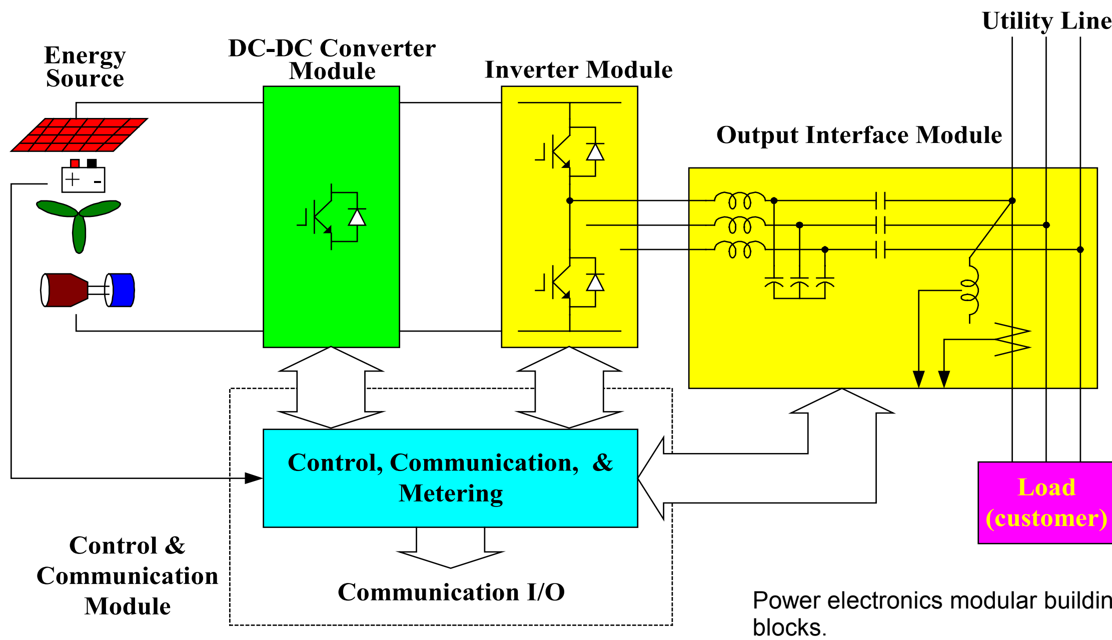
- Soft-switching inverters, multilevel inverters, buck/boost converters, capacitors, magnetic materials, and other materials for improved power electronics.

Technology Status/Applications

- Transportation: Displacement of internal combustion engines and enabling power electronic components for alternate approaches to standard vehicle systems (traction drives, flywheels, auxiliary drives, alternators).

- Industrial: Enabling components for more efficient motors and introduction of adjustable speed drives to match drives to loads for fans, pumps, and compressors.
- Utilities: Power-quality systems, high-voltage DC power transmission systems.
- Renewable energy: Inverters to convert DC power from photovoltaics and wind turbines to AC power.
- Power supplies: Converters embedded in systems to alter the electrical power from one type to another.
- Defense: Grid and equipment interfaces to allow for mobile and emergency backup of transmission and distribution infras.

Current Research, Development, and Demonstration



Power electronics modular building blocks.

RD&D Goals

- Build a power electronic system on a base of modules. Each module or block is a subsystem containing several components, and each one has common power terminals and communication connections. A systems engineer can pick up one module to hook up to the system without knowing much detail of what is inside the module. Each manufacturer can perfect their blocks and work more independently of the other manufacturers once standardized ratings have been determined.
- The figure represents a strategy in which the interface is partitioned into four basic blocks with each one performing a different system function: (1) DC-DC converter; (2) power electronics, (3) output interface and filtering; and (4) control, communication, and metering. Each of the power blocks will have their own control and communication interface such that a group of modules can coordinate their actions to act as an ideal interface to interconnect distributed energy resources to the utility system. Also, with each block having its own control and communication interface, these modules can be combined to form a multilevel configuration as well as other series/parallel connections as necessary to meet the voltage and current requirements for the particular installation. In addition, this approach will allow for future capacity increases, enhancement to functionality, redundancy, and reconfiguration.

RD&D Challenges

- Smaller, lighter, more efficient, and lower-cost inverters.
- Increase reliability and lower cost.
- Improved materials and devices: Solders, capacitors, ferrite semiconductors, low-loss drivers, thermal

management, passive devices, DC disconnects, connectors, and new semiconductor materials such as silicon carbide.

- Increase modularity of power electronic components.
- Present-day power electronics exhibit a number of serious problems and limitations. Some of the most significant of these are (1) the need for difficult-to-meet switching device ratings (and associated reliability issues), (2) the need for transformers (and associated design limitations), (3) high cost, (4) control limitations, (5) limitations on voltages that can be attained, (6) creation of high levels of harmonic distortion.
- USCAR is pursuing the development of electric devices as an enabling technology.
- Developing power electronic building blocks.
- The Federal initiatives in transmission and distribution system long-range R&D were canceled.

RD&D Activities

- The DOE Energy Storage Program supports research in power electronics for megawatt-level inverters, fast semiconductor switches, sensors, and devices for Flexible AC Transmission Systems (FACTS). Projects in these areas recently won two R&D 100 awards.
- Office of Naval Research and DOE have a joint program to develop power electronic building blocks.
- The military is developing more electricity-intensive aircraft, ships, and land vehicles, providing power electronic spin-offs for infrastructure applications.
- The Superconductivity Technology Program funds R&D of more efficient motor technology under the Superconductivity Partnership Initiative.

Recent Progress

- Soft-switching inverter topologies have been recently developed for improved inverter efficiency, reliability, and performance.
- High-power solid-state inverters with improved efficiency and reduced cost and size have been developed.
- A multilevel inverter has been developed, which when deployed will allow 26% more energy to be extracted from photovoltaic or other renewable energy sources.

Commercialization and Deployment Activities

- Major U.S. motor and drive manufacturers are beginning to expand their product lines to include improved power electronics.
- U.S. power semiconductor manufacturers are expanding product lines and facilities to regain market position from foreign competitors.

1.4 INDUSTRY

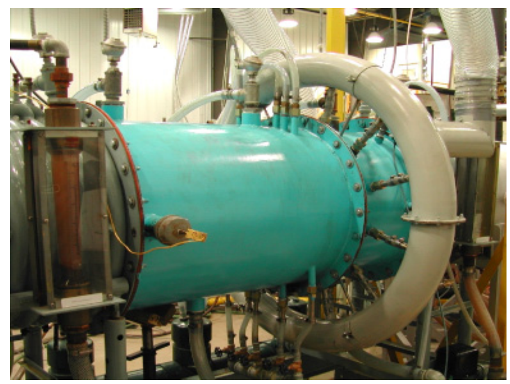
1.4.1 ENERGY CONVERSION AND UTILIZATION

Technology Description

Energy conversion and use account for a large share of carbon emissions from the industrial sector. An integrated systems approach to energy conversion and utilization incorporating the best technologies could significantly reduce greenhouse gas (GHG) emissions and improve industrial competitiveness. Energy utilization gains can be achieved through the increased adoption of existing technology in the areas of combined-cycle power generation and cogeneration of power and heat, referred to as combined cooling, heating, and power (CHP). Many opportunities also exist for improving the efficiency of energy generation, including advanced combustion technologies, fuel cells, gasification technologies, and advanced steam cycles. GHG reductions also can be achieved through increased use of fuels with low or no net GHG products, such as biomass and hydrogen. Opportunities in energy utilization include making economical use of waste heat and minimizing generation of low-level heat.

System Concepts

- The industrial sector could significantly reduce GHG emissions by improving energy utilization efficiency; switching to low-GHG fuels; gasifying waste materials to create useful fuels; and using high-efficiency, distributed generation technologies with low-GHG emissions (such as fuel cells).
- Modern design techniques and an integrated systems approach to mill or plant design could minimize the generation of low-level heat that cannot be used economically.



A revolutionary super boiler now under development should substantially reduce energy use and carbon emissions throughout industry.

Representative Technologies

- Energy conversion technologies include high-efficiency burners and boilers; advanced steam cycles; oxy-fuel combustion, with or without flue gas recirculation; gasification of in-plant process streams and cofiring of biomass with fossil fuels; hydrogen-enriched combustion and fuel cells; and reforming of liquid and gaseous fuels to hydrogen, combined with carbon management. As an example of DOE-supported technology, ITP is working with the Gas Technology Institute and other industry partners to develop a revolutionary super boiler that could save several hundred trillion Btu of energy annually and reduce emissions (see inset).
- Energy utilization technologies include on-site combined heat and power systems and waste heat-recovery systems.
- Advances in heat exchangers and furnace design also will allow for the more efficient utilization of energy.

Technology Status/Applications

- Technologies with higher efficiencies have been demonstrated in several applications, but have not been uniformly adopted by industry.
- Energy-generation technologies currently used by industry typically have thermal efficiencies ranging from 25% to 55%; the next generation of energy-generation technologies promises substantially higher thermal efficiencies, perhaps ranging from 45% to 80%. This efficiency improvement would significantly reduce the amount of fuel required for industrial heat and power, thus reducing GHG emissions. Additionally, aggressive development and deployment of distributed on-site generation technologies could avoid transmission and distribution losses, which average approximately 7%.
- Use of in-plant wastes and residues from production processes to generate energy is a promising area for reducing energy intensity and GHG emissions. RD&D is needed to increase the use and cost-effectiveness of this technology.

Current Research, Development, and Demonstration

RD&D Goals

- Effect an aggressive transition to highly energy-efficient, on-site generation technologies, such as CHP systems, improved boilers and furnaces, and low- or zero-carbon fuels such as natural gas, biomass, or hydrogen to support the overall DOE Industrial Technologies Program goal of contributing to a 30% reduction in the energy intensity (Btu per unit of industrial output as compared to 2002) of energy-intensive industries by 2020. Reductions in energy intensity could significantly reduce industrial GHG emissions.
- By 2006, demonstrate a >95% efficient packaged boiler; by 2010, packaged boilers will be commercially available with thermal efficiencies 10%-12% higher than conventional technology.
- Continue to focus technology development efforts on key energy-intensive industries, which collectively account for three-quarters of energy use by the industrial sector.
- Assist industry efforts to develop advanced glass technologies that will reduce the gap between actual melting energy use (more than 11 million Btu to melt a ton of glass as measured in 1996) and the theoretical minimum (2.5 million Btu per ton) by 50% by 2020.
- Develop technical advances in gasification technology and non-combustion, high-efficiency power generation techniques such as fuel cells (requiring advances in fuel reforming technologies).

RD&D Challenges

- Better understanding of enabling technologies will allow developments of processes and equipment for improved energy recovery.
- Advanced, low- or zero-GHG-emission, power-generation technologies must be made economically competitive.
- Technical advances are required in gasification technology and noncombustion, high-efficiency, power-generation techniques such as fuel cells (requiring advances in fuel-reforming technologies).

RD&D Activities

- DOE is developing and demonstrating advanced, high-efficiency combustion systems, waste heat-utilization technologies, a systems approach to mill or plant design, and gasification technologies.
- RD&D activities related to this pathway are sponsored by DOE, the Environmental Protection Agency, the National Institute of Standards and Technology's Advanced Technology Program, and other Federal agencies. This pathway will work closely with these programs and also leverage past investments.

Recent Progress

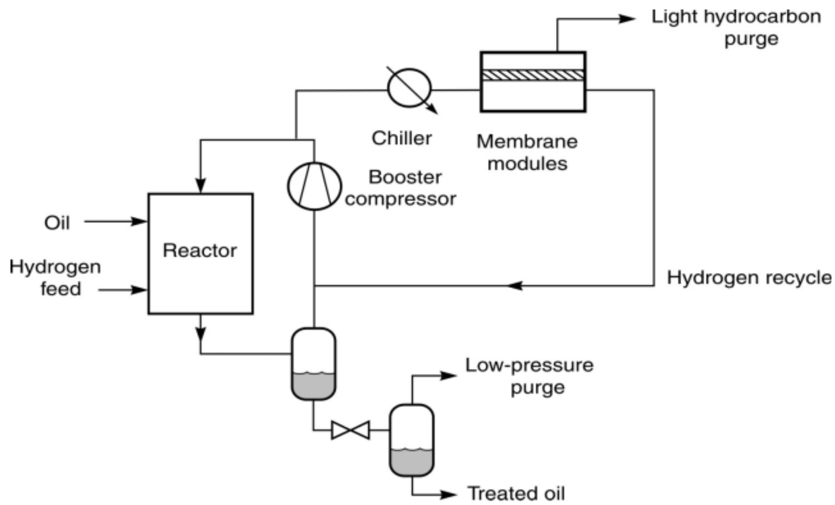
- The forced internal recirculation burner is beneficial to all industries that generate steam from natural gas burners. This new technology combines several techniques to dramatically reduce NO_x and carbon monoxide emissions from natural gas combustion without sacrificing boiler efficiency.
- Waste heat was tapped at two refineries to power absorption refrigeration units. The power generated was used to chill waste fuel streams that contained substantial amounts of propane or heavier hydrocarbons. With chilling, the refineries were able to condense and recover about half of the valuable hydrocarbons in the waste streams for increased profits; and, at the same time, reduce the amount of gas flared off as waste, reducing carbon dioxide emissions to the atmosphere.
- A high-luminosity, low-NO_x burner for oxy-fuel fired glass furnaces was developed to reduce NO_x formation by up to 50% and also increase heat transfer compared to conventional burners. The technology has been demonstrated in both fiberglass and float glass plants.

Commercialization and Deployment Activities
• Industry is already making substantial investments in commercializing and deploying economical technologies: combusting wastes and residues, fuel switching in combustion systems, employing oxy-fuel combustion, and energy cascading from high temperature to lower temperature uses within plants. Availability of capital and competition for R&D and demonstration funds will impact deployment of new technology. Cost competitiveness with existing technologies will be achieved when the newer technologies have completed their R&D cycles.
Market Context
• Markets include all manufacturing industries that use boilers or process heating. In 1998, process heating and boiler fuel accounted for at least 6.8 quads of fossil energy consumption in the manufacturing sector alone. Significant potential exists for additional or more efficient on-site generation of electricity in manufacturing.

1.4.2 RESOURCE RECOVERY AND UTILIZATION

Technology Description

Resource recovery and utilization technologies help minimize waste from industrial processes, reducing energy and material requirements. Wastes include materials, process byproducts, chemical reactants, gases, solvents, diluents, wastepaper, plastics, cooling water, and more. These materials can be reprocessed for use as feedstocks, used to make different products, burned as fuels, or recycled. These practices mitigate greenhouse gas (GHG) emissions by improving plant efficiency and eliminating the energy required to treat wastes and to produce the displaced feedstocks. One example of recovery and reuse is a membrane separation process being developed to recover valuable chemicals from gas streams that are currently burned as low-value fuel. The process will efficiently and economically separate light hydrocarbons (ethane, methane, ethylene, propylene) and hydrogen for use as chemical feedstocks, which are two to three times more valuable than the fuel.



Recovery of olefins such as ethylene and propylene reduces the use of fuel and feedstocks.

System Concepts

- Resource recovery and utilization involves cradle-to-grave stewardship over industrial products. In the example cited, the recovery of feedstock chemicals mitigates CO_2 emissions because it increases product yield and displaces some of the fuel energy initially required to produce the feedstock, which is a petroleum fraction.
- The approximate 30 million tons of ironmaking and steelmaking byproducts generated each year – oxide dusts, sludges, scale, and slags – contain nearly 7 million tons of valuable iron units. Currently, about 50% of this volume is recovered and recycled. Research leading to increased internal recycling of these residues can increase the steel industry's primary yield while reducing disposal costs and saving energy.
- Resource recovery and utilization can involve advanced separations, new chemistries, improved catalysts, advanced materials, optimal process and engineering design, sensors and controls, post-consumer processing, market sensitivity, and close coordination among producers, users, and post-consumer processors.
- This pathway includes technologies that impact the other three industry technology pathways, particularly energy conversion and utilization and industrial process efficiency.

Representative Technologies

- Recovery technologies include advanced separations, new and improved chemistries, sensors and controls, capture of methane (coal beds, landfills, agricultural), and the capture of carbon monoxide and NO_x.
- Reuse technologies include recycling; new and improved chemistries; and closed-loop, sustainable plant design.
- Improved understanding of fundamental chemistry allows use of carbon dioxide and other recovered byproducts as feedstocks. Technologies include C1 chemistry (single carbon) to produce chemicals from carbon dioxide, and chemistries to create fuels from plastics and rubber.
- Component technologies include advanced separations, improved chemistry, improved catalysts, advanced materials, optimal process and engineering design, sensors and controls, and post-consumer

processing. An example of DOE-supported component technology is the recovery of thermoplastics via froth flotation, which enables the recycling of plastics from auto shredder waste.

Technology Status/Applications

- Many industries make a concerted effort to reuse wastes to minimize the high cost of handling and disposal. Others, like the refining and pulp-making industries, rely heavily on byproduct fuels produced on site. However, there are still many opportunities to reuse wastes and byproducts that are not captured because technology does not exist, is currently not economical, or is not practical for other reasons.

Current Research, Development, and Demonstration

RD&D Goals

- R&D goals target a range of improved recycling/recovery efficiencies. For example, in the chemicals industry the goal is to improve recyclability of materials by as much as 30%.
- Identify new and improved processes to use wastes or byproducts; improve separations to capture and recycle materials, byproducts, solvents, and process water; identify new markets for recovered materials, including ash and other residuals such as scrubber sludges.

RD&D Challenges

- Specifically target the energy-intensive U.S. industries and contribute to their goals of reducing energy, water use, and toxic and pollutant dispersion per unit of output.
- Enhance understanding of advanced computing; modeling capabilities for improved process and engineering design; and technology transfer.
- Develop efficient and economical separation processes; demonstrate the viability of new markets; improve sensing and control capabilities; analyze process and engineering design for optimized materials use; and develop durable advanced materials.

RD&D Activities

- Solicitations by the Industries of the Future program and the National Industrial Competitiveness Through Energy, Environment, and Economics program have funded projects to improve energy efficiency and reduce waste; participants include industry, DOE laboratories, small businesses, and academia.
- Ongoing activities include novel techniques for effective separation of materials in industrial streams for recovery and reuse, recycling of water and other liquid and solid-waste streams, recycling of wood byproducts and pulping waste into high-value products, and recycling of problematic wastes such as sludges, refractories, slag, and mill scale.
- DOE is working with CQ Inc. and other partners to improve energy recovery and reduce waste in coal processing. By adding a binding agent into the process, mills can improve the physical characteristics of the coal to create a more acceptable fuel, improve processing efficiency, and reduce environmental impact.

Recent Progress

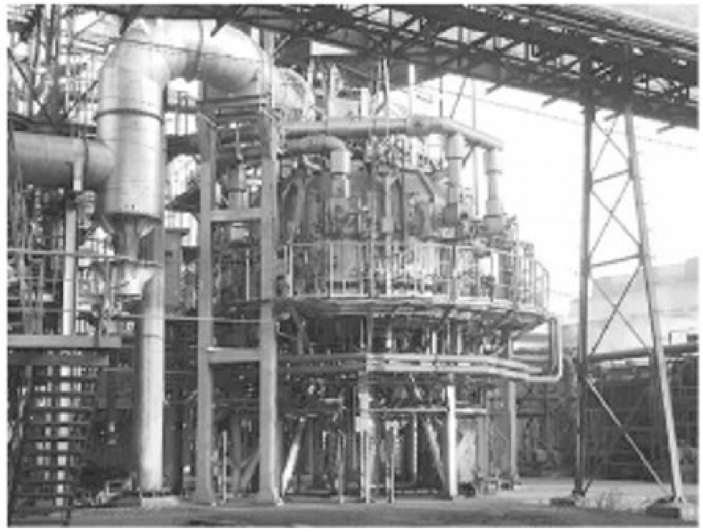
- A new process has been developed to allow the recovery and reuse of caprolactam from waste carpet. Discarded nylon carpets are converted back to virgin-quality caprolactam and used to make new carpets, saving nearly 700,000 barrels of oil annually. The process also saves fuel energy and reduces the amount of carpet that winds up in landfills.
- Researchers have developed a process called froth flotation to cost-effectively separate thermoplastics of various densities without using hazardous chemicals. Recovering and separating various waste plastics can help industries reduce their costs for raw materials, and the process is environmentally sound as it reduces the amount of waste plastic sent to landfills.
- DOE supported development of an energy-efficient process employing pressure swing adsorption refrigeration (PSA) for the recovery of olefins from polyolefin plant vent gases. There already are two commercial applications of the PSA technology. Widespread commercialization could yield a recovery rate of more than 17 million pounds of olefins per year, as well as energy and emission reductions.

Commercialization and Deployment Activities
• Technologies that compete with resource recovery and utilization include waste disposal in landfills, incinerators, and approved hazardous waste-disposal sites. • The economics of resource recovery and utilization technologies are an important factor in deployment. Markets and applications for recovered materials must be well-defined if commercialization is to be successful. **Market Context** • Markets for recovered materials are as diverse as the manufacturing industry and the products it creates. Significant commercial success already has been achieved in various markets, such as the use of recovered post-use steel, aluminum, paper, glass, and plastic. Several new market opportunities are available in these – as well as other – areas and are just now being explored.

1.4.3 INDUSTRIAL PROCESS EFFICIENCY

Technology Description

Industrial process efficiency is affected by a number of factors: technology design, age and sophistication of equipment, materials of construction, mechanical and chemical constraints, inadequate or overly complex designs, and external factors such as operating environment and maintenance and repair practices. In many cases, processes use a lot more energy than the theoretical minimum energy requirement. In the chemical industry, for example, distillation columns operate at efficiencies as low as 20-30%, and require substantially more energy than the theoretical minimum. In this case, thermodynamic and equipment limitations (e.g., height of the column) directly impact efficiency and increase energy use. Technologies under development focus on removing or reducing process inefficiencies, lowering energy consumption for heat and power, and reducing the associated greenhouse gas emissions. One example is a revolutionary steelmaking process that uses a one-step furnace operation to produce high-quality iron, using substantially less energy than conventional processes. The process under development eliminates the need for the coke oven plant, which is a significant source of emissions in steelmaking.



A new one-step furnace operation could revolutionize iron making and substantially reduce energy use and associated emissions.

System Concepts

- Process efficiency is improved by optimizing individual processes, eliminating process steps, or substituting processes within the principal manufacturing steps for primary conversion of raw materials, secondary or value-added processing, and product separation. Optimizing the overall manufacturing chain also improves process efficiency, including the material and energy balance.

Representative Technologies

- Process redesign can eliminate energy-intensive process steps, as demonstrated by the one-step furnace operation under development for ironmaking. Smaller changes to a process can also result in increased process efficiency. For example, DOE is supporting research to modify steel-casting methods that will reduce energy use and produce cleaner, lower-weight castings of improved quality.
- Advanced separation technologies include membrane separation and pressure swing adsorption, where separation is facilitated by novel materials and is energy-efficient.
- Catalysts with higher selectivities enable the conversion of a larger fraction of the feedstock into the desired product rather than the less desirable byproduct. Lower byproduct generation also can positively impact the energy consumption of separation and purification technologies.
- Alternative processes involve developing a new route to the same product and can incorporate advanced separation technologies and new and improved catalysts. An example of this is the process currently under development to convert natural gas to acetic acid using a new biocatalyst.

Technology Status/Applications

- Components of more efficient processing technologies under development (e.g., membranes) are in limited use today, but many need stronger economics or technical viability to increase their attractiveness to industry. The biggest opportunities to reduce GHG emissions in industrial processing will come from introducing revolutionary technologies as replacements for conventional operations. Examples include direct steelmaking and use of membranes as substitutes for energy-intensive distillation separations. Other options include developing new processes that increase product yields, reduce byproducts and wastes, or use alternative manufacturing pathways.

Current Research, Development, and Demonstration

RD&D Goals

- Between 2002 and 2020, contribute to a 30% improvement in energy intensity by the energy-intensive industries through the development and implementation of new and improved processes, materials, and manufacturing practices.
- By 2010, in partnership with industry, assist efforts to implement advanced water-removal technologies in papermaking resulting in an energy efficiency improvement of 10% in paper production compared to conventional industry practices.
- By 2010, develop advanced aluminum production technologies, such as carbothermic reduction, noncarbon inert anodes, and wettable cathodes, for a 25%-30% energy reduction – and, in some cases, elimination of greenhouse gas emissions from primary production.
- By 2010, develop mining technologies that reduce the energy intensity required to crush a short ton of rock by 20%-30% (from 1998 baseline).
- By 2010, in partnership with industry, assist efforts to develop a commercially viable technology that will eliminate the use of energy-intensive coke as a feedstock in the steelmaking process.
- In partnership with industry, assist efforts to enable major technical advances in the metal-casting industry to implement new design techniques and practices, increase yield, and reduce scrap and energy use.
- In partnership with industry, assist efforts to develop separation and new process chemistry technologies that will increase energy efficiency by up to 30% by 2020, compared to conventional 1998 technologies: Develop advanced chemical reactors, including short contact-time reactors, reactors for nonthermal processes (plasma, microwave, photochemical), reactors for alternative media or dry processing, and flexible processing units; improve catalytic processes including selective oxidation, hydrocarbon activation, byproduct and waste minimization, stereo-selective synthesis, functional olefin polymerization, and alkylation.
- Develop advanced separations technology, including membrane separations (advanced inorganic membranes, ruggedized membranes, selective membranes, anti-fouling), reactive separations, and separative reactors for use across various industries (chemicals, refining, pulp and paper).
- In partnership with industry, assist efforts to reduce energy consumption in carburizing processes, heat treatment of castings, welding processes, and aluminum alloy-forging processes.

RD&D Challenges

- Specific R&D needs are unique to each individual industry. In general, R&D challenges include economic and innovative separation techniques, improved understanding and prediction of chemical and material behavior, materials fabrication methods, in situ and/or rapid analytical protocols and process screening procedures, advanced computational tools, and more efficient process design.

RD&D Activities

- RD&D activities relating to these technology areas are sponsored by DOE, the Department of Commerce, the Department of Defense, the National Science Foundation, and the Environmental Protection Agency. DOE has funded projects to improve energy efficiency and reduce waste; participants include industry, DOE laboratories, small businesses, and academia.
- Ongoing activities include development of technology to enable more efficient processes in the following industries: aluminum, chemicals, forest products, glass, steel, metal casting, mining, and supporting industries such as forging, welding, and others. The primary focus of R&D is the development of economic, energy-efficient, commercially viable, and environmentally sound manufacturing technology. Industrial partners are involved with R&D early on to facilitate deployment and commercialization.
- Michigan Technological University is leading a dozen industrial partners in developing a Total Ore Processing Integration and Management System. This novel system will allow mine and mill personnel to

respond rapidly to upstream and downstream changes to optimize the entire mineral processing stream, reducing mill and mine energy use by 10%.

Recent Progress

- Researchers have developed and tested a nozzle that generates a high-temperature, high-momentum oxygen jet, which provides superior mixing and combustion conditions for blast furnace coal injection in steelmaking. This technology enables increased coal injection into the furnace, allowing steelmakers to displace some of the coke typically used in blast furnaces with coal and thus reduce fugitive emissions associated with coke-making.
- A fiber-optic sensor for on-line measurement of paper basis weight has been developed and tested to improve wet-end control in papermaking and produce fine paper with more uniform basis weight. The sensor enables continuous measurements across the full paper sheet and will minimize raw material and energy requirements in the paper industry.
- DOE has supported the development of a portable gas-imaging device for an advanced leak-detection system designed for use in the petroleum and petrochemical industries. The portable gas leak detector reduces the amount of time required for leak surveys, enabling inspections to be performed more frequently than with current detection methods. Gas leaks can be identified and repaired more quickly, reducing emissions.

Commercialization and Deployment Activities

- Applications of many of the described technologies already have an impact in the marketplace. For example, catalytic processes are responsible for about 75% by value of all chemical and petroleum processing products. Catalytic processes generate about $900B in products annually. The ready acceptance of certain applications of these technologies reduces barriers to implementation of process improvements or their application in new processes. Powerful drivers still exist for implementing advancements in these technologies for GHG reduction. The estimated total annual consumption of energy (fuels and electricity) by the U.S. chemical process industries is 5.8 quads; nearly 43% of that (2.5 quads) is required for separation processes, including distillation, extraction, adsorption, crystallization, and membrane-based technologies. Any process facilitating such separations will result in enormous savings of both energy and waste. Given the scale of many relevant industrial processes, the chief barriers to technology deployment are likely to be the capital expenditures required for any substantial process modifications.

Market Context

- The markets for these technologies are industry-specific. Targets of opportunity are the basic industries, including aluminum, chemicals, forest products, glass, mining, steel, and crosscutting industries such as forging, metal-casting, and welding.

1.4.4 ENABLING TECHNOLOGIES FOR INDUSTRIAL PROCESSES

Technology Description

Improvements in the enabling technologies used broadly throughout industry can provide new operational capabilities, as well as significant energy and carbon savings. Greenhouse gases can be reduced by increasing the efficiency of industrial processes, reducing waste and rework of products, and achieving a longer and more controlled operating lifetime for industrial components. Enabling technologies will increase understanding of the processes and systems required to make products, facilitate improvements, and enable new manufacturing processes. The technologies range from advanced materials, sensors and controls systems, and chemical pathways, to systems and product-oriented design and processing that incorporate environmental and energy benefits in their initial and overall implementation. These types of activities will impact the reduction and more efficient use of energy in current and new industrial processes.

System Concepts

- Enabling technologies will complement and be developed cooperatively with other technology pathways, particularly the energy conversion and utilization – as well as the industrial process efficiency – pathways. Enabling technologies will have a positive impact in many industrial areas.
- Increased understanding of processes, development of new materials and control methods, and innovative techniques for fabricating products will impact the entire industrial sector.

Representative Technologies

- Advanced materials with attributes such as improved corrosion resistance and the ability to operate at higher temperatures and pressures enable more efficient industrial processes. Material categories under investigation include degradation-resistant materials, materials for separations, metal alloys, ceramics, composites, polymers, and nano-materials.
- Sensors, controls, and automation enable more robust industrial process operations. Areas of emphasis include real-time, nondestructive sensing and monitoring; wireless technologies; and distributed intelligence to interpret and integrate data from various sensor types to aid in optimizing process control.
- Other enabling technologies with potentially large industrial impacts include new chemical pathways, combinatorial methods, and modeling and simulations.

Technology Status/Applications

- Advances are being made continuously in the development of new materials, including high-temperature materials, new coatings, smart materials, nano-materials, films, and materials with reactive or self-assembly properties. Abundant opportunities remain for developing new materials that can make a significant impact on industrial energy use and emissions (e.g., catalysts, inorganic-organic hybrids, thin film composites, refractories, sensor materials).
- Intelligent controls have been implemented in industry, but are still technically inadequate in a number of areas. Further impacts can be made in global and remote sensing, and nondestructive on-line evaluation of process parameters and equipment.
- New computational techniques are emerging every day, but have yet to keep pace with the phenomenal increase in computing power. Experimental methods based on combinatorial techniques – such as those used in drug discovery – could revolutionize the way new materials and products are developed, but are only slowly being adapted to industrial use.
- The use of model-based control systems and neural networks that can "learn" and improve process/energy efficiency will lower emissions of GHG from manufacturing processes.

Current Research, Development, and Demonstration
RD&D Goals • Develop new enabling technologies that meet a range of cost goals depending on the technologies and on the applications where they are to be used. Cost targets when considered on a system basis are expected to be between 0.5 to 2 times those of typical technologies. • Develop new classes of advanced materials and sensor and automation technologies. • By 2010, in partnership with industry, develop technology necessary for the aluminum industry to move from batch production to a continuous process using new sensor systems, starting with a demonstration of the technology in the aluminum industry. • By 2010, in partnership with industry, develop for commercial adoption 20 new materials for high-temperature, harsh, corrosive, and other industrial environments. **RD&D Challenges** • Develop new, economic material compositions, measurement technologies, and intelligent control and predictive maintenance systems. • Enable increased understanding of chemical, metallurgical, and biotechnology processes. • Develop functional and protective materials for sensors, actuators, and other devices deployed in industrial environments. • Develop materials property/engineering databases for materials used in industrial applications. • Validate mathematical models to enable improved and integrated process design and operations. • Scaling up of technologies from the laboratory to commercial application while achieving anticipated economies of scale, maintaining performance goals, and ensuring component integrity. • Achieving established targets for equipment service life and performance levels to attract industry interest and investment. • Assuring compatibility with real-world manufacturing environment to avoid degrading performance of existing processing and production systems. **RD&D Activities** • Development of industrial system components including high-temperature and corrosion-resistant production systems used for melting, heat treating, or combustion systems; chemicals and pulp- and paper-processing systems; and boilers and gasifiers. • Ongoing R&D activities on enabling technologies include the Advanced Industrial Materials and Sensors and Automation projects in DOE. Additional applied research activities are in the Department of Commerce Advanced Technology Program and in the Environmental Protection Agency. Basic research activities are in DOE's Office of Science and the National Science Foundation (NSF).
Recent Progress
• Nickel aluminides have been commercialized in several applications. For example, in heat-treating operations, nickel aluminides are being used by Delphi Automotive Systems in heating trays and fixtures. Nickel aluminides are also being used in forging dies and steel transfer rolls. • Advances have been achieved in cathodic arc deposition technology; continuous fiber ceramic composite immersion tubes; ceramic composite radiant burner screens; and new bearings for high-performance machinery.

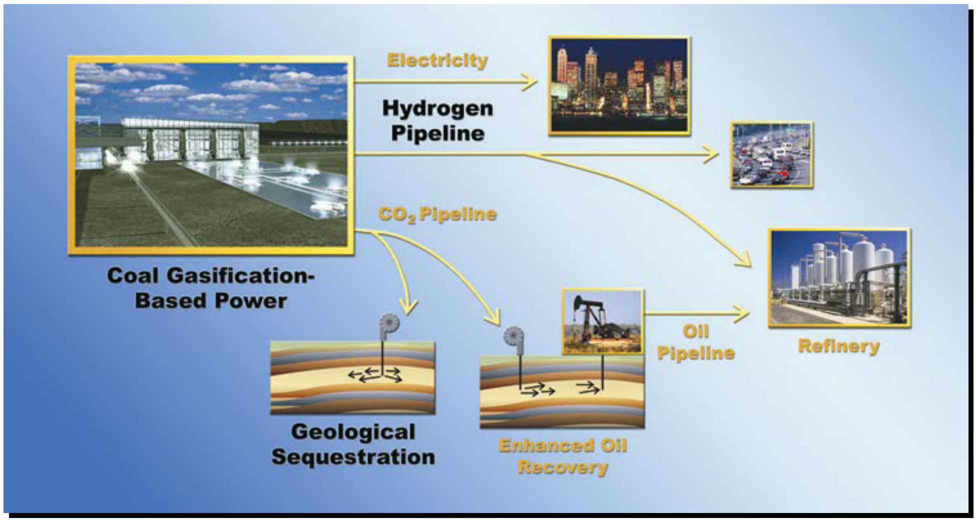
Commercialization and Deployment Activities
• The industrial segment of the economy is substantial, and enabling technologies are impacting every industrial sector. New materials are being introduced in the manufacturing of steel; new measurement systems and in situ temperature measurements in harsh environments have been developed and are being used in industry; understanding of chemicals processes is leading to improved processes; and new capabilities in design and modeling methodologies are reducing the energy use and greenhouse gas emissions of production plants. • The introduction of new technologies is often sensitive to initial cost, and cost benefits must be evaluated based on life-cycle benefits. **Market Context** • Applications for enabling technologies are many and encompass the various industrial segments of the economy. Every industry segment will benefit from the activities, and the efforts will be coordinated with other pathways.

2.0 REDUCING EMISSIONS FROM ENERGY SUPPLY

2.1 LOW EMISSIONS FOSSIL-BASED POWER AND FUELS

2.1.1 ZERO-EMISSION POWER, HYDROGEN, AND OTHER VALUE-ADDED PRODUCTS

Technology Description



FutureGen Power Plant

Coproduction technology focuses on developing plants that coproduce electricity and transportation fuel from fossil or opportunity fuels with very large reductions in CO_2 emissions compared to present technologies. Two approaches may be developed. Both approaches employ synthesis gas generated from natural gas reforming or coal gasification. Carbon emissions are reduced in the near-term approach principally by improving process efficiency (e.g. warm gas cleanup, separation membranes); and in the longer term, via more advanced system components such as high-efficiency fuel cells. In both the near and long term, incorporating CO_2 collection into the process, followed by permanent sequestration will be required to achieve zero emissions.

System Concepts

- Synthesis gas is used from a variety of feedstocks including coal, petroleum coke, biomass, opportunity fuel, and natural gas. For solid feedstocks, the initial processing involves gasification followed by gas cleanup (particulate matter, sulfur, nitrogen compounds). For natural gas feed, the initial step is partial oxidation reforming. All new technologies to be developed for the long-term approach of coproduction will work equally well with solid or gas feedstocks.
- The core approach is to employ water gas shifting of syngas to maximize production of hydrogen and carbon dioxide, which allows carbon capture prior to combustion.
- Nominal carbon capture for the near-term approach (including both net power and fuel production) is 90% of feedstock carbon used for conversion. For the long-term approach, carbon capture will be more than 99%.
- Power production is via combustion turbine/steam turbine combined cycle in the near-term approach. Power production is via solid-state fuel cell combined cycle in the long-term approach.
- The near-term approach accomplishes carbon capture by absorption from shifted syngas into a physical solvent such as Selexol. Use of a physical solvent instead of chemical solvents such as amines yields energy savings in CO_2 recovery.
- The principal fuel product anticipated with the near-term approach is Fischer-Tropsch diesel fuel, a premium fuel or blending stock with ultra-low sulfur and aromatics. The principal fuel product with the long-term approach is high-purity hydrogen.
- The long-term approach will employ ceramic membranes for oxygen separation and for hydrogen separation.

Representative Technologies

- Gasifiers for solid feedstocks.
- Partial oxidation reformers for natural gas feedstock.
- Shift reactors (both approaches).
- Hydrogen-fueled combustion turbines (near-term approach).
- Steam turbines for combined cycle power generation (near-term approach).
- Fischer-Tropsch reactors and product recovery train (near-term approach).
- Physical solvent-based absorption system for CO_2 recovery (near-term approach).
- Cryogenic oxygen separation (near-term approach).
- Ion transport membranes for oxygen separation and ceramic membranes for hydrogen recovery (long-term approach).
- Solid-oxide fuel cells (long-term approach).
- CO_2 compression and drying system (both approaches).

Technology Status/Applications

- The only technology module that needs to be developed for the near-term approach is the hydrogen combustion turbine. Major turbine manufacturers (e.g., GE, Siemens-Westinghouse) have performed design studies on the modifications that would be required on existing combustion turbines. Test results indicate the modifications are technically feasible.
- Absorption of CO_2 in a physical solvent has not been practiced commercially at the large scale that will be required at a central coproduction plant (about 5,000 tpd CO_2 for a 250-MW plant). All aspects of the technology are proven, however, so scale-up should be straightforward.
- Fischer-Tropsch conversion is a commercial process used in South Africa (Arge reactors) to convert both coal- and natural-gas-derived syngas to liquid fuels and chemicals. Fischer-Tropsch conversion is also used commercially by Shell in Malaysia to convert natural gas to diesel fuel, solvents, and wax products. In the United States, liquid-phase synthesis with unshifted coal-derived syngas has been practiced at the LaPorte, Texas, pilot facility, and at the Eastman Chemical Co. Clean Coal Technology demonstration project.
- Ceramic membrane reactor development projects for both oxygen separation and hydrogen recovery are underway with industrial partners as part of the DOE Vision 21 program. The Vision 21 roadmap calls for both technologies to be ready for commercial use by 2015.
- Compression, drying, and transport of CO_2 at supercritical pressures already are practiced in recovery and use of CO_2 from underground sources for tertiary oil recovery.

Current Research, Development, and Demonstration

RD&D Goals

- Ten-year demonstration project (FutureGen) to create the world's first coal-based, zero-emissions electricity and hydrogen power plant. This project will be undertaken with international partners, and power and advanced technology providers to dramatically reduce air pollution and capture and store emissions of greenhouse gases.
- By 2010: Design a near-term coproduction plant configuration at 275-MW size ready for commercial deployment; demonstrate pilot-scale reactors using ceramic membranes for oxygen separation and hydrogen recovery; demonstrate $400/kW solid-oxide fuel cell.
- By 2020: Design a long-term coproduction plant at 275-MW or larger scale.

RD&D Challenges

- Hydrogen combustion turbine design modifications.
- CO_2 absorber demonstration at full scale.
- Plant integration issues for coproduction of Fischer-Tropsch liquids and power.
- Integration of coproduction plant with sequestration site planning.
- Ion transport membranes for oxygen separation.
- Long-term membrane reactor for hydrogen recovery.

- Low-cost solid-oxide fuel cells.
- Plant integration issues for coproduction of hydrogen and power.

RD&D Activities

- Vision 21 ion transport oxygen separation membranes
- Vision 21 hydrogen separation membranes
- Early-entrance coproduction plant designs

Recent Progress

- Air Products' liquefied petroleum methanol pilot plant at LaPorte, Texas, was scaled up to Eastman Chemicals Clean Coal Technology Project.
- Eastman Chemicals Clean Coal Technology Project successfully produced 80,000 gpd of 97% methanol, and was selected for scale-up in Global's early-entrance coproduction plant design study for the Wabash River site.

Commercialization and Deployment Activities

- Early entrance coproduction plant projects begin with a Phase I plant design for eventual commercial scale demonstration in follow-up phases.

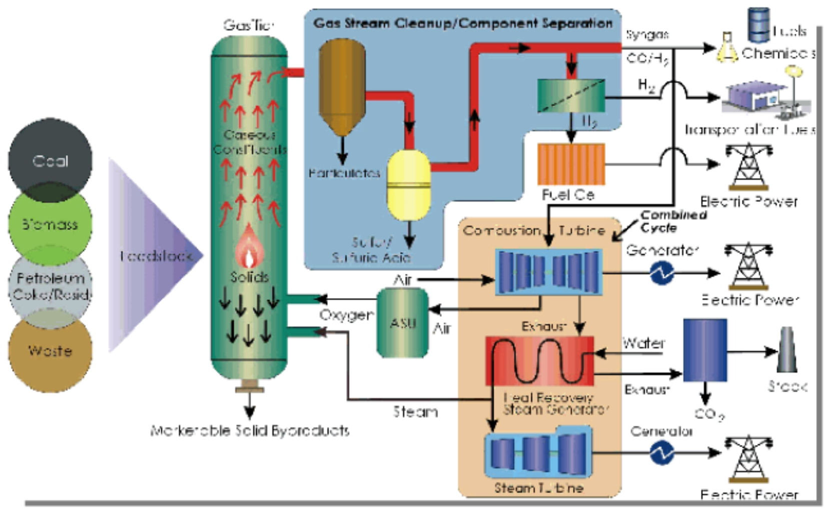
Market Context

- Coproduction plants like those described here address both the power and transportation sectors, providing energy with very large reductions in carbon intensity from large point sources of CO_2 (such as central generating stations) and could become the new world standard for providing environmentally responsible power and transportation.

2.1.2 HIGH-EFFICIENCY COAL/SOLID FEEDSTOCK

Technology Description

Advanced Gasification System



Advanced coal-fired, power-generation technologies can achieve significant reductions in CO_2 emissions while providing a reliable, efficient supply of electricity. Significant improvements in reducing CO_2 have been demonstrated via efficiency improvements and cofiring of coal and biomass. While current power plant efficiencies are about 33%, increasing efficiencies ultimately to 60% or more will reduce CO_2 emissions by more than 50% per unit of electricity. Future development of CO_2 sequestration could reduce carbon emissions to near-zero levels.

System Concepts

- Gasification technology increases the coal power-generation cycle efficiency by combining two or more energy cycles, a high-temperature gas turbine, and a steam turbine. In a typical configuration, the gasifier converts coal into a low- or medium-BTU gas, which is burned in the combustion section of the gas turbine to produce electric power. The exhaust gases from the gas turbine are cooled in the heat-recovery steam generator. The steam is routed to the steam turbine, producing additional electric power. Depending on the quality of the gas produced, the gas also may be used as the feedstock to coproduce a variety of chemicals and fuels. Steam also may be replaced with a more efficient working fluid (e.g., air or long-term binary mixtures).
- Combustion technology, including chemical looping, may use oxygen separation coupled to a coal-fired power plant featuring oxygen combustion, carbon capture, and ultra-supercritical steam-cycle operation.

Representative Technologies

- Vision 21 – the ultra-clean energy plant of the future.
- Integrated gasification combined cycle (IGCC).
- Pressurized fluidized bed combustion.
- Oxygen-combustion systems.
- Unconventional combustion (e.g., use of chemical cycling for CO_2 enrichment).

Technology Status/Applications

- Current IGCC systems based on oxygen-blown, entrained-bed gasifiers are 40%-42% efficient.
- IGCC systems with efficiencies of 40%-45% are scheduled to be available for commercial deployment by 2005.

- Efficiencies of a portfolio of IGCC technologies are expected to average 50% by 2008 and 60% by 2015.
- The cost of electricity for these technologies is expected to be 3¢–4¢/kWh (in 1997$) by 2015.
- Gasifier capital costs are expected to decrease to 90% of current costs as these technologies mature around 2010.
- Supercritical coal-fired technologies without carbon sequestration are available now with efficiencies of 42%.
- Ultra-critical steam cycles using coal-fired technologies with efficiencies in the 45% range are expected by 2010.
- Coal-fired technologies with significant potential for carbon capture are expected by 2015.
- Oxygen-fed, coal-fired power plants with near-zero CO_2 emissions are expected by 2020.

Current Research, Development, and Demonstration

R&D Goals

- Current DOE RD&D program efficiency goals range from 48%-52% in 2008 to more than 60% in 2015 at an electricity cost that is 75%-90% of current pulverized-coal-based generation.
- Emissions of criteria pollutants are targeted to be much less than one-tenth of current new source performance standards.

RD&D Challenges

- Long-term systems need to maintain relatively high temperatures between the combustion/gasification stage and the turbine stage to achieve efficiency goals.
- High-temperature materials that are stable and resistant to corrosion, erosion, and decrepitation are a primary technology development need.
- Long-term materials are needed for heat exchangers, turbine components, particulate filters, and SO_2 removal. Other challenges include the use of alternate working fluids and heat-exchange cycles, CO_2 capture methods, cycle optimization, environmental control technologies with low energy penalties, and solids handling.

RD&D Activities

- The portfolio of high-efficiency coal power systems under development through DOE is comprised of IGCC, pressurized fluidized bed combustion, and Vision 21 plants.
- DOE activities are supplemented by up to 50% cost share from the private sector.
- Current development encompasses a broad range of activities including major efforts by UNDERC, Southern Company Services, and others to develop a new class of gasifiers.
- Four IGCC clean coal demonstration projects are in various stages of completion.

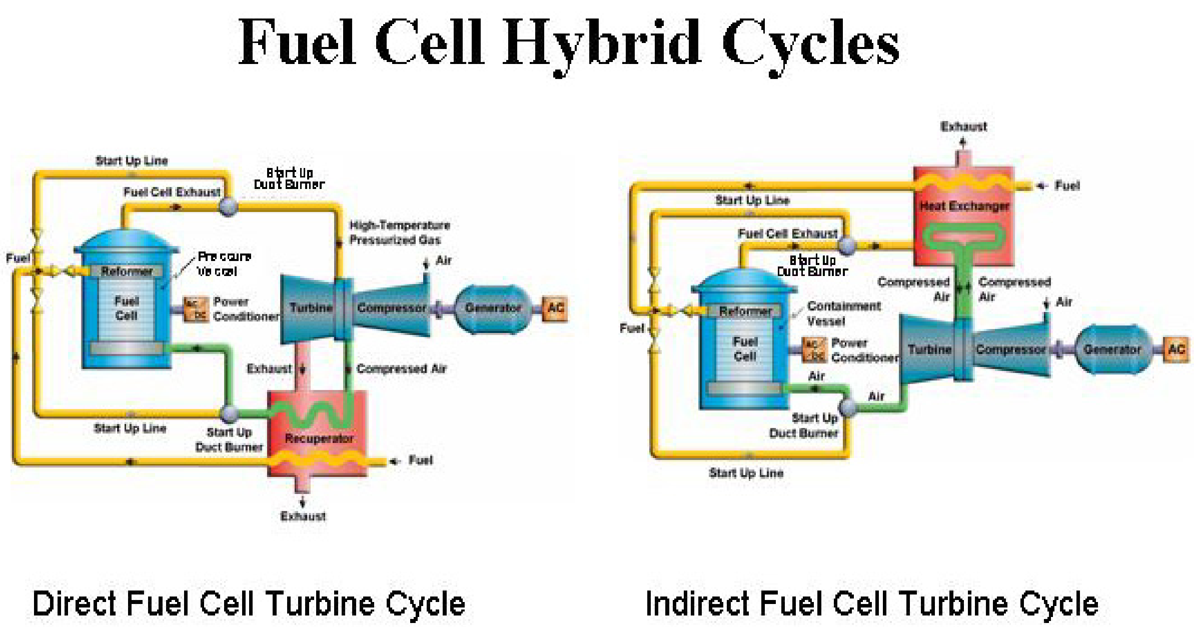
Recent Progress

- In 1996, the IGCC Wabash River project received *Power Magazine's* Power Plant of the Year Award, "a technology to bridge the millennium…to minimize environmental impact and maximize efficiency." As one of 40 projects in the Clean Coal Technology Program, the 260-MW Wabash River repowering project increased the efficiency of an older pulverized coal unit by one-third, to 39% efficiency. Since starting in 1995, Wabash has operated more than 15,000 hours, consuming more than 1.5 Mt of coal to produce more than 4 GWh of electricity.
- In July 1996, the Polk Power Station of Tampa Electric Company began operating their gasifier. Since then, the gasifier has operated more than 25,700 hours to produce more than 7.4 GWh of electricity. During 2000, the Polk Power Stations' gasifier reached its project goal of 80% online availability. The project was presented the 1997 Power Plant Award by *Power Magazine*. Sulfur capture for the project is greater than 98%, while NO_X emissions are 75% less than a conventional pulverized coal-fired power plant.

Commercialization and Deployment Activities
• The gasification technology is under development with several recent proof-of-concept greenfield and repowering installations. Existing plants may be repowered with higher-efficiency coal technologies at or below the price of the natural gas combined-cycle plants. Where natural gas is not available (a considerable portion of the United States and a major portion of the international market) or if gas costs stay above \$4/mmbtu, high-efficiency coal plants will be the lowest-cost choice. • Internationally, where natural gas is not available, the market share for coal is expected to be much higher. **Market Context** • The market for new or repowered capacity from now until 2020 is estimated to be as much as 400 GW in the United States and more than that internationally. Domestically, the primary competition for this technology profile is expected to be natural gas combined cycle.

2.1.3 HIGH-EFFICIENCY GAS FUEL CELL/HYBRID POWER SYSTEMS

Technology Description



The ultimate goal of this technology is to develop systems that use natural gas or hydrogen (from coal, natural gas, or other sources) for highly efficient power generation. This also includes standalone applications of small to medium gas turbine systems, as well as advanced turbine systems for cogeneration application. Near-zero CO_2 emissions could be achieved with the integration of CO_2 capture.

System Concepts

- Hybrid systems that combine fuel cells and gas turbines to create a high-efficiency power module with near-zero emissions for central power or grid support applications.
- High-performance gas turbines that utilize ATS and advanced aircraft technology that use natural gas or hydrogen fuels from coal.
- Unique fuel cell turbine hybrid cycles that incorporate intercoolers, humidified air cycles, and high-pressure ratios to achieve the highest efficiency.
- High-efficiency coproduction (electricity and hydrogen) energy systems, utilizing waste heat for making hydrogen from natural gas.
- Integration in the long term of CO_2 capture technologies with all of the above systems.
- Integration of fuel cells with other heat engines (reciprocating engines, Stirling engines, etc.) to create highly efficient and clean power modules.
- Fuel cell systems, including high- and low-temperature units.

Representative Technologies

- Low- and high-temperature fuel cells.
- Optimized gas turbines with higher-pressure ratios, intercoolers, oil-less bearings.
- Smart control systems.
- Hydrogen separation membranes.
- Natural gas reforming.
- CO_2 capture.
- Membrane separators for air, hydrogen, and CO_2.
- Ultra-high temperature steam turbines.

Technology Status/Applications

- Two different fuel cell turbine hybrid power systems (300 kW) have been designed, built, and operated (Siemens Westinghouse and FuelCell Energy Inc.). Both prototype systems logged more than 3,000 hours of operation each and achieved efficiencies of approximately 52% with near-zero emissions.
- The Solid State Energy Conversion Alliance (SECA) is in the second year of an eight-year program to develop low-cost (< $400 / kW) fuel cell modules for standalone and hybrid applications.
- Micro gas turbines (available now) and certain fuel cell systems are being used now in industrial and residential (limited) applications for both power and heat.
- Proton-exchange membrane, fuel cells are available now.
- Solid oxide fuel cell technology has demonstrated long-term performance (see first bullet above). ATS spin-off technologies are being infused into mature product lines in commercial operation.
- ATS gas turbines are engaged in large-scale demonstration and poised for commercial deployment for retrofitting existing plants, for new central-station technology, and for onsite or distributed power generation.
- High-temperature fuel cells – such as molten carbonate and tubular solid oxide – are engaged in commercial-scale demonstration tests, but not yet competitively on the market.
- Fuel cells and turbines are being integrated and demonstrated at commercial scales.
- Various elements of high-performance cycles need to be developed to integrate long-term CO_2 capture, membrane separation, optimized turbines, low-cost high-performance SECA fuel cells, and ultra-high temperature steam turbines need extensive development.

Current Research, Development, and Demonstration

RD&D Goals

By 2010

- Demonstrate integrated fuel cell and turbine systems achieving efficiencies of 60% on natural gas.
- Reduce the costs of the Solid-state Energy Conversion Alliance fuel cell power system to $400/kW.

By 2020

- Demonstrate integrated fuel cell and turbine systems achieving efficiencies of 60% on coal and 75 % on natural gas.
- Integrate optimized turbine systems into zero-emission power plants.

By 2030

- Demonstrate fuel cell hybrid systems incorporating carbon capture methods that achieve near-zero CO_2 emissions to the environment.

RD&D Challenges

- Low-cost, high-performance materials.
- Compatible fuel cell and micro-gas-turbine components.
- Simpler manufacturing process and materials in fuel cells to lower costs.
- Grid interconnection.
- Reforming technology.
- Fuel cell turbine control system for steady-state and dynamic operation.
- System-specific energy-efficient environmental controls for NO_x.
- Developing new components required by long-term cycles integrating CO_2 capture.

RD&D Activities

- High-temperature fuel cell performance advancement for FCT hybrid application.
- Development of large gas turbines for FCT hybrid application.
- Systems integration and controls for hybrid FCT application.
- Hybrid systems and component demonstration.
- Low-cost fuel cell systems.
- Develop hydrogen separation, transport, and storage.
- Develop methods for CO_2 sequestration and/or capture.

- Develop high-performance materials, catalysts, and processes for reforming methane.
- Develop membranes for separation of air, hydrogen, and CO_2.

Recent Progress

- Siemens-Westinghouse has demonstrated a nominal 300 kW fuel cell turbine direct-cycle hybrid for more than 3,000 hrs. and achieved an electrical efficiency of 53%.
- FuelCell Energy, Inc., (FCE) has demonstrated a nominal 300 kW fuel cell turbine indirect cycle hybrid for more than 6,000 hrs. and achieved an electrical efficiency of 52%. FCE is currently building a fully integrated version of their 300 kW hybrid.
- Siemens-Westinghouse demonstrated a 25-kW solid oxide fuel cell for more than 13,000 hours and a 125-kW unit for more than 14,000 hours.
- The ATS program has resulted in successful design, fabrication, and testing of a gas turbine power system.
- ATS technologies developed for the ATS machine are being infused into mature gas turbine product lines yielding significant savings in fuel and emissions.
- The first commercially sold Advanced Turbine System (ATS) has been deployed by GE to Baglan Bay, U.K. The 400 MW (50 Hz.) 60% efficient unit has passed the commercial acceptance test and met power output and emissions requirements. By the end of 2003, the machine will be commercially deployed.

Commercialization and Deployment Activities

- Fuel cells are becoming viable in niche applications, and increased production rates are expected to lower capital costs.
- More than 200 fuel cell units (mostly 200-kW size) are operating worldwide.
- Currently, there are six industrial teams in the SECA program developing low-cost (< $400/kW) solid oxide fuel cell technology. The SECA program is supported by a significant core technology program to resolve technical issues. Three of the six SECA industry team have shown significant interest in developing fuel cell turbine hybrid products.
- Ballard is the primary developer of proton exchange membrane fuel cells.
- Energy losses and cost are expected to decline with system refinements.
- ATS technologies such as brush seals, coatings, and compressor technology are currently being used in a majority of the latest turbine designs.

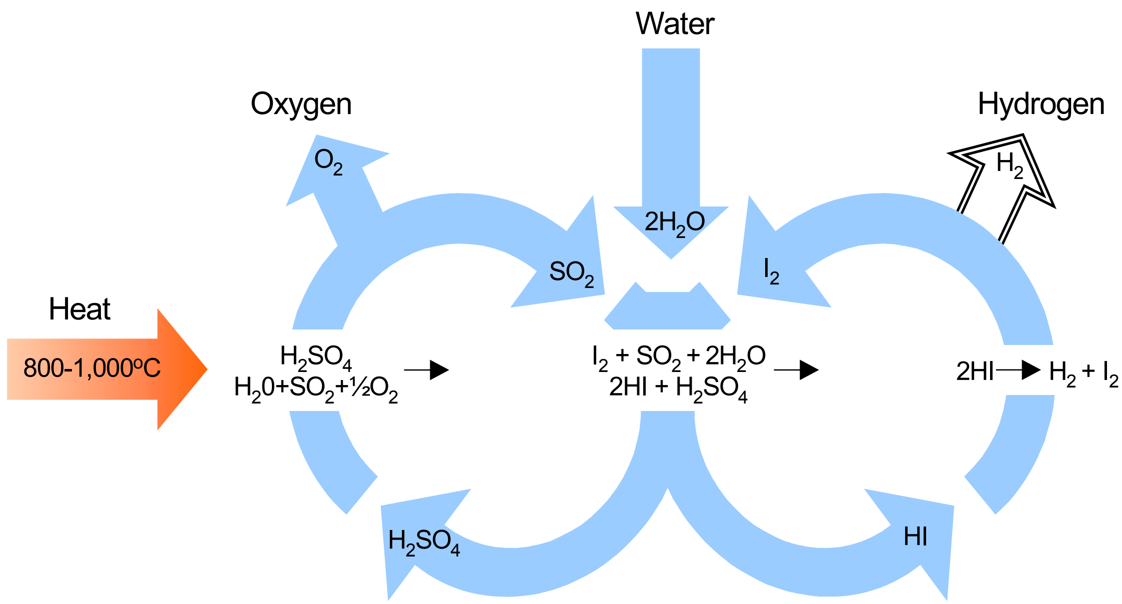
Market Context

- Fuel cell technology would provide power and space conditioning to residential, commercial, and industrial developments.
- Large domestic and international markets, greater than 200 GW both domestically and internationally. Potential applications include retrofitting existing plants and building new central-station capacity.

2.2 HYDROGEN

2.2.1 HYDROGEN PRODUCTION FROM NUCLEAR FISSION AND FUSION

Technology Description



Hydrogen is a carbon-free fuel that can be used in vehicles, homes, businesses, and power plants, and it can serve as a chemical feedstock. When hydrogen is produced from fossil fuels, CO_2 appears as a concentrated byproduct. Advanced nuclear fission and fusion systems can be used to produce hydrogen without generating CO_2. Very high-temperature, high-efficiency nuclear power plants can produce electricity to electrolyze water vapor and supply temperatures sufficiently high to drive chemical cycles for hydrogen production. Implementing these hydrogen technologies will reduce carbon emissions significantly below what is possible with nuclear-generated electricity alone.

System Concepts

- Very high-temperature, high-efficiency nuclear systems are used to drive processes for hydrogen production by electrolysis of water vapor and chemical cycles for water decomposition.
- Solid metallic alloys are used to store hydrogen without high pressurization or liquefaction.

Representative Technologies

- Very high-temperature, high-efficiency gas fission reactor.
- Lead bismuth-cooled or molten-salt-cooled fission reactor.
- Fusion reactor using gas, liquid-metal, or molten-salt cooling.

Technology Status/Applications

- Very high-temperature reactors cooled by gas or molten salts are being developed.
- Fusion technology is in development and making steady progress.
- Gas-cooled reactors operate in Japan at the temperatures of interest.
- Chemical cycles for the decomposition of water to yield hydrogen are being designed.
- Electrolysis of water vapor rather than liquid water is showing economic promise.
- Fuel-cell-powered vehicles using hydrogen are being developed and demonstrated by industry.

Current Research, Development, and Demonstration

RD&D Goals

- Economic hydrogen production without generation of CO_2.
- High-temperature, high-efficiency fission and, when available, fusion power plants to produce electricity to generate hydrogen from water economically.

- High-temperature reactors to drive chemical cycles for hydrogen production.

RD&D Challenges

- Develop reactor designs and materials that operate at temperatures high enough to achieve needed efficiencies.
- Overcome barriers to economic hydrogen generation by electrolysis.
- Develop chemical processes for water decomposition that operate efficiently and reliably.
- Demonstrate production and large-scale storage of hydrogen using a nuclear power plant.

RD&D Activities

- Preconceptual design of gas-cooled and lead-bismuth-cooled reactors and hydrogen production systems are underway as part of the Nuclear Energy Research Initiative.
- Concept development for high-temperature blanket/cooling systems is underway as part of the fusion program.

Recent Progress

- Chemical cycles for hydrogen production are being evaluated, and the conceptual design is being prepared for a gas-cooled reactor to couple to the most promising cycles.
- Japan's gas-cooled, high-temperature test reactor operates at 950°C.
- Recent analyses indicate that, because of low fuel costs, fission systems could provide cost-effective off-peak electricity for electrolysis at either onsite or offsite filling stations.

Commercialization and Deployment Activities

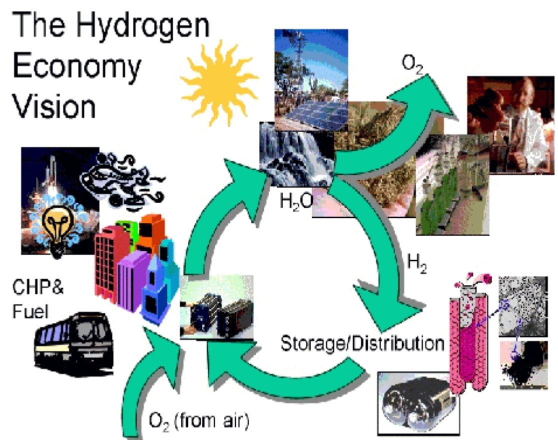
- Very high-temperature, high-efficiency test reactors are being developed in Japan.
- Fuel cell-powered vehicles will create demand for hydrogen in addition to existing demand of the process chemical industry.
- Conceptual design of high-temperature reactors has been initiated as part of the Nuclear Energy Research Initiative. High-temperature operation will make reactors competitive with other methods of electrical power generation.
- Partnering with industry to demonstrate hydrogen production using electricity during off-peak demand periods has been proposed.
- Fusion plants could be commercialized late in the second quarter of this century.

Market Context

- The potential for carbon emissions reductions using these technologies is enormous, including consideration of the GHG reduction from the significant improvements in the efficiency of electrical power generation.
- Hydrogen fuel cell vehicles will create a demand for hydrogen as a transportation fuel in addition to the demand by the process chemical industry. Petroleum industry demand for hydrogen will grow as the use of lower-quality crude oils becomes more common in refining.
- Extends the applicability of large fission energy resources and essentially unlimited fusion energy resources to the transportation sector.

2.2.2 INTEGRATED HYDROGEN ENERGY SYSTEMS

Technology Description



Like electricity, hydrogen can be produced from many sources, including fossil fuels, renewable resources, and nuclear energy. Hydrogen and electricity can be converted from one to the other using electrolyzers (electricity to hydrogen) and fuel cells (hydrogen to electricity). Hydrogen is an effective energy-storage medium, particularly for distributed generation. Implementation of hydrogen energy systems could play a major role in addressing climate challenges and national security issues through 2030 and beyond. Today, hydrogen is produced primarily from natural gas using widely known commercial thermal processes. In the future, it could be produced directly from renewable resources. In the meantime, we can adapt current technologies to produce hydrogen with significantly reduced CO_2 emissions, through carbon capture and sequestration processes, and by using renewable and nuclear electricity to produce hydrogen with no production-side CO_2 emissions. Using hydrogen in combustion devices or fuel cells results in few, if any, harmful emissions.

The vision for a hydrogen economy is based on a clean and simple cycle: separate water into hydrogen and oxygen using renewable energy such as solar. Use the hydrogen to power a fuel cell, where hydrogen and oxygen (from air) recombine to produce electrical energy, heat, and water to complete the cycle. This process produces no particulates, no carbon dioxide, and no pollution.

In the next 20-30 years, hydrogen systems used for stationary and vehicular applications could solve many of our energy and environmental security concerns. Hydrogen is likely to be affordable, safe, domestically produced, and used in all sectors of the economy and in all regions of the country.

System Concepts and Representative Technologies

- A hydrogen system is comprised of production, storage and distribution, and use. Technologies are in various stages of development across the system. Hydrogen made via electrolysis from excess nuclear or renewable energy can be used as a sustainable transportation fuel or stored to meet peak-power demand. It also can be used as a feedstock in chemical processes.
- Hydrogen produced by decarbonization of fossil fuels followed by sequestration of the carbon can enable the continued use of fossil fuels in a clean manner during the transition to the ultimate carbon-free hydrogen energy system.
- For hydrogen to become an important energy carrier – as electricity is now – an infrastructure must be developed. Although the ultimate transition to a hydrogen economy requires significant infrastructure investments, it is possible to develop the components of a hydrogen energy system in parallel with infrastructure. As hydrogen applications become more cost effective and ubiquitous, the infrastructure will also evolve. Beginning with fleets of buses and delivery vans, the transportation infrastructure will evolve to include sufficient refueling islands to enable consumers to consider hydrogen vehicles as attractive and convenient. The development of distributed power systems will begin with natural gas-reformer systems and evolve to provide hydrogen from a variety of resources (for all services), including hydrogen-to-fuel vehicles, reliable/affordable power, lighting, heating, cooling, and other services for buildings and homes.

Technology Status/Applications

- Today, hydrogen is primarily used as a chemical feedstock in the petrochemical, food, electronics, and metallurgical processing industries. Hydrogen is receiving new capital investments for transportation and power-generation applications.
- Nearly half of the worldwide production of hydrogen is via large-scale steam reforming of natural gas, a relatively low-carbon fuel/feedstock. In the United States, almost all of the hydrogen used as a chemical (i.e., for petroleum refining and upgrading, and ammonia production) is produced from natural gas. Today,

we safely use about 90 billion m^3 (3.2 trillion ft^3) of hydrogen yearly. Although comparatively little hydrogen is currently used as fuel or as an energy carrier, there are emerging trends that will drive the future consumption of hydrogen.

- The long-term goal of the DOE Hydrogen, Fuel Cell & Infrastructure Technologies (HFC&IT) Program is to make a transition to a hydrogen-based energy system in which hydrogen will join electricity as a major energy carrier. Furthermore, much of the hydrogen will be derived from domestically plentiful resources, making the hydrogen economy an important foundation for sustainable development and energy security.
- Requirements in California – especially the Los Angeles basin – are propelling the development of zero-emission vehicles, which in turn, provide incentives for the growth of fuel cell cars, trucks, and buses. Several bus fleets are currently incorporating hydrogen and fuel cell technologies into their fleets. Major car manufacturers are developing fuel cell vehicles in response to concerns about greenhouse gas and other emissions, and in response to policy drivers, especially for higher efficiencies and reduced oil consumption.
- Integrating the components of a hydrogen system in a variety of applications enables the continued development of infrastructure that is needed as we move from concept to reality. The development of the components of an integrated hydrogen system has begun:
- *Production*: Hydrogen production from conventional fossil-fuel feedstocks is commercial, and results in significant CO_2 emissions. Large-scale CO_2 sequestration options have not been proven and require R&D. Current commercial electrolyzers are 70%-80% efficient, but the cost of hydrogen is strongly dependent on the cost of the electricity used to split water into hydrogen and oxygen. Production processes using wastes and biomass are under development, with a number of engineering scale-up projects underway. Longer-term, direct hydrogen production processes (photoconversion) are largely in the research stage, with significant progress being made toward development of cost-effective, efficient, clean systems.
- *Storage and Distribution*: Liquid and compressed gas tanks are available and have been demonstrated in a small number of bus and automobile demonstration projects. Lightweight, fiber-wrapped tanks have been developed and tested for higher-pressure hydrogen storage. Experimental metal hydride tanks have been used in automobile demonstrations. Alternative solid-state storage systems using alanates and carbon nanotubes are under development. Current commercial practices for the distribution and delivery of hydrogen – including truck, rail, and barge delivery of liquid or compressed gas – will provide the most cost-effective hydrogen until demand increases and additional infrastructure is developed.
- *Use*: Small demonstrations by domestic and foreign auto and bus companies have been undertaken. Small-scale power systems using fuel cells are being beta-tested. Small fuel cells for battery replacement applications have been developed.

Current Research, Development, and Demonstration

RD&D Goals

- By 2005: (1) develop auxiliary equipment (including sensors) that enable the use of hydrogen as a fuel and energy carrier; (2) investigate material compatibility and durability issues, as well as evaluate network capacity related to distribution of hydrogen; (3) install refuelers in key locations; and (4) adopt codes and standards for hydrogen systems.
- By 2010: (1) define a cost-effective hydrogen delivery infrastructure; (2) verify technologies that reduce the delivery cost of hydrogen for distances less than 200 miles to less than $.70/kg; and (2) verify technologies that reduce the moving and handling cost of hydrogen within the refueling station or power generation facility to less than $.60/kg.
- By 2015: (1) verify technologies to deliver hydrogen from the point of production to the point of use for a cost of less than $1/kg.

RD&D Challenges

- Codes and standards must be developed and implemented; appropriate supporting research and modeling are needed to validate system designs and operating procedures.
- Enabling technologies such as sensors need to be developed and commercialized.
- Infrastructure can be developed step-wise for the near-term, but eventually must be widespread and cost-effective. Thoughtful development schemes are needed to maximize the value of the investment.

RD&D Activities

- DOE's HFC&IT Program is carried out by national laboratories, universities, and the private sector, including CRADA collaborations between industry and the labs, and cost-shared industry-led efforts.
- The overall strategy of the HFC&IT Program is to conduct a comprehensive and balanced program that includes mid- and long-term research and development of hydrogen production, storage, and utilization technologies; integrated systems and technology validation using close collaboration with industry that develops, demonstrates, and deploys critical technologies emerging from research and development; and an analysis element that helps determine the performance and cost targets that technologies must meet to achieve goals of the HFC&IT Program, as well as specific project objectives determined by peer review.

Recent Progress

- A complex integrated demonstration project is operated by SunLine Transit (Thousand Palms, California). The project includes both fossil- and renewable-hydrogen production, compressed gas storage and hydrogen use for transportation (public transit), and stationary power (educational displays). The refueling facility is open to the public and provides pressurized and liquid hydrogen, hydrogen/natural gas blends, and natural gas. The transit fleet includes buses running on hydrogen/natural gas blends and an Xcellsis fuel cell bus.
- A number of hydrogen/fuel cell personal vehicles (modified golf carts) have successfully been operated by Palm Desert (California), in conjunction with the Schatz Energy Research Center/Humboldt State University and with support from the DOE HFC&IT Program.
- Hydrogen refueling equipment (liquid delivered to the facility) – to provide hydrogen to the small fleet of hydrogen fuel cell vehicles that are currently being tested in California – has been installed by the California Fuel Cell Partnership (Sacramento, California).

Commercialization and Deployment Activities

- Major industrial companies are pursuing R&D in fuel cells and hydrogen reformation technologies with a mid-term (5-10 years) timeframe to deploy these technologies for both stationary and vehicular applications. These companies include ExxonMobil, Shell, Texaco, BP, General Motors, Ford, Daimler-Chrysler, Toyota, Honda, United Technology Corporation Fuel Cells, Ballard, Air Products, and Praxair.
- To address the key barrier of perceived safety, the DOE initiated a successful effort to have the International Code Council (ICC) form a special committee to develop provisions specific to hydrogen for incorporation into its model building, fire, and fuel gas codes, which the ICC will publish for adoption by local jurisdictions throughout the United States. The ICC model codes will incorporate standards for hydrogen components and equipment being developed by leading organizations, such as the Society of Automotive Engineers and the International Standards Organization.
- The DOE completed a technology vision and roadmapping effort with industry to develop a framework for public-private partnerships to develop and deploy a national hydrogen infrastructure. The report was unveiled on November 12, 2002, by the Energy Secretary.

2.2.3 HYDROGEN PRODUCTION

Technology Description

Similar to electricity, hydrogen can be produced from many sources, including fossil fuels, renewable resources, and nuclear energy. Today, hydrogen is produced primarily from natural gas using widely known commercial thermal processes. In the future, it could be produced directly from renewable resources. In the meantime, we can adapt current technologies to produce hydrogen with significantly reduced CO_2 emissions, through carbon capture and sequestration – and by using renewable and nuclear electricity to produce hydrogen with no production-side CO_2 emissions.

System Concepts and Representative Technologies

- Feedstock flexibility is an essential and unique feature of hydrogen systems. With only minor modifications to existing and developing technologies, hydrogen can be produced efficiently and cleanly from nearly any resource.
- Hydrogen made via electrolysis from excess nuclear or renewable power can be used as a sustainable transportation fuel or stored to meet peak-power demand. Hydrogen as a storage medium enables intermittent renewable power systems to provide reliable power, even when the wind is not blowing or the sun is not shining.
- Hydrogen produced by decarbonization of fossil fuels (followed by sequestration of the carbon) can enable the continued use of fossil fuels in a clean manner during the transition to the ultimate carbon-free hydrogen energy system.
- Biomass can be used to produce hydrogen and other value-added coproducts such as activated carbon, fuel additives, and adhesives, when it is thermally treated under relatively mild conditions. This is part of the biorefinery concept, wherein chemicals, fuels, and materials are produced from biomass resources in an integrated process.
- Hydrogen separation and purification process improvements offer cost reduction and efficiency improvement opportunities for current fossil-based systems.
- An ultimate hydrogen economy vision features hydrogen production from sunlight and water via photoconversion. Several processes, including semiconductor and biological, are under development to provide clean hydrogen for the hydrogen economy.

Technology Status/Applications

- Nearly half of the worldwide production of hydrogen is via large-scale steam reforming of natural gas (a relatively low-carbon fuel/feedstock). In the United States, almost all of the hydrogen used as a chemical (i.e., for petroleum refining and upgrading, ammonia production) is produced from natural gas. Today, we safely use about 90 billion m^3 (3.2 trillion ft^3) of hydrogen yearly. Although comparatively little hydrogen is currently used as fuel or as an energy carrier, there are emerging trends that will drive the future consumption of hydrogen.
- Hydrogen production from conventional fossil-fuel feedstocks is commercial (on a large scale), but results in significant CO_2 emissions.
- Current commercial electrolyzers are 70%-80% efficient, but the cost of hydrogen is strongly dependent on the cost of electricity.
- Small-scale reformers are under development for use as on-site hydrogen generators at refueling sites or in power parks.
- Biomass (dedicated feedstocks, agricultural and forest residues, and municipal waste) is being evaluated and tested as feeds for multiproduct biorefineries.
- Longer-term, direct hydrogen production processes – such as nuclear-based thermochemical cycles and high-temperature water-splitting, as well as photoconversion (photobiological, photoelectrochemical, and photochemical) water-splitting – are largely in the research stage. Significant progress is being made toward development of cost-effective, efficient, clean systems.

Current Research, Development, and Demonstration

RD&D Goals

Hydrogen production by photovoltaic hydrolysis.

- By 2005: (1) demonstrate small-scale steam methane reformers with a projected cost of \$3.00/kg hydrogen at the pump; (2) develop alternative reactors, including autothermal, ceramic membrane, and microchannel reactors; (3) verify renewable integrated hydrogen production with water electrolysis at a projected capital cost of \$300/kW for 236 kg/day capacity, delivered at 5,000 psi.
- By 2010: (1) demonstrate, at the pilot-scale, membrane separation and reactive/membrane separation technology for cost-effective hydrogen production from coal; (2) demonstrate hydrogen production from natural gas or liquid fuels that project to a cost equivalent to gasoline.
- By 2012: complete design of commercial-scale, nuclear-based hydrogen production system.
- By 2015: (1) demonstrate, at lab-scale, nuclear/thermochemical cycle hydrogen production; (2) demonstrate, at lab-scale, a photoelectrochemical water-splitting system; (3) demonstrate, at lab-scale, a biological system for water-splitting; (4) demonstrate a zero-emission coal plant for power and hydrogen production, with plant-gate hydrogen costs of \$.79/kg.

RD&D Challenges

- Efficient and cost-effective small-scale reformers have not been demonstrated. New design concepts, including alternative catalysts, need to be fully developed and tested. Start-up and system cycling need to be addressed.
- Alternative reactor designs (autothermal, ceramic membrane, and microchannel) show promise for fossil-based production, but need to be tested and optimized before they can be considered for commercial development and operation.
- Electrolyzers operating at higher temperatures could provide more cost-effective hydrogen (higher efficiency/reduced electricity demand). Integration with intermittent renewable resources requires development of control strategies and/or design modifications.
- Engineering challenges need to be addressed in the scale-up and operation of the integrated biorefinery concept at an industrial site, including process control during start-up, shutdown, and upset conditions; process optimization; and integration with existing facilities.
- Hydrogen production via chemical cycles using high-temperature waste heat from nuclear power plants will need to be developed and then demonstrated in alternative facilities before it can be considered for integration near nuclear facilities.
- Photoconversion R&D efforts – including photoelectrochemical, photobiological, and photochemical processes – are presently at the basic research stage. In order to continue advancing these technologies to the applied and engineering stages, research must be supported at universities and national labs.

RD&D Activities

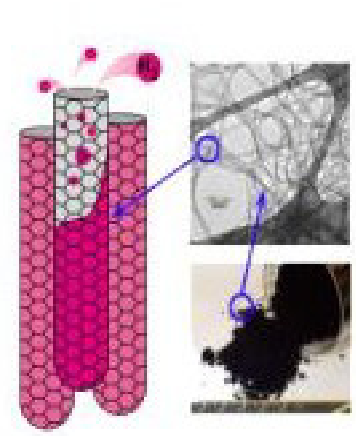
- DOE's HFC&IT Program is carried out by national laboratories, universities, and the private sector, including CRADA collaborations between industry and the national labs, and cost-shared industry-led efforts.
- The overall strategy of the HFC&IT Program is to conduct a comprehensive and balanced program that includes mid- and long-term research and development of hydrogen production, storage, and utilization technologies; integrated systems and technology validation with close industry collaboration that develops, demonstrates, and deploys critical technologies emerging from research and development; and an analysis element that helps to determine the performance and cost targets that technologies must meet to achieve the overall goals of the HFC&IT Program, as well as the specific project objectives determined by peer review.

Recent Progress
• A cooperative project between industry and an Arizona utility demonstrated a fully functional integrated renewable hydrogen utility system for the generation of hydrogen using concentrated solar power. • Intermittent renewable resources (wind and solar) were used to produce hydrogen via electrolysis in a renewable energy fuel cell system in Reno, Nevada. • An industry-led project has developed fueling appliances for small fleets and for home refueling of passenger vehicles. Both types of refueling appliance deliver gaseous hydrogen at up to 5,000 psi to the vehicle. • An autothermal reformer was installed and operated at a transit agency in California to generate hydrogen for buses and other vehicles. Also at this facility, a PV-electrolysis system is operated to provide renewable hydrogen to the same vehicles.
Commercialization and Deployment Activities
• In an industry-university-national lab partnership, agricultural residues are being used to produce hydrogen and valuable coproducts. Peanut shells represent both a waste-disposal issue and a valuable resource. Pyrolysis of the densified shells results in a valuable vapor stream that can be used to produce chemicals and hydrogen, and in a solid stream that is used to make activated carbon. This concept is currently being tested in a pilot plant, in preparation for operation at an industrial site in Georgia. • An industry-led project is installing a small-scale steam methane reformer to provide hydrogen for vehicles in the Las Vegas, Nevada, area.

2.2.4 HYDROGEN STORAGE AND DISTRIBUTION

Technology Description

Unlike electricity, hydrogen can be stored for long periods of time and distributed over long distances without significant losses. Today, hydrogen is stored as a liquid or compressed gas, and distributed by truck, rail, and (to a limited extent) pipeline. In the future, it could be stored in chemical and metal hydrides and carbon nanostructure materials, and distributed via a vast network of pipelines. In the meantime, current technologies can be adapted to store and distribute hydrogen to the emerging transportation and stationary markets for hydrogen.



Carbon nanotube structure and micrographs.

System Concepts and Representative Technologies

- There are five hydrogen storage approaches under development at the present time: high-pressure composite tanks; low-temperature hydrogen storage; pressurized cryotanks; novel carbon structures as storage media; and reversible catalyst-assisted chemical and metal hydrides.
- Solid-state storage may offer increased safety for onboard storage of hydrogen, since tank punctures or ruptures would not result in large energy releases. These systems also require less volume than pressurized or liquid systems. Stationary applications also would benefit from the successful development of these systems.
- Distribution concepts include evaluation of existing natural gas pipelines for material compatibility, utilization of the existing delivery infrastructure to provide hydrogen to emerging markets, and improved auxiliary equipment (compressors, liquefaction equipment, valves, and gauges).

High-pressure, all-composite gaseous hydrogen storage cylinders encourage commercialization of hydrogen gas-powered vehicles.

Technology Status/Applications

- Hydrogen is stored as a liquid at 20 K in insulated dewars or as a compressed gas. Metal hydrides are used in limited stationary applications where weight is not a critical factor and where waste heat is available at the appropriate temperature for hydrogen release.
- Current R&D efforts are focused on improving such factors as weight, volume, cost, and safety.
- Particularly notable are recent advances in storage energy densities, primarily focused on mobile applications. The composite tank development is a prime example of a successful technology partnership among the national labs, DOE, and industry.
- Industrial investment in chemical hydride development has recently been initiated.
- Continued improvements are still required to meet perceived customer demands in vehicular applications, in particular with respect to convenience, safety, and cost.

Current Research, Development, and Demonstration

RD&D Goals

- By 2005: develop storage system with 4.5 wt%, 1,200 watt-hrs/liter energy density, at a cost of $6/kWh of stored energy.

- By 2010: demonstrate storage system with 6 wt%, 1,500 watt-hrs/liter energy density, a range >300 miles, at a cost of $4/kWh of stored energy.

RD&D Challenges

- Fundamental understanding of chemical and metal hydrides and carbon nanotubes as hydrogen storage media is needed to enable the efficient and timely development of storage systems that are inherently safe and more efficient and convenient than current systems.
- Onboard hydrogen storage for transportation applications requires increased storage density, so that the volume of storage on a vehicle can be reduced while providing range equal to that of a conventionally fueled vehicle, without compromising vehicle weight and performance.
- Development of improved low-permeability membrane liners for pressurized storage systems is needed to further improve storage volumes and reduce container weight.
- Research and development of advanced solid-state hydrogen storage systems – including chemical hydrides, metal hydrides such as alanates, and carbon materials – needs to be broadened, with deployment of the resultant systems in prototype vehicles and/or at user sites.
- Production processes for solid-state materials need to be developed and scaled up with industry.
- Compression energy requirements at high storage pressures are significant. Improved hydrogen compressors are needed.
- Improved liquefaction equipment that uses less energy to liquefy hydrogen compared to conventional processes (where 30%-35% of the energy contained in the hydrogen is required) could provide additional storage options for stationary applications.

RD&D Activities

- DOE's HFC&IT Program is carried out by national laboratories, universities, and the private sector, including CRADA collaborations between industry and the labs, and cost-shared industry-led efforts.
- The overall strategy of the HFC&IT Program is to conduct a comprehensive and balanced program that includes mid- and long-term research and development of hydrogen production, storage, and utilization technologies; integrated systems and technology validation with close industry collaboration that develops, demonstrates, and deploys critical technologies emerging from research and development; and an analysis element that helps to determine the performance and cost targets that technologies must meet to achieve the overall goals of the HFC&IT Program, as well as the specific project objectives determined by peer review.

Recent Progress

- High-pressure, composite storage tanks have been developed through the combined efforts of industry, national labs, and universities. These tanks have been tested and certified, and are being used in prototype hydrogen fuel cell vehicles.
- Hydride storage systems have been developed for use in mining vehicles, where the added weight of these storage systems is a benefit (improved traction).
- Sodium borohydride ($NaBH_4$) is being considered for use in fuel cell vehicles as a storage/delivery system for hydrogen.

Commercialization and Deployment Activities

- A novel thermal hydrogen compressor is being developed in an industry-led project. This compressor operates in conjunction with advanced hydrogen production technologies and improves the efficiency and economics of the compression and hydrogen utilization process. The thermal compressor is an absorption-based system that uses the properties of reversible metal hydride alloys to silently and cleanly compress hydrogen; hydrogen is absorbed into an alloy bed at ambient temperature; and, subsequently, is released at elevated pressure when the bed is heated with hot water. Compression energy can be supplied by waste heat or solar hot water.
- An industry-led project is developing metal-hydride storage containers for use on scooters, wheelchairs, and other personal mobility products.

2.2.5 HYDROGEN USE

Technology Description

In the next 20-30 years, solutions for energy and environmental security may be based on the development of hydrogen systems for stationary power and vehicle applications. Hydrogen is likely to be affordable, safe, domestically produced, and used in all sectors of the economy and in all regions of the country.

Fuel cells are an important enabling technology for the Hydrogen Future. Using hydrogen to power a fuel cell – where hydrogen and oxygen (from air) combine to produce electrical energy, heat, and water – produces no particulates, no carbon dioxide, and no pollution. Even in an early transition strategy using fossil fuels, fuel cells can have near-term environmental benefits through higher-efficiency conversion of chemical energy to electrical energy. The high efficiency of the fuel cell compared to conventional conversion devices results in lower emissions of greenhouse gases and overall reduced fossil fuel use. In addition to fuel cells, turbines and internal combustion engines are being developed or modified to run on hydrogen or hydrogen-blended fuels, with reduced emissions. High-value products, such as uninterruptible power supplies and portable power generators, are likely early-entry markets for hydrogen systems. In the longer-term, hydrogen also is expected to be used in airplanes and in ships to provide carbon-free transportation.

The demand for distributed generation that provides reliable, high-quality efficient power is spurring the development of fuel cells that will provide electricity both to the grid and to on-site consumers. These distributed power systems can achieve even higher efficiencies when waste heat is used on-site for space heating or hot-water systems.

System Concepts and Representative Technologies

- Transportation sector: internal combustion engines or fuel cells to power vehicles with electric power trains, with long-term use as an aviation fuel and in marine applications.
- Industrial sector: ammonia production, reductant in metal production, hydrotreating of crude oils, hydrogenation of oils in the food industry, reducing agent in electronics industry, etc.
- Power sector: fuel cells, gas turbines, generators for distributed power generation.
- Buildings sector: combined heat, power, and fuel applications using fuel cells.

Technology Status/Applications

- The emphasis of current RD&D efforts for transportation applications is on the polymer electrolyte membrane (PEM) fuel cell, which offers simplicity, high-power density, and projected system durability. The low operating temperature of PEM fuel cells allows rapid start-up and makes them attractive for transportation applications, where many start-stop cycles are expected. Industrial participation in PEM system development is booming, with all major automobile manufactures and several fuel cell-specific companies investing in development and deployment activities.
- Emission-reduction requirements are propelling the development of zero-emission vehicles – which, in turn, provide incentives for the growth of hydrogen-powered fuel cell cars, trucks, and buses. Several transit bus fleets are currently incorporating hydrogen and fuel cell technologies into their fleets via limited demonstration projects. Major car manufacturers are developing fuel cell vehicles in response to growing concerns about greenhouse gas and other emissions; and in response to policy drivers, especially for higher efficiencies, significantly lower tailpipe emissions, and reduced oil consumption.
- Current R&D on hydrogen-fueled internal combustion engines (ICEs) is reasonably mature. Several auto manufacturers have developed hydrogen ICEs – Daimler (1975), BMW (1990s), Mazda (1991), Ford

(1999); BMW is currently touring with its 740-series, hydrogen-fueled sedan; and hydrogen-natural gas blends are used for light-duty trucks and transit buses.

- The electrical generator is based on developed internal combustion reciprocating engine technology. It is able to operate on many hydrogen-containing fuels. The efficiency and emissions are comparable to fuel cells (50% fuel to electricity conversion efficiency and essentially zero NO_x). This electrical generator is applicable to stationary power and hybrid vehicles. It allows some markets to use hydrogen economically.

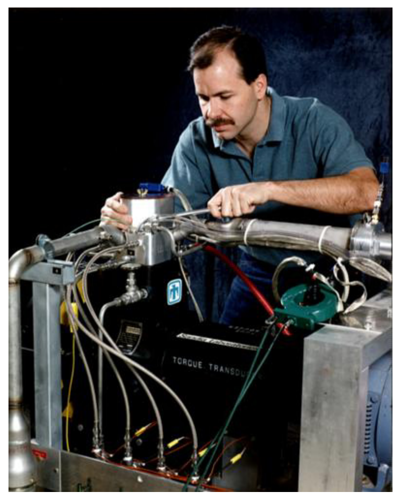
Current Research, Development, and Demonstration

RD&D Goals

- By 2005: (1) demonstrate PEM fuel cells and hydrogen ICEs in a small number of vehicles; (2) demonstrate uninterruptible power supplies and hydrogen applications in power parks.
- By 2010: (1) demonstrate a solid oxide fuel cell with projected capital costs of $400/kW for coal-fueled fuel cell/turbine hybrids; (2) demonstrate hydrogen-fueled PEM fuel cells in automobile application with a 60% peak efficiency, 220 W/liter energy density, 325 W/kg specific power, at a projected cost of $45/kW; (3) demonstrate hydrogen PEM fuel cell vehicles with 2,000 hours of durability at multiple sites.
- By 2015: (1) demonstrate PEM fuel cells for automotive applications at a projected cost of $30/kW; (2) demonstrate a fuel cell/turbine hybrid operating on coal with a system efficiency of 70% with carbon sequestration and capital costs of $400/kW.

RD&D Challenges

- Efforts to reduce costs and improve reliability of high-temperature and reversible fuel cells for stationary applications are needed.
- New high-temperature, anhydrous fast-proton-conducting membranes for use in new high-performance fuel cells need to be further developed. These new nanoengineered glass-ceramic proton conducting membranes are expected to yield high proton conductivities between 100° and 300°C, excellent thermal stability up to 300°C, superior electrochemical and chemical stability, and zero fuel crossover diffusion.
- Increased hydrogen content in natural gas-hydrogen blends needs to be tested in gas turbines to establish hydrogen's impact on reducing NO_x emissions. Development of a detailed understanding of the effect of hydrogen addition to gas turbines (kinetics, fluid dynamics, flame structure) is needed, working with industrial partners to implement hydrogen-natural gas turbines as distributed and centralized generation devices.



RD&D Activities

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Recent Progress

- Air-Breather fuel cells were developed that are exceedingly simple and most effective for small power demands such as pocket-sized portable devices.
- A gasoline ICE scooter was converted to run on hydrogen, with an onboard metal hydride storage system. Because the foreign market for scooters is very large (compared to the U.S. market), this represents a large export opportunity.

• A retrofit strategy for light- and medium-duty vehicles was developed and implemented to convert them to operate on mixtures of hydrogen and natural gas. The vehicles achieve equal vehicle range and reduced exhaust emissions, and are more powerful than the same vehicle operating on natural gas alone.
Commercialization and Deployment Activities
• Major industrial companies are pursuing R&D in fuel cells with a mid-term (5-10 years) timeframe for deployment of these technologies for both stationary and vehicular applications. These companies include General Motors, Ford, Daimler-Chrysler, Toyota, Honda, United Technology Corporation Fuel Cells, Xcellsis, and Ballard. • Several auto manufacturers have developed hydrogen ICEs – Daimler (1975), BMW (1990s), Mazda (1991), Ford (1999); BMW is currently touring with its 740-series hydrogen-fueled sedan; and hydrogen-natural gas blends are used for light-duty trucks and transit buses. • The program has launched a technology vision and roadmapping effort with industry to develop a framework for public-private partnerships to develop and deploy a national hydrogen infrastructure.

2.2.6 HYDROGEN INFRASTRUCTURE SAFETY RESEARCH AND DEVELOPMENT

Technology Description

Like other commodities used as fuels in today's energy and transportation systems, hydrogen is classified as a hazardous material. Direct transport and storage of hydrogen can be achieved via pipelines, compressed gas storage vessels/cylinders, cryogenic vessels, as a hydride, or contained in a nanostructured material. Other commodities, including natural gas and methanol, also can be used as hydrogen carriers that are later reformed. Extensive hydrogen infrastructure is already in place to meet the transport needs of the petrochemical, electronics, and food industries. However, in order to meet the potential future demands for hydrogen and expand its use as a fuel, additional infrastructure and advanced storage and transport methods and technologies will need to be developed and safely, securely, and reliably integrated into the existing transportation and energy infrastructures of the United States.

System Concepts and Representative Technologies

- There are currently three primary methods of hydrogen transport and storage: pipeline, vehicular commodity transport via tube-trailer/pressure vessels and cryogenic vessels, and stationary/fixed storage and fueling infrastructure.
- Within the United States, each of the three primary methods of hydrogen transport and storage is governed by a different set of regulations established by: The U.S. Department of Transportation (DOT)/Research and Special Programs Administration (RSPA) Office of Pipeline Safety, DOT/RSPA Office of Hazardous Materials Safety, and local and state fire marshals.
- The current system for transporting natural gas and hydrogen provides a reasonable foundation and model for expanding the hydrogen infrastructure. However, the current paradigm, with the exception of motor fuels and natural gas, is for hazardous materials (HAZMAT) transport to divert or restrict the transport of these materials into urban areas and through tunnels and other vulnerable transportation infrastructure.
- Current technologies include: small diameter hydrogen pipelines; DOT-approved pressure vessels and cylinders; DOT-approved cryogenic vessels; and, for stationary applications, pressure vessels complying with the American Society of Mechanical Engineers (ASME) boiler and pressure vessel code.
- New technologies developed or being proposed include very high-pressure (13,000-15,000 psi), all-composite pressure vessels meeting both DOT and ASME requirements; advanced pipeline materials that reduce and/or catalyze permeated or leaked hydrogen; hydrides; below-ground cryogenic vessels; and nanostructured materials.
- These new technologies may be additions to or replace current transportation infrastructure, or may be integrated into the existing infrastructure.

Technology Status/Applications

- Hydrogen has been transported and stored within the United States safely, securely, and reliably, for several decades using the current conventional (under 4,500 psi) technologies.
- New technologies to increase the efficiency and reduce the cost of hydrogen transport, such as advanced carbon composite cylinders and storage, are being adapted. New technologies are being reviewed and evaluated within the framework of the appropriate and necessary Federal regulations and other codes and standards. To date, many of the technologies have not met the burden of proof to demonstrate that they can meet the necessary safety requirements for transporting hydrogen in commerce.
- Other technologies, such as carbon nanotubes and advanced pipeline materials, are still in an early research and development (R&D) phase and are not ready for commercialization.
- The DOT/RSPA Office of Hazardous Materials Safety is currently reviewing applications for exemption for several technologies, including hydrides and high-pressure composite cylinder mobile fuelers, and is working with industry and the Department of Energy (DOE) to help guide safe and successful development and deployment of these technologies.

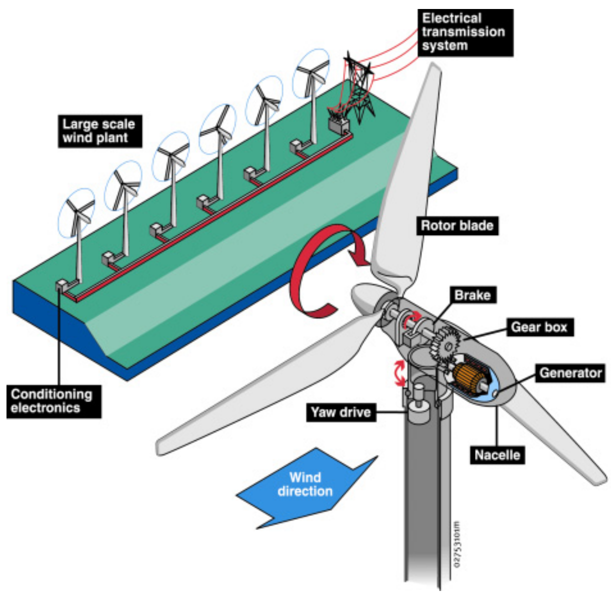
Current Research, Development, and Demonstration
RD&D Goals • Work within the Federal government and with industry to develop, test, and approve new storage and monitoring technologies. • Continue to use the exemption and regulatory development process to keep pace with the emerging technologies and applications. • Conduct a thorough and comprehensive transportation and storage infrastructure assessment to address capacity, safety, security, reliability, operations, and environmental compliance evaluating all conceived scenarios for near-term and long-term development and implementation of hydrogen infrastructure. • Conduct risk analysis for each technology and application. • Collect data on the safety, security, reliability, and operation of new technologies and systems to guide regulatory development and future deployment. • Develop a future system that offers improved safety, security, reliability, and functionality vs. the current transportation and storage systems. **RD&D Challenges** • Gain a fundamental understanding of fatigue and failure modes of advanced composites and other storage media. • Establish effective monitoring, inspection, and recertification technologies and procedures for hydrogen transport and storage. • Adapt aging infrastructure to accommodate new demands. • Educate and train operators, regulators, and users effectively. **RD&D Activities** • The Operating Administrations of DOT, specifically RSPA and the National Highway Traffic Safety Administration (NHTSA), are actively engaged in domestic and international consensus codes and standards development. • DOT staff are supporting DOE R&D activities and committees, and the activities and committees of the various consensus codes- and standards-setting organizations. • DOT staff continues to work with the National Association of State Fire Marshals to educate and train personnel and to promote safe handling and storage practices.
Recent Progress
• DOT/RSPA Office of Hazardous Materials Safety has recently approved an exemption for hydride storage of hydrogen. • In conjunction with DOE, progress is being made in the development and revision of consensus codes and standards.

2.3 RENEWABLE ENERGY AND FUELS

2.3.1 WIND ENERGY

Technology Description

Wind turbine technology converts the kinetic energy in wind to electricity. Grid-connected wind power reduces greenhouse gas emissions by displacing the need for natural gas- and coal-fired generation. Village and off-grid applications are important for displacing diesel generation and for improving quality of life, especially in developing countries.



System Concepts

- Most modern wind turbines operate using aerodynamic lift generated by airfoil-type blades, yielding much higher efficiency than traditional windmills that relied on wind "pushing" the blades. Lifting forces spin the blades, driving a generator that produces electric power in proportion to wind speed. Turbines either rotate at constant speed and directly link to the grid, or at variable speed for better performance, using a power electronics system for grid connection. Utility-scale turbines for wind plants range in size up to several megawatts, and smaller turbines (under 100 kilowatts) serve a range of distributed, remote, and standalone power applications.

Representative Technologies

- Two machine configurations are commonly used today. Three-bladed wind turbines are operated "upwind" of the tower, with the blades facing into the wind. The other common wind turbine type is the two-bladed, downwind turbine. To improve the cost-effectiveness of wind turbines, technology advances are being made for rotors and controls, drive trains, towers, manufacturing methods, and site-tailored designs.

Technology Status/Applications

- Thirty-seven states have land area with good winds (13 mph annual average at 10 m height, wind Class 4, or better). By the end of 2003, 19 states are expected to have more than 20 megawatts (MW) in operation, and wind energy installations across the United States are expected to approach 6,000 MW.
- Current performance is characterized by levelized costs of 4-6¢/kWh (depending on resource quality and financing terms), capacity factors of 30-40%, availability of 95-98%, total installed costs of $800-$1,000/kW, and efficiencies of 65-75% of theoretical (Betz limit) maximum.

Current Research, Development, and Demonstration

RD&D Goals

- Wind-farm cost/performance varies by wind resource class, ownership type, and time. Current costs range from 4¢-6¢/kWh.
- By 2004: 3¢/kWh at sites with annual average wind speeds of 16 mph (wind Class 6).
- By 2012: 3¢/kWh at sites with average wind speeds of 13 mph (wind Class 4).

RD&D Challenges

- Developing wind technology that will be economically competitive at low (13 mph) wind-speed sites requires optimizing increasingly large turbine designs for 30-year life in a fatigue-driven environment with minimal or no component replacements, requiring improved knowledge of wind inflow, aerodynamics, structural dynamics and materials, and optimal control of turbines and wind farms.
- Developing information and strategies to facilitate and optimize integration of wind power into electric grid systems.

- Develop offshore wind technology to take advantage of the immense wind resources in shallow and deep waters of U.S. coastal areas and the Great Lakes near large energy markets.
- Conduct analysis and R&D to explore the role of wind power in the production of hydrogen, in both large-scale and distributed systems.

RD&D Activities

- Core and university research: wind characteristics and forecasting, aerodynamics, structural dynamics and fatigue, and control systems for turbines and wind farms.
- Turbine research: cost-shared design and testing of next-generation utility-grade technology for low wind-speed sites, performance verification of new prototypes, development of advanced small turbines for distributed power applications, and component and system testing at the National Wind Technology Center (NWTC).
- Cooperative research and testing: collection of wind turbine-performance data, power-systems integration, resource assessment, industry technical support, participation in international standards development, wind turbine-certification assistance, and regionally targeted outreach.

Recent Progress

- In 1989, the wind program set a goal of 5¢/kWh by 1995 and 4¢/kWh by 2000 for sites with average wind speeds of 16 mph. The program and the wind industry met the goals as part of dramatic cost reductions from 25¢-50¢/kWh in the early 1980s to 4¢-6¢/kWh today.
- Wind power is the world's fastest-growing energy source. The worldwide wind market continues to grow at an annual rate above 30% with new markets opening in many developing countries. During 2002, more than 7,000 MW of new capacity was added to the electricity grid in the world.
- Domestic public interest in environmentally responsible electric generation technology is reflected by new state energy policies and in the success of "green marketing" of wind power throughout the country. U.S. wind energy installations have grown at an average rate of 24.5% during the past five years.
- The National Wind Technology Center (operated by the National Renewable Energy Laboratory in Golden, Colorado) is recognized as a world-class center for wind energy R&D and has many facilities – such as blade structural test stands and a large dynamometer – not otherwise available to the domestic industry or its overseas competitors.

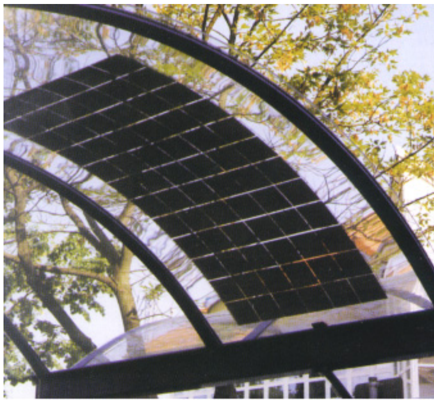
Commercialization and Deployment Activities

- Installed wind capacity expanded by nearly 10% in the United States during 2002 to 4,685 MW, with 410 MW of new equipment going into service. California has the greatest capacity, followed by Texas, Iowa, Minnesota, Washington, Oregon, Wyoming, and Kansas. Worldwide, more than 31,000 MW are installed, and large growth rates illustrate the industry's ability to rapidly increase production with the proper market incentives.
- Wind technology is competitive today in bulk power markets with support from the production tax credit – and in high-value niche applications or markets that recognize noncost attributes. Its competitiveness by 2005 will be affected by policies regarding ancillary services and transmission and distribution regulations. Substantial cost reductions are expected for wind turbines designed to operate economically in low wind-speed sites, which will increase the resource areas available for wind development by 20-fold and move wind generation five times closer to major load centers.

- The principal markets for wind energy are substitution for new natural gas combined-cycle plants (expected to be 97 GW in 2010 and 696 GW in 2030) or displacement of fuel from existing plants, and replacement of coal-generated power plants (expected to be 315 GW in 2010 and 328 GW in 2030).
- Utility restructuring is a critical challenge to increased deployment in the near term because it emphasizes short-term, low-capital-cost alternatives and lacks public policy to support deployment of sustainable technologies such as wind energy.
- In the United States, the wind industry is thinly capitalized, except for General Electric Wind Energy, which recently acquired wind technology and manufacturing assets in April 2002. About six manufacturers and six to 10 developers characterize the U.S. industry.
- In Europe, there are about 12 turbine manufacturers and about 20 to 30 project developers. European manufacturers have established North American manufacturing facilities and are actively participating in the U.S. market.
- Initial lower levels of wind deployment (up to 15%-20% of the total U.S. electric system capacity) are not expected to introduce significant grid reliability issues. Since wind blows intermittently, intensive use of this technology at larger penetrations may require modification to system operations or ancillary services. Transmission infrastructure upgrades and expansion will be required for large penetrations of wind energy to service major load centers.
- Small wind turbine sales are increasing dramatically as a direct result of state incentive programs. California, for example, implemented a rebate of up to $4,500 for the purchase of a wind turbine rated at less than 10 kW. As a result, one small wind turbine manufacturer sold more than 10,000 of their 400 watt and 1,000 watt turbines in 2001 and 2002. About half were sold domestically and half exported. Another manufacturer, whose sales increased 30% in 2002, now has machines ranging from 1 to 10 kW operating in all 50 states and in more than 90 countries.

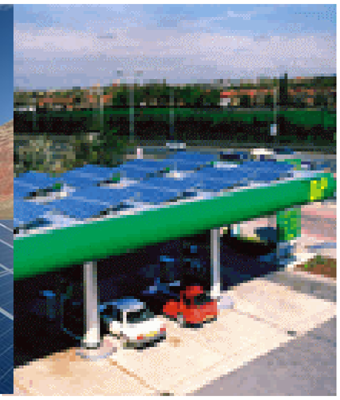
2.3.2 SOLAR PHOTOVOLTAIC POWER

Technology Description



Semi-transparent PV canopy

PV solar arrays for larger-scale electricity.



PV panels on rooftop.

Solar photovoltaic (PV) arrays convert sunlight to electricity without moving parts and without producing fuel wastes, air pollution, or greenhouse gases. Using solar PV for electricity – and eventually using solar PV for transportation in electric vehicles or by producing hydrogen from water – will help reduce carbon dioxide emissions worldwide.

System Concepts

- Flat-plate PV arrays use global sunlight; concentrators use direct sunlight. Modules are mounted on a stationary array or on single- or dual-axis sun trackers. Arrays can be ground-mounted or on all types of buildings and structures (e.g., see semi-transparent solar canopy, right). The DC output from PV can be conditioned into grid-quality AC electricity, or DC can be used to charge batteries or to split water to produce hydrogen.
- PV systems are expected to be used in the United States for residential and commercial buildings, peak power shaving, and intermediate daytime load following. With energy storage, PV can provide dispatchable electricity and/or produce hydrogen.
- Almost all locations in the United States and worldwide have enough sunlight for PV. For example, U.S. sunlight in the contiguous states varies by only about 25% from an average in Kansas. Land area is not a problem for PV. Not only can PV be more easily sited in a distributed fashion than almost all alternatives (for example, on roofs or above parking lots), a PV-generating station 140 km by 140 km sited at a high solar location in the United States (such as the desert Southwest) could generate all of the electricity needed in the country (2.5×10^6 GWh/year, assuming a system efficiency of 10% and an area packing factor of 50% to avoid self-shading).

Representative Technologies and Status

- Wafers of single-crystal or polycrystalline silicon – best cells: 25% efficiency; commercial modules: 13%-17%. Silicon modules dominate the PV market and currently cost about \$2/W_p to manufacture.
- Thin-film semiconductors (e.g., amorphous silicon, copper indium diselenide, cadmium telluride, and dye-sensitized cells) – best cells: 12%-19%; commercial modules: 5%-11%. A new generation of thin-film PV modules is going through the high-risk transition to first-time and large-scale manufacturing. If successful, market share could increase rapidly.
- High-efficiency, single-crystal silicon and multijunction gallium-arsenide-alloy cells for concentrators – best cells: 25%-37% efficient; commercial modules: 15%-24%; prototype systems are being tested in high solar areas in the southwest United States.
- Grid-connected PV systems currently sell for about \$5-\$8/W_p (20¢-32¢/kWh), including support structures, power conditioning, and land.

Current Research, Development, and Demonstration

RD&D Challenges and Goals

- Improve fundamental understanding of materials, processes, and devices to provide a technology base for advanced PV options.
- Optimize PV cell materials, cell designs, and modules; scale up laboratory cell results to product size (10^4 increase in area).
- Validate new module technologies outdoors and in accelerated testing to achieve 30-year outdoor lifetimes.
- Improve and invent new low-cost processes and technologies; reduce module and balance-of-systems manufacturing costs.
- Address substantial technical issues associated with high-yield, first-time, and large-scale (>100 MW/yr) manufacturing for advanced technologies.
- Develop and validate new, lower-cost systems hardware and integrated applications.
- Meet long-term, cost-competitive goal of manufacturing and installing PV systems under $\$1/W_p$.

RD&D Activities

- Capabilities at national labs and university centers of excellence have been developed, both in expertise and unique facilities. Funding is split 50-50 between national labs and external contracts with universities and industry. Public/private R&D partnerships, including extensive national R&D teams, have been the favored approach. All subcontracts have been awarded via competitive solicitations to select the best and most committed research partners.
- DOE and the National Center for Photovoltaics have worked with state regulatory agencies and influenced the direction of state programs.
- The Department of Defense (DOD) has some funding through special programs in which PV has a role supplying power for military systems.
- The National Aeronautics and Space Administration (NASA) has some research funds for PV. Though this effort has decreased during the past decade, advanced PV has become even more important for space missions (e.g., the high-performance cells on the Sojourner probe on Mars).
- Japan and Europe have significant funding for PV research.
- States have individual subsidy and utility portfolio programs related to PV; for example, California has a buy-down program for residential and commercial PV systems.
- U.S. PV businesses are marginally or not yet profitable and are unable to fund their own advanced research for low-cost PV.

Recent Progress

- Because of public/private partnerships, such as the Thin-Film Partnership with its national research teams, U.S. PV technology leads the world in measurable results such as record efficiencies for cells and modules. Another partnership, the PV Advanced Manufacturing R&D program, has resulted in industry cost reductions of more than 60% and facilitated a sixteen-fold increase of manufacturing capacity during the past 12 years.
- A new generation of potentially lower-cost technologies (thin films) is entering the marketplace. A 25-megawatt amorphous silicon thin-film plant by United Solar is reaching full production in 2005. Two plants (First Solar and Shell Solar) using even newer thin films (cadmium telluride and copper indium diselenide alloys) are in first-time manufacturing at the MW-scale. Thin-film PV has been a focus of the Federal R&D efforts of the past decade because it holds considerable promise for module cost reductions.
- During the past two years, record sunlight-to-electricity conversion efficiencies for solar cells were set by federally funded universities, national labs, or industry in copper indium gallium diselenide (19%-efficient cells and 13%-efficient modules) and cadmium telluride (16%-efficient cells and 11%-efficient modules). Cell and module efficiencies for these technologies have increased more than 50% in the past decade.
- A unique multijunction gallium-arsenide-alloy cell was spun off to the space power industry, leading to a record cell efficiency (35%) and an R&D 100 Award in 2001. This device configuration is expected to dominate future space power for commercial and military satellites.

Commercialization and Deployment Activities
• Worldwide, more than 510 MW of PV were sold in 2002, with systems valued at more than $5 billion; total installed PV is about 2 GW. The U.S. world market share is about 20%. • Worldwide, market growth for PV has averaged 25%/year for the past decade as a result of reduced prices and successful global marketing. In 2001, sales grew 36%, and in 2002, 31%. About two-thirds of U.S.-manufactured PV is exported. • Hundreds of applications are cost effective for off-grid needs. However, the fastest growing segment of the market is grid-connected PV, such as roof-mounted arrays on homes and commercial buildings in the United States. California is subsidizing PV systems to reduce their dependence on natural gas, especially for peak daytime loads which match PV output, such as air-conditioning. **Market Context** • Electricity for remote locations, especially for billions of people worldwide who do not have electricity. • U.S. markets: retail electricity for residential and commercial buildings; distributed utility systems for grid support, peak-shaving, and other daytime uses. • Future electricity and hydrogen storage for dispatchable electricity, electric car-charging stations, and hydrogen production for portable fuel.

2.3.3 SOLAR BUILDINGS

Technology Description

Solar building technologies deliver heat, light, and cooling to residential and commercial buildings. By combining solar building technologies with solar electric generation (using photovoltaics) and very energy-efficient building envelopes, lighting, and appliances, it is possible to create "Zero Energy Buildings" (see photo for an example demonstration home). Zero-energy buildings have a zero net need for off-site energy on an annual basis.

Zero-energy home, the "Solar Patriot."

System Concepts

- In solar heating systems, solar-thermal collectors convert solar energy into heat, usually for domestic hot water, pools, and space heating.
- In solar cooling systems, solar-thermal collectors convert solar energy into heat for absorption chillers or desiccant regeneration.
- In solar lighting systems, sunlight is transmitted into the interior of buildings using glazed apertures, light pipes, and/or optical fibers.

Representative Technologies

- Active solar heating systems use pumps and controls to circulate a heat-transfer fluid between the solar collector(s) and storage. System sizes can range from 1 to 100 kW.
- Passive solar heating systems do not use pumps and controls but rather rely on natural circulation to transfer heat into storage. System sizes can range from 1 to 10 kW.
- Transpired solar collectors heat ventilation air for industrial and commercial building applications. A transpired collector is a thin sheet of perforated metal that absorbs solar radiation and heats fresh air drawn through its perforations.
- Hybrid solar lighting systems focus concentrated sunlight on optical fibers and, with a controller, combine natural daylight with conventional illumination, depending on sunlight availability.

Technology Status/Applications

- Typical residential solar systems use glazed flat-plate collectors combined with storage tanks to provide 40%-70% of residential water heating requirements. Typical systems generate hot water equivalent to supplying 2,500 kWh/year at a cost of about 8¢/kWh.
- Typical solar pool heating systems use unglazed polymer collectors to provide 50%-100% of residential pool heating requirements. Typical systems generate 1,600 therms or 46,000 kWh/year and have 25% of the market.

Current Research, Development, and Demonstration

RD&D Goals

- Near-term solar heating and cooling RD&D goals are to reduce the costs of solar water and space heating systems to 4¢/kWh from their current cost of 8¢/kWh using polymer materials and manufacturing enhancements.
- Near-term, zero-energy building RD&D goals are to reduce the annual energy bill for an average-size home by 50% by 2004 and to zero by 2020.
- Near-term solar lighting RD&D goals are to demonstrate the second generation of the system with an enhanced control system.

RD&D Challenges

- Solar heating and cooling RD&D efforts are targeted to reduce manufacturing and installation costs, improve durability and lifetime, and provide advanced designs for system integration. One key R&D issue is durability. Polymer materials in solar heating systems must survive harsh service environments that include exposure to elevated temperatures, moisture, and ultraviolet radiation.
- Zero-energy building RD&D efforts are targeted to optimize various energy efficiency and renewable energy combinations, integrate solar technologies into building materials and the building envelope, and incorporate solar technologies into building codes and standards.
- Demonstration of hybrid lighting-system performance and reliability in the field are critical to the success of solar lighting.

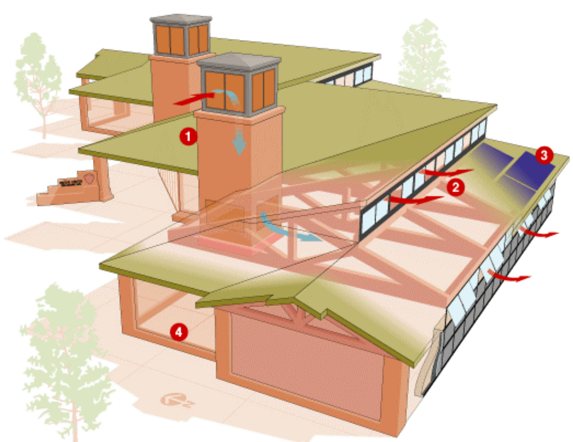
RD&D Activities

- Key DOE program activities are targeted to demonstrate lower cost and improved reliability of components and systems, develop advanced systems and applications, and support the next commercial opportunities for these technologies.
- DOE support of RD&D has been required because solar manufacturers are generally small businesses with limited resources and expertise. These manufacturers are constantly facing manufacturing and system design issues that affect the reliability, lifetime systems costs, and overall cost effectiveness of their products, yet they do not have the resources to conduct reliability and cost-reduction R&D. DOE and its national laboratories, however, have extensive expertise and facilities that can be critical to the long-term success of these manufacturers.

Recent Progress

- More than 1,000 MW of solar buildings PV systems are operating successfully in the United States, generating more than 3 million MWh/year.
- The energy costs of solar-thermal systems have been reduced through technology improvements by more than 50%, saving more than 5 million MWh/yr in U.S. primary energy consumption.

Commercialization and Deployment Activities



Zero-energy buildings require integrated design of the entire building, including energy-saving features, one or more electricity-generating sources, and an energy-management system to monitor and control operations. The Zion National Park Visitor Center, while not totally zero-energy, is one of the Park Service's most energy-efficient buildings.

- About 1.2 million solar water-heating systems have been installed in the United States. However, due to relatively low energy prices, there are currently only approximately 8,000 installations per year.
- Several hundred transpired solar collector systems have been installed, including installations for Ford Motor Company, General Motors, Federal Express, the U.S. Army, and the Bureau of Reclamation.
- Four multidisciplinary and four state-based homebuilding teams have begun the initial phase of designing and constructing Zero Energy Homes for various new construction markets in the United States. One homebuilder, Shea Homes in San Diego, is currently building and selling 300 houses with Zero Energy Home features, including solar electric systems, solar water heating, and very energy-efficient construction.

Market Context

- Retrofit markets: There are 73 million existing single-family homes in the United States. A potential replacement market of 29 million solar water-heating systems is based on the assumption that only 40% of the homes have been built with suitable orientation and absence of shading needed for solar water-heating systems.

- New construction markets: In 2000, 1.2 million new single-family homes were built in the United States. Assuming 70% of these homes could be sited to enable proper orientation of solar water-heating systems, new construction represents another 840,000 possible system installations each year.
- The ultimate market for zero-energy buildings includes both residential and commercial buildings. However, the near-term focus is on residential buildings and, in particular, single-family homes in the Sunbelt areas of the country. Of the1.2 million new single-family homes built in the United States in 2000, 44% of these new homes were in the southern region of the country and 25% were in the western region, which are prime areas for solar buildings and technologies.
- Solar building technologies will reduce daytime peak electricity requirements.

2.3.4 CONCENTRATING SOLAR POWER

Technology Description

Concentrating Solar Power (CSP) systems concentrate solar energy 50 to 5,000 times to produce high-temperature thermal energy, which is used to produce electricity for distributed or bulk generation process applications.

Luz Trough Power Plant

System Concepts

- In CSP systems, highly reflective sun-tracking mirrors produce temperatures of 400°C to 800°C in the working fluid of a receiver; this heat is used in conventional heat engines (steam or gas turbines or Stirling engines) to produce electricity at solar-to-electric efficiencies for the system of up to 30%. Systems using advanced photovoltaics (PV) cells may achieve efficiencies of 33%.
- CSP technologies provide firm, nonintermittent electricity generation (peaking or intermediate load capacity) when coupled with storage.
- Because solar-thermal technologies can yield extremely high temperatures, the technologies could some day be used for direct conversion (rather than indirect conversion through electrochemical reactions) of natural gas or water into hydrogen for future hydrogen-based economies.

Representative Technologies

- A parabolic trough system focuses solar energy on a linear oil-filled receiver to collect heat to generate steam to power a steam turbine. When the sun is not shining, steam can be generated with a fossil fuel to meet utility needs. Plant sizes can range from 1.0 to 100 MW_e.
- A power tower system uses many large heliostats to focus the solar energy onto a tower-mounted central receiver filled with a molten-salt working fluid that produces steam. The hot salt can be stored extremely efficiently to allow power production to match utility demand, even when the sun is not shining. Plant size can range from 30 to 200 MW_e.
- A dish/engine system uses a dish-shaped reflector to power a small Stirling or Brayton engine/generator or a high-concentrator PV module mounted at the focus of the dish. Dishes are 2-25 kW in size and can be used individually or in small groups for distributed, remote, or village power; or in larger (1-10 MW_e) clusters for utility-scale applications, including end-of-line support. They are easily hybridized with fossil fuel.

Technology Status/Applications

- Nine parabolic trough plants, with a rated capacity of 354 MW_e, have been operating in California since the 1980s. Trough system electricity costs of about 12¢-14¢/kWh have been demonstrated commercially.
- Solar Two, a 10-MW_e pilot power tower with three hours of storage, provided all the information needed to scale up to a 30-100 MW commercial plant, the first of which is now being planned in Spain.
- A number of prototype dish/Stirling systems are currently operating in Nevada, Arizona, Colorado, and Spain. High levels of performance have been established; durability remains to be proven, although some systems have operated for more than 10,000 hours.

Current Research, Development, and Deployment

RD&D Goals

- RD&D goals are to reduce costs of CSP systems to 5¢-8¢/kWh with moderate production levels within five years and below 4¢/kWh at high production levels in the long term.

RD&D Challenges

- RD&D efforts are targeted to improve performance and lifetime, reduce manufacturing costs with improved designs, provide advanced designs for long-term competitiveness, and address barriers to market entry.
- Improved manufacturing technologies are needed to reduce the cost of key components, especially for first-plant applications where economies of scale are not yet available.
- Demonstration of Stirling engine performance and reliability in the field are critical to the success of dish/engine systems.

RD&D Activities

- Key DOE program activities are targeted to support the next commercial opportunities for these technologies, demonstrate improved performance and reliability of components and systems, reduce energy costs, and develop advanced systems and applications.
- Several European countries and Israel have programs comparable in size to the United States.
- DOE support of RD&D has been required because of the specialized technology development and the need for reducing costs and for reducing barriers to market penetration. The Federal CSP program provides expert technical support, as well as serving as a catalyst and facilitator for participation of utilities and manufacturers to assist in driving down system costs.

Recent Progress

- New commercial plants are being considered for California, Nevada, and Arizona.
- The 10-MW Solar Two pilot power tower plant operated successfully near Barstow, California, leading to the first commercial plant being planned in Spain.
- Operations and maintenance costs have been reduced through technology improvements at the commercial parabolic trough plants in California by 40%, saving plant operators $50 million.

Commercialization and Deployment Activities

- Parabolic troughs have been commercialized and nine plants (354 MW total) have operated in California since the 1980s.
- The state of Nevada announced plans to build a 50-MW parabolic trough plant near Boulder City. Nevada Power and Sierra Pacific Power will purchase the power to comply with the solar portion of Nevada's renewable portfolio standard.
- Successful operation of Solar Two has provided the basis for a partnership to provide the first 30-100 MW power tower plant.
- The World Bank's Solar Initiative is pursuing CSP technologies for less-developed countries. The World Bank considers CSP to be a primary candidate for Global Environment Facility funding, which could total $1-$2 billion for projects during the next two years.

Market Context

- There is currently 350 MW of CSP generation in the United States, all of it in Southern California's Mojave Desert.
- Power purchase agreements have been signed for 150 MW of new CSP capacity (50 MW in Nevada and 100 MW in Spain). The plants are anticipated to come on-line within the next two to three years. Significant domestic and international interest will likely result in additional projects.
- According to a recent study commissioned by the Department of Energy, CSP technologies can achieve significantly lower costs (below 4¢/kWh) at modest production volumes.
- Congress asked DOE to scope out what would be required to deploy 1,000MW of CSP in the Southwest United States. DOE is actively engaged with the western Governors to map a strategy to deploy 1-5 GW of CSP in the Southwest by 2015.
- A near-term to mid-term opportunity exists to build production capacity in the United States for both domestic use and international exports.

2.3.5 BIOCHEMICAL CONVERSION OF BIOMASS

Technology Description

Biomass resources are agricultural crops and residues, wood residues, grasses, and trees. Biomass absorbs CO_2 as it grows, offsetting the CO_2 emissions from harvesting and processing, and can be a substitute for fossil resources in the production of power, fuels, and chemicals. Biomass feedstocks currently supply about 3 quadrillion Btus (Quads) to the nation's energy supply, based primarily on the use of wood. The potential exists for increasing the total biomass contribution up to 10 Quads nationwide, which would have a positive impact on the farm economy. Cost, sustainable supply availability, biomass variability, and transportation systems are key challenges for biomass utilization. The use of biomass as an alternative to fossil resources reduces most emissions, including emissions of greenhouse gases (GHGs). Through the use of biomass materials that would otherwise go to waste, biomass systems can represent a net sink for GHG emissions because methane emissions that would result from landfilling the unused biomass would be avoided.

Sugars are important platform intermediates for producing fuels, products, and power from biomass. Technologies in manufacturing platforms – such as the sugars platform – can provide the basis for a biorefinery or be combined with those from other platforms. The sugars platform is used to break down biomass, cellulose, and hemicellulose polymers into their building blocks. The building blocks are sugars that can be converted to many products including liquid fuels (e.g., ethanol), monomeric components for the polymer market (e.g., lactic acid), and hydrogen. In addition to the sugars platform, DOE is working on the glyceride platform, which uses biomass rich in vegetable oil (oil seeds like soybean) and converts the oil into esters that can be combusted like petroleum-based diesel. Other valuable biobased products can be produced from this conversion as well.

The biorefinery is analogous to an oil refinery. Multiple feedstocks are converted to a slate of products via multiple technology routes. Fuel production provides a large-volume product to achieve economies of scale, while lower-volume biobased coproducts and power can improve the economic competitiveness of biomass as a sustainable source of energy. Integrated biorefinery systems are being evaluated for their feasibility in producing fuels and products for potentially large commercial markets. A major challenge is to develop the ability to convert the fractionated biomass components into value-added products as efficiently as the current petrochemical business.

System Concepts

- The most common sugar-platform process consists of pretreating a biomass feedstock to release sugars from the fibrous cellulose and hemicellulose fractions. These sugars can be converted biologically into products such as ethanol or lactic acid, and can also be converted catalytically into products such as sorbitol. The products are then purified and sold as liquid fuels, sold into commodity chemical markets, or further converted and sold into other markets. The residue remaining from the sugar process can be burned to produce steam and electricity or further processed into other products such as animal feed.
- The glyceride platform consists of squeezing oil from an oil seed and transesterifying the oil to produce esters and glycerol. The esters can be purified for use as a liquid fuel (biodiesel), and purified glycerol can be sold as a commodity chemical or converted to other products (e.g., 1,3 propanediol).

Representative Technologies

- Sugar platform: hydrolysis of fibrous biomass that utilizes enzymes or acid catalysts, followed by microbial or catalytic conversion of the sugars to products.
- Glyceride platform: thermochemical transesterification of triglycerides.

- Fractionating biomass materials from grain and oil seeds, agricultural and forestry residues, or dedicated biomass feedstocks (such as grasses and woody crops) into component parts allows further development of value-added products such as chemical intermediates, wood products, biodiesel fuel, and composite materials.

Technology Status/Applications

- Acid hydrolysis: This sugar-platform technology is mature, with only the recovery of acid to be proven at industrial scale. One DOE partner is working with local and state governments to plan and design a facility that would separate MSW and convert its biomass portion to fuel-grade ethanol.
- Enzymatic hydrolysis: A major barrier of this sugar-platform technology has been development of low-cost cellulase enzyme cocktails. DOE has cost-shared subcontracts with Genencor International and Novozyme Biotech to reduce the cost of enzymes to improve the economics of the process. Process options using those enzymes will lead to the first large-scale, sugar-platform biorefineries.
- R&D advances have been identified to lower the cost of sugars for products including biofuels. As production costs for biofuels are reduced commensurately, larger fuel markets will become accessible. The technical challenge is to advance biomass processing to a level of maturity comparable to that of the existing petroleum industry.
- Glyceride platform: Many small glyceride facilities exist. The technology challenge is to convert batch-type facility designs to continuous processes that are built with greater capacity. Larger, continuous facilities will produce diesel products that can better compete with crude oil-based diesel. Development of coproducts also will help.
- Biobased products will be key elements in the development of integrated processes for producing fuels, chemicals, and power from both the sugar and glyceride platforms.

Current Research, Development, and Demonstration

RD&D Goals

By 2005

- Enzyme industry partners will provide new cellulase enzymes that are 10 times more cost effective than what is commercially available today.

By 2010

- Technologies will be developed for producing ethanol from cellulosic feedstocks at $1.29/gallon or less.
- Government will work with U.S. industry to introduce up to four new biobased chemical intermediate processing systems.
- Technologies will be developed for producing a mixed sugar stream from cellulosic feedstocks at $0.07/lb.

RD&D Challenges

- Low-cost enzymatic hydrolysis process technologies need to be developed.
- Pretreatment cost, yield, and equipment reliability need to be improved.
- Process integration and optimization needs to be developed.
- Fermentation organisms need to be developed and improved.

RD&D Activities

- Evaluation of pretreatment options and advanced R&D to understand biomass feedstock mechanisms.
- Industrial partnerships for demonstrating biochemical conversion technology on corn stover.
- Joint DOE and USDA solicitations targeting key enabling technologies to meet the RD&D challenges.

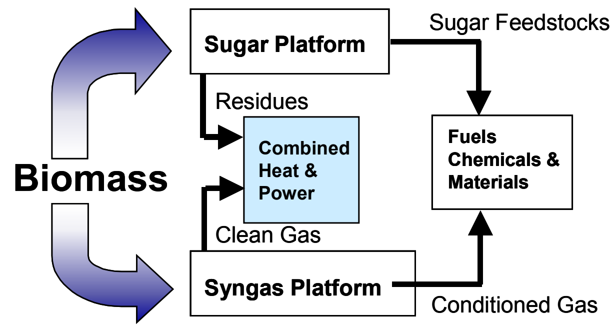
Recent Progress

- Cargill-Dow, a corporate partner, has built a facility that can produce almost 300 million pounds of lactic acid annually from corn starch. The facility also converts lactic acid into PLA for the polymers markets.
- Genencor International has announced that it met the target of a 10X reduction in the cellulase portion of the production cost of ethanol from biomass. Novozyme Biotech has announced that it expects to achieve the same goal by the end of its subcontract in 2004.
- Breakthroughs in genetically engineered microorganisms capable of fermenting the broad range of sugars found in biomass. These advances have led to an R&D 100 award and a number of patents.

• A conceptual design and cost estimate of a cellulosic ethanol facility has been completed and updated by DOE and engineering and construction firms. The report outlines the process necessary to meet cost targets.
Commercialization and Deployment Activities
• Conversion of cellulosic biomass to sugars and products from those sugars is not yet commercial. The U.S. capacity to produce ethanol from corn is 3 billion gallons annually. Ethanol is used as a fuel extender and, increasingly, as an oxygenating additive for reformulated gasoline wherever MTBE is phased down. • Starch crops play a transitional role, but large-scale displacement of petroleum will rely on cellulose. • About 15-21 million gallons of biodiesel is produced annually in the United States. • Biobased products can replace 1:1 their chemically derived counterpart if the cost is competitive. This approach is of interest to the existing biomass-processing community; their infrastructure is already in place. • Oil-based products or fuels have essentially a 1:1 displacement of petroleum-based products or fuels; this is attractive in efforts to reduce dependence on imported oil. • Biobased products can bring new properties and functions to materials and chemical intermediates. This characteristic can enable biorefinery operations and the development of small businesses. Here, the market is not fully defined, capital risk is high, and time to commercialize may be long. Investments by the Federal government can lower some of these barriers. **Market Context** • For ethanol: 1 Quad of biomass: 1% of projected petroleum imports for 2020 5 Quads of biomass: 6% of projected petroleum imports for 2020 • For fuels and chemicals (depending on the mix of products): 1 Quad of biomass: 0.5-1% of projected petroleum imports for 2020 5 Quads of biomass: 5-10% of projected petroleum imports for 2020

2.3.6 THERMOCHEMICAL CONVERSION OF BIOMASS

Technology Description



Biomass resources are agricultural crops and residues, wood residues, grasses, and trees. Biomass absorbs CO_2 as it grows, offsetting the CO_2 emissions from harvesting and processing, and can be a substitute for fossil resources in production of power, fuels, and chemicals. Biomass feedstocks currently supply about 3 quadrillion Btus (Quads) to the nation's energy supply based primarily on wood resources. The potential exists for increasing total biomass contribution to 10 Quads nationwide, which would create positive impacts on farming and forest products industries. Cost, sustainable supply availability, biomass variability, and delivery systems are key challenges for biomass utilization. Use of biomass resources as an alternative to fossil resources reduces most emissions, including emissions of greenhouse gases (GHGs). Through use of materials that would normally be waste, biomass systems bring about a net sink for GHG emissions, because methane emissions that would result from landfilling are avoided.

Thermal conversion of biomass is a manufacturing platform comprised of many technology routes and involves use of heat to break down biomass feed into an oil-rich vapor in pyrolysis and/or synthesis gas in gasification, which is used for generation of heat, power, liquid fuels, and chemicals. Technologies in this platform can provide the basis for a biorefinery, or be combined with other platform technologies. One advantage of thermal conversion processes is that they can convert nearly all biomass feedstocks into synthesis gas, including some feedstock components that are difficult to process by chemical or biological means.

The biorefinery is analogous to an oil refinery. Multiple feedstocks are thermally converted to a slate of products via multiple technology routes. Fuel production provides a large-volume product to achieve economies of scale, while lower volume biobased coproducts and power can improve the economic competitiveness of biomass as a sustainable source of energy. Integrated biorefinery systems are being evaluated for their feasibility in producing fuels and products for potentially large commercial markets. A major challenge is to develop the ability to convert the fractionated biomass components into value-added products as efficiently as the current petrochemical business of today.

Biomass combustion is a thermal process that converts biomass entirely to carbon dioxide and water vapor; and, thus, precludes conversion to intermediate fuels or chemicals. The existing biomass power industry primarily uses combustion to produce steam for heat and electricity generation. Co-combustion of biomass with coal, or "cofiring" has received recent interest as a way to reduce fossil carbon emissions from coal power plants. There are few significant technical barriers to increase use of these technologies.

System Concepts and Representative Technologies

Thermal conversion technology is important and has several key roles in an emerging bioeconomy:

- Most current biomass conversion is for heat and power generation and is based on direct combustion in small, biomass-only plants with relatively low electric efficiency of about 20%. Technology exists so that total system efficiencies can approach 90% if combined heat and power systems are applied. Most biomass direct combustion generation facilities use the basic Rankine steam cycle for electric power generation, which is made up of a steam boiler, an electric turbine, a condenser, and a pump. Evolution of combined cycles that integrate the use of gas and steam turbines can increase generation efficiency by up to two times. Cofiring of biomass with coal also can increase overall biomass-to-electricity conversion efficiency.
- A source of syngas for catalytic production of fuels, chemicals, and hydrogen is important. Once a clean synthesis gas is obtained, it is possible to access and leverage mature process technologies developed in the petroleum and chemicals industry for the production of a wide range of liquid fuels and chemicals.
- A source of heat and power for biorefinery operation. Virtually all other conversion processes – whether physical or biological – produce residue that cannot be directly converted to the primary product(s). In order to mitigate waste streams and to maximize the efficiency of the biorefinery, these residues can and

should be used for heat and power production. In existing biorefineries, residues are combusted in a steam boiler. There is a technological opportunity however, to use a gasifier coupled to a gas turbine combined cycle that can double conversion efficiency to electricity, while still producing steam from the gas turbine waste heat. Use of a biomass gasifier in a gasifier combined-cycle system can leverage on public and private investments in development of advanced- and next-generation gas turbine systems (more than $1 billion).

- Thermal conversion is a way to derive additional value from process residues. Within a biorefinery, thermal conversion and gasification can push many residues "up the value chain" through production of hydrogen or other higher-value products via thermal conversion to syngas followed by separation or synthesis steps.
- Gasification converts biomass to a syngas that can be substituted for natural gas in combustion turbines, shifted into hydrogen for fuel cell or other applications, or used in existing commercial catalytic processes for production of liquid fuels and chemicals. Several technologies exist in various stages of development for production of a suitable syngas, including indirect gasification, steam reforming of biomass, and gasification with oxygen or enriched air.
- Pyrolysis of biomass produces an oil-rich vapor that can be condensed for direct use as a fuel or as a hydrogen carrier, or refined for producing a variety of higher-value chemical products.

Technology Status/Applications

- The existing biopower sector, nearly 1,000 plants, is mainly comprised of direct combustion plants, with an additional small amount of cofiring (approximately 400 MW_e). Plant size averages 20 MW_e, and the biomass-to-electricity conversion efficiency is about 20%. Grid-connected electrical capacity was 9,700 MW_e in 2001; more than 75% of this power is generated in the forest products industry's combined heat and power applications for process heat. Combined utility and industrial generation in 2001 was more than 60 billion kilowatt-hours (about 75% of nonhydro renewable generation). Recent studies estimate that on a life-cycle basis, existing biopower plants represent a net carbon sink of 4 MMTC/yr. Biopower electricity prices generally range from 8¢–12¢/kWh.
- U.S. investment in equipment is $300-$500 M/year. At least six major engineering procurement and construction companies and several multinational boiler manufacturers are active.
- Biomass cofiring with coal ($50–$250/kW of biomass capacity) is the most near-term option for large-scale use of biomass for power-only electricity generation. Cofiring also reduces sulfur dioxide and nitrogen oxide emissions. In addition, when cofiring crop and forest product residues, GHG emissions are reduced by a greater percentage (e.g. 23% GHG emissions reduction with 15% cofiring).
- Small biopower and biodiesel systems have been used for many years in the developing world for electricity generation. OE is developing systems for village power applications for distributed generation that are more efficient, reliable, and clean for the developed world. These systems range in size from 3 kW to 5 MW, with field verification completed by the end of 2003.

Current Research, Development, and Demonstration

RD&D Goals

By 2005

- Resolve tar issues through integrated testing of candidate materials, catalysts, and technologies at appropriate scale.
- Verify hydrogen-production system and fuel cell operation.

By 2010

- Validate integration of gas treatment system with syngas-based biorefinery.
- Validate integration of hydrogen production or fuel cell operation with syngas-based biorefinery.
- Validate distributed fuels and chemicals production through industrial demonstration projects. Help the U.S. industry to introduce up to four new biobased chemical intermediate processing systems.By 2015
- Validate integrated syngas biorefineries through industrial demonstration projects.

RD&D Challenges

- Feed Preparation/Gasification – Improved feed processing for operational reliability need to be developed.
- Gas Cleanup – Improved methods of removing contaminants from syngas and modifying gas composition are needed.
- Synthesis gas utilization – The feasibility and optimization of syngas use in fuels, chemicals, and heat/power applications needs to be demonstrated on both a laboratory and industrial pilot scale.
- System Integration – Careful integration of the entire conversion system to maximize efficiency and reduce costs is needed.
- Development of enabling technologies is needed so that industry can reduce their risk of development and reduce development-cycle time.
- Verification and quantification of environmental and other benefits of themochemically derived fuels and chemicals is needed.

RD&D Activities

- Core research in feed preparation and handling, gasification, gas cleanup and conditioning, syngas utilization, and sensors and controls.
- Solicitation(s) for industry and university core research in targeted areas addressing specific barriers, e.g., high-pressure feeder development, novel gasification concepts, gas cleanup, hydrogen production, and sensors and controls.
- Solicitation(s) for precommercial validation of integrated processes for distributed fuels, chemicals, and hydrogen; and for integrated biorefinery applications.
- Joint DOE and USDA solicitations targeted to key enabling technologies can have an impact on meeting RD&D challenges.
- USDA has extensive research in crop production and is beginning to fund community-based, small-system demonstrations in collaboration with DOE.

Recent Progress

- R&D 100 award for the Burlington, Vermont, gasifier (Future Energy Resources Corporation, Battelle, and DOE Labs).
- Successfully demonstrated NO_x reductions from cofiring in excess of cofired percentage.
- Completed life-cycle assessments verifying and quantifying environmental benefits of biopower systems.
- Successful energy crop (switchgrass and willow) harvesting and cofiring in Iowa, Louisiana, and New York.
- Public release of modeling software (BIOCOST) that allows evaluation of energy crop production cost scenarios.

- Annual switchgrass yields of more than 10 t/acre obtained from best test plots in three southern states.
- Successful collaboration between private industry, DOE, and the USDA-Forest Service to demonstrate the small-scale modular production of heat and power in community settings (schools, small businesses).
- Demonstration at commercial prototype scales the use of biomass-derived resins from bark for engineered wood products.

2.3.7 BIOMASS RESIDUES

Technology Description

Biomass residues are the organic byproducts of green plants used for food, fiber, and forest production and processing. Major sources of residues include grain crops such as corn, wheat, and rice; animal waste; forest harvest; fuel-reduction treatments, and processing. These residues can be used as an alternative fuel source and for other purposes. This profile addresses the issues of harvesting, storing, and transporting biomass residues.

System Concepts

- The sustainable use of biomass residues for energy requires understanding when and where residues can be removed from agricultural and forest soils without reducing long-term productivity.
- Under certain circumstances, residues may have greater economic and ecological value when left on the land to restore nutrients, reduce erosion, and stabilize soil structure than if harvested for fuel. Biomass residue energy production may be most effective in locations where crop yields and soil organic levels are high, and erosion is not a major concern.

Representative Technologies

- Agricultural residues (corn stover, straws from wheat, rice, and other grain crops).
- Wood residues resulting from lumber, furniture, and fiber production.
- Forest residues (tops and limbs from harvest for wood products, material from fuel reduction treatments).
- Black liquors from pulp production.
- Animal wastes from confined production of chickens, pigs, and cows.
- Clean wood from urban yard trimmings and construction/demolition.

Technology Status/Applications

- Sustainable and recoverable amounts of corn stover, wheat straw, rice straw, and cotton stalks are estimated at about 150 MdT/year (less than 50% of the amount actually produced). Some corn stover is being removed presently for production of chemicals and animal bedding. Straws are being used in Europe as a bioenergy resource.
- More than 2.1 quadrillion Btu of primary biomass energy is consumed by industry, and it generates 56 million MWh of electricity plus heat. Nearly two-thirds of this electricity is derived from wood and wood wastes (including spent pulping liquors, wood residues, byproducts from mill processing, and forest residues). About one-third of the electricity and heat is derived from municipal solid waste and landfill gas.
- Some technologies are available to combust or gasify animal wastes. The most widely known option is to capture methane gas, a byproduct of anaerobic digestion.

Current Research, Development, and Demonstration

RD&D Goals

- By 2004, obtain measurable cost reductions in corn-stover supply systems with modifications of current technology.
- By 2007, develop whole-crop harvest systems for supplying biorefineries to make multiple products.
- By 2010, develop a system of whole-crop harvest and fractionation for maximum economic return, including returns to soil for maximum productivity and conservation practices.
- By 2015, develop an integrated system for pretreatment of residues near harvest locations and a means of collecting and transporting partially treated substrates to a central processing operation.
- By 2020, develop fully integrated crop and residue harvesting, storage, and transportation systems for food, feed, energy, and industrial applications.

RD&D Challenges

- Develop environmental data to make decisions on residue removal from agricultural and forest lands.
- Assemble better information on the characteristics of residue feedstock to assist in cost-effective harvest/handling and storage systems, and to assist potential users in optimizing their systems to handle residue feedstock.
- Develop cost-effective drying, densification, and transportation techniques to create more “standard” feedstock from residues.

- Develop efficient and environmentally sound infrastructure for residue supply systems (collection, handling, storage, transport).
- Gain public acceptance for the removal of agricultural and forest residues where shown to be sustainable.
- Develop methods for estimating residue availability based on published or easily accessible information sources.
- Develop effective and publicly acceptable ways of using animal wastes.

RD&D Activities

- Reduce feedstock costs and enhance feedstock quality through improving and adapting the existing collection, densification, storage, transportation, and information technologies (precision agriculture and forestry) to bioenergy supply systems.
- Enhance the sustainability of feedstock supply enterprises (production and handling) by developing and servicing robust machines for multiple applications and extended use.
- Research the engineering properties of novel aqueous and nonaqueous multiphase bioenergy feedstocks.

Recent Progress

- Critical operations contributing to the cost of residue harvest have been identified. It is now clear that a reduction in the number of operations is the key to reduction in feedstock costs.
- Farm-equipment manufacturers in the United States are becoming increasingly aware of opportunities in biomass harvesting and handling systems. Large and small companies are building alliances with research institutions to develop equipment for handling large quantities of biomass.
- Green power producers are making greater use of landfill gas as a resource for electricity production.

Commercialization and Deployment Activities

- Use of biomass residues for bioenergy and bioproducts is already commercial where those materials are captured internally by an industry or where disposal fees are high enough to encourage delivery of these materials to an energy end user for little to no cost.

2.3.8 ENERGY CROPS

Technology Description

Energy crops are fast-growing, genetically improved trees and grasses grown under sustainable conditions for harvest at 1 to 10 years of age. End uses of energy crops include biomass power (combustion and gasification), biofuels (ethanol), and new bioproducts such as plastics and many types of chemicals.

System Concepts

- Biomass feedstock supply systems are widely available throughout the United States but locally optimized for climate and soil conditions and end-use requirements.
- Quantities must be sufficient to support large-scale processing facilities.
- In the future, some crops will likely be genetically tailored in a way that facilitates separations and conversion processes for selected end uses.

Representative Technologies

- Short rotation woody crops – selected tree varieties grown as single-stem trees under sustainable conditions for year-round harvest within 4-10 years with replanting assumed.
- Woody coppice crops – selected tree varieties grown as multistemmed "bushes" under sustainable conditions for year-round harvest.
- Perennial grass crops – selected high-yield varieties of grasses grown under agronomic conditions for fall and winter harvest with stand regrowth assumed for up to 10 years, involving some modification to standard forage harvest systems.
- Genetic improvement, pest and disease management, sustainability optimization, and harvest equipment development R&D ongoing for all of the above.

Technology Status/Applications

- Short-rotation woody crops are produced commercially in the Pacific Northwest and North Central regions of the United States and many parts of the world (Brazil, Australia, Spain, etc.) for combined fiber and energy use.
- Woody coppice crops are produced commercially in Northern Europe and are being adapted to and tested at an operational scale in New York.
- Perennial grass crops have high yield potential and have been demonstrated in south, southeastern, mid-west, and north-central parts of the United States. Technology is being tested as a biomass feedstock supply system for biomass power in Iowa.

Current Research, Development, and Demonstration

RD&D Goals

- By 2005, develop feedstock crops with experimentally demonstrated yield potential of 6-8 dry ton/acre/year.
- By 2005, develop cost-effective, energy-efficient, environmentally sound harvest methods.
- By 2010, identify genes that control growth and characteristics important to conversion processes in few model energy crops.
- By 2010, improve understanding of biotechnology impacts on environment and ecology.
- By 2010, achieve low-cost, "no-touch" harvest/processing/transport of biomass to process facility.
- By 2020, increase yield of useful biomass per acre by a factor of 2 or more compared with year 2000 yields.
- By 2020, energy crops will be contributing strongly to meeting biomass power and biofuels production goals.

RD&D Challenges

- Transfer genomics information gained from arabidopsis, rice, and corn to acceleration of domestication of poplars and switchgrass.
- Develop gene maps and increased functional genomics understanding for model crops.
- Develop an efficient infrastructure for energy crop supply and utilization systems.
- Scale up seed to large-scale commercial deployment.

- Demonstrate that energy crop production is sustainable and environmentally beneficial.
- Gain acceptance by the public for the use of genetic engineering of energy crops.
- Develop expertise on machinery and logistics aspects of agricultural and forest engineering.

RD&D Activities

- Crop yield improvement research on two model woody crops (poplars and willow) and one herbaceous species (switchgrass) is being conducted by researchers in academic and USDA research organizations in many locations throughout the country.
- Genetic maps have been developed for poplars and are in process for switchgrass; work has been initiated to identify genes important to accelerated domestication of poplars and switchgrass.
- Cost-supply relationships are being generated for energy crop supplies in different regions of the country.
- Environmental research to optimize energy crop sustainable production techniques is being conducted in a few locations.
- Research on control of diseases and pests through genetics and/or cultural management.

Recent Progress

- Yields of up to 10 dry tons/acre/year have been observed in small experimental plantings of poplars, willows, and switchgrass in selected locations with genetically superior material.
- Yields of 5-7 dry tons/acre/year have been measured in small pilot-scale regional field trials of energy crops in some locations.
- Two major industrial enzyme companies are developing a new generation of cellulase enzymes to support an enzyme sugar platform.
- Farmers are engaged in energy crop R&D in several regions of the country through Federally supported demonstrations.
- An economic model for energy crop production costs has been released for public use.
- Joint USDA/DOE analysis on the economic impacts of bioenergy crop production on U.S. agriculture has shown the potential for net farm income to increase from $2.8 billion to $6 billion depending on production scenarios and feedstock prices.
- A nutrient cycling spreadsheet model applicable to forestry and short rotation woody crop applications has recently been completed and made available to industry and the public on the Web.

Commercialization and Deployment Activities

- Between 1983 and 1998, 70,000 acres of poplars were established commercially in the Pacific Northwest with significant utilization of new hybrid materials generated by the DOE-funded research programs. Opportunistic market conditions, together with short-rotation crop technology readiness and technology transfer activities, were all critical to the commercialization success in the Pacific Northwest.
- Other types of short-rotation crops – including eucalyptus, sweetgum, sycamore, and willow, and established in other parts of the country – contribute to an approximate total level of commercialization of short-rotation woody crops of about 120,000 acres. Willow contributes a partial wood supply to a cofiring biomass power demonstration project. Switchgrass is already a crop planted on many Conservation Reserve Program acres, and it is the feedstock supply for two biomass power cofiring demonstrations.

2.3.9 PHOTOCONVERSION

Technology Description

Photoconversion technology encompasses sunlight-driven quantum-conversion processes (other than solid-state photovoltaics) that lead to the direct and potentially highly efficient production of electrical power or fuels, materials, and chemicals from simple renewable substrates such as water, carbon dioxide (CO_2) and nitrogen. This technology has the potential to eliminate the need for fossil fuels by substituting renewable sources and conversion processes that are either carbon neutral (any carbon generated is reused during plant growth) or carbon free (e.g., hydrogen from water). These technologies also can convert CO_2 into liquid and gaseous fuels via processes that are often termed biomimetic, or bio-inspired.

A photoconversion process to produce hydrogen from metabolically engineered algae.

System Concepts

- Photoconversion processes use solar photons directly to drive biological, chemical, or electrochemical reactions to generate electricity, fuels, materials, or chemicals.
- System components include biological organisms or enzymes, semiconductor structures (photoelectrochemical cells, colloids, nanocrystals, certain plastics or polymers, quantum dots or nanoparticles, or superlattices), biomimetic molecules, dye molecules, synthetic catalysts, or combinations of the above.

Representative Technologies

- Elements of this future solar technology include photobiological, photochemical, photoelectrochemical, photocatalytic, and dark catalytic processes for energy production.
- Photoconversion technologies can produce electrical power, hydrogen, biodiesel, organic acids, methane, methanol, and plastics. These technologies also can remove CO_2 from the atmosphere through photoreduction of CO_2 to fuels, materials, and chemicals. Moreover, they can achieve atmospheric nitrogen fixation (independent of natural gas) and convert biomass to fuels, materials, or chemicals.
- Most of these technologies are at early stages of research, but some are at the development level, and some that produce high-value products are commercial.

Technology Status/Applications

- Power production: dye-sensitized, nanocrystalline, titanium dioxide semiconductor solar cells are 8%-11% efficient and are potentially very cheap. In contrast to solid-state PV solar cells, light is absorbed by dye molecules in contact with an electrolyte rather than solid-state semiconductor materials. Novel photoelectrochemical cells with integrated fuel cells and in situ storage for 24-h solar power have been demonstrated at 6%-7% efficiency in 4-by-8-foot panels using a system developed by Texas Instruments, and photochargeable batteries that include electrochemical storage have been demonstrated with 24-h power output. Hot-carrier photoconversion technology for increasing solar-conversion efficiencies (with theoretical efficiency limits of 65%-86%, depending on the solar photon concentration) is making progress. The term “hot carrier” refers to the utilization of highly energetic electrons (called hot electrons and created upon absorption of photons with energies larger than the semiconductor bandgap) for useful chemical production or electrical power, rather than converting the excess electron energy to heat by photon emission. In present photoconversion and photovoltaic devices, the hot electrons cool, and their excess energy is lost as heat in a picosecond (1E-12 sec) or less. Semiconductor nanostructures have been found to slow the cooling time of hot electrons by up to two orders of magnitude, thus enhancing the probability for hot electron conversion.

- Fuels production: Photoelectrochemical and photobiological processes that will lead to hydrogen production from water or gasified biomass are at the early stages of research, and important advances have been made recently; biodiesel, methane, and methanol production from water, waste, and CO_2 are at various stages of R&D; and fuels, such as methanol – produced by the direct electrocatalytic or photocatalytic reduction of CO_2 – are at the early fundamental research stage. Electrocatalytic concentration of CO_2 from the atmosphere is being studied as well; it is of interest to people involved in atmospheric control in small spaces (i.e., submarines and the space station) and has potential for removing CO_2 from the atmosphere in the future.
- Materials and chemicals production: Producing materials and chemicals from CO_2 and/or biomass, as well as producing fertilizer from atmospheric nitrogen and renewable hydrogen, will reduce CO_2 emissions compared with the fossil fuels used currently.
- Photobiological production of pigments (e.g., astaxanthin), health foods, nutritional supplements (e.g., omega-3 fatty acids), protein, and fish food is commercial. Production of biopesticides and pharmaceuticals is under development. Production of commodity chemicals such as, but not limited to, glycerol, hydrogen peroxide, and bioemulsifiers is possible. Photocatalytic production of specialty or high-value chemicals has been demonstrated.

Current Research, Development, and Demonstration

RD&D Goals

- Most photoconversion technologies are at the fundamental research stage, where technical feasibility must be demonstrated before cost and performance goals can be assessed. Minimum solar conversion efficiencies of 10% are generally thought to be necessary before applied programs can be considered. Cost goals need to be competitive with projected costs of current technologies.
- Electrical power and high-value chemicals applications are either currently commercial or will see dramatic growth during the next 5-10 years. Large-scale power production should begin in 2010-2015. Materials and fuels production will begin in 2015-2020, and commodity chemicals production begins in 2020-2030.

RD&D Challenges

- Develop the fundamental sciences in multidisciplinary areas involving theory, mechanisms, kinetics, biological pathways and molecular genetics, natural photosynthesis, materials (semiconductor particles and structures), catalysts and catalytic cycles, and biomimetic components. Progress in fundamental science is needed to underpin the new photoconversion technologies.
- Maintain critical mass research groups in vital areas long enough for sustained progress to be made.

RD&D Activities

- A significant level of basic research activities in solar photoconversion is currently being performed by the DOE Office of Science; some exploratory R&D is being performed by DOE Office of Energy Efficiency and Renewable Energy/Office of Solar Technologies.
- Some basic research support by the National Science Foundation and the U.S. Department of Agriculture is complementary.

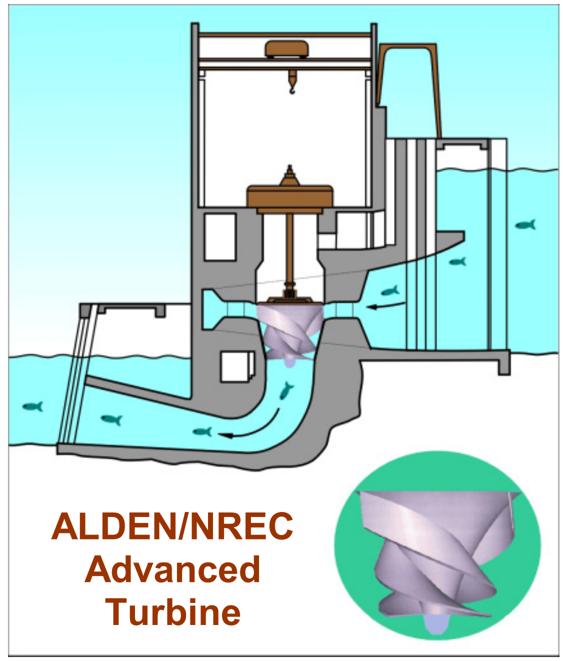
Recent Progress

- Prototype dye-sensitized nanocrystalline semiconductor solar cells have been demonstrated as power sources in small niche markets. Commercial interest is very high because they also can be configured to produce hydrogen.
- Scientific breakthroughs during the past seven years have been made in microbial and enzymatic R&D; natural photosynthesis; semiconductors, nanostructures, quantum dots, and superlattices; CO_2 catalysis; and energy and electron transfer in artificial donor/acceptor molecules.

Commercialization and Deployment Activities
• Astaxanthin, a pigment synthesized from petroleum, is used as a coloring agent in the poultry and salmon industries. Algal production of the pigment just started in Hawaii and is replacing the fossil version for health and environmental reasons. Large-scale algal ponds are producing high-value chemicals on a commercial basis using photobiological processes. As an example, the current astaxanthin market is $180 M/year and is expected to rise to $1 B/year in five years. • European and Japanese companies are beginning to commercialize dye-sensitized, nanocrystalline cell-powered watches. The market is estimated to be 100 million units. **Market Context** • Besides the applications discussed above, many spin-off technologies are possible. These include optoelectronics, biosensors, biocomputers, bioelectronics, and nanoscale devices.

2.3.10 ADVANCED HYDROPOWER

Technology Description



Hydroelectric power from falling water generates no greenhouse gas. To the extent that existing hydropower can be maintained or expanded by addressing environmental concerns through advances in technology, it can continue to be an important part of a greenhouse gas emissions-free energy portfolio. Advanced hydropower is technology that produces hydroelectricity both efficiently and with improved environmental performance. Traditional hydropower may have environmental effects, such as fish mortality and changes to downstream water quality and quantity. The goal of advanced hydropower is to maximize the use of water for generation while eliminating these environmental side effects.

System Concepts

- Conventional hydropower projects use either impulse or reaction turbines to convert kinetic energy in flowing or falling water into turbine torque and power. Source water may be from free-flowing rivers, streams, or canals, or water released from upstream storage reservoirs.
- New environmental and biological criteria for turbine design and operation are being developed to help sustain hydropower's role as a clean, renewable energy source – and to enable upgrades of existing facilities and retrofits at existing dams.

Representative Technologies

- New turbine designs that improve survivability of fish that pass through the power plant.
- Autoventing turbines to increase dissolved oxygen in discharges downstream of dams.
- Reregulating and aerating weirs used to stabilize tailwater discharges and improve water quality.
- Adjustable-speed generators producing hydroelectricity over a wider range of heads and providing more uniform instream-flow releases without sacrificing generation opportunities.
- New assessment methods to balance instream-flow needs of fish with water for energy production and to optimize operation of reservoir systems.
- Advanced instrumentation and control systems that modify turbine operation to maximize environmental benefits and energy production.

Technology Status/Applications

- Hydropower provides about 78,000 MW of the nation's electrical-generating capability. This is about 80 percent of the electricity generated from renewable energy sources.
- Existing hydropower generation faces a combination of real and perceived environmental effects, regulatory pressures, and changes in energy economics (deregulation, etc.); potential hydropower resources are not being developed for similar reasons.
- Some new environmentally friendly technologies are being implemented (e.g., National Hydropower Association's awards for Outstanding Stewardship of America's Rivers and the Tennessee Valley Authority's (TVA's) Lake Improvement Program).
- DOE's Advanced Hydropower Turbine System (AHTS) program is working through public-private partnerships with industry to demonstrate new turbine designs are feasible.

Current Research, Development, and Demonstration

RD&D Goals

- By 2010: Complete testing of a commercially viable hydroelectric turbine technology capable of reducing the rate of fish mortality to 2%, which is equal to or better than other methods of fish passage (e.g. spillways or fishways).

- By 2010: Complete the development of Advanced Hydro Turbine Technology in support of maintaining hydroelectric generation capacity due for relicensing between 2010 and 2020.

RD&D Challenges

- Biological design criteria for new technology are limited by poor understanding of how fish respond to turbulent flows and other physical stresses inside turbines and downstream of dams.
- To affect public perception, field-testing will be needed to provide the evidence that fish survival through turbines is equal to or greater than survival in other passage routes around dams. Regulatory trends are shifting power plant operation from peaking to baseload, effectively reducing the energy value of hydroelectricity and reducing plant capacity factors; higher instream-flow requirements are reducing total energy production to protect downstream ecosystems, but scientific justification is weak.

RD&D Activities

- DOE's AHTS program constructed a test facility for pilot-scale testing of a new turbine design to evaluate hydraulic and biological performance; testing at this facility was completed in FY 2003.
- New biological design criteria to protect fish from shear and pressure have been developed in controlled laboratory experiments; computational fluid dynamics modeling and new sensor systems are producing new understanding of turbulence in turbines and draft tubes.
- Regional efforts by the Army Corps of Engineers and Bonneville Power Administration are producing solutions to some site-specific problems, especially in the Columbia River basin; but they are not addressing the national situation that is driven by market pressures and environmental regulation.
- Resource assessments of low-head and low-power resources are being conducted.

Recent Progress

- TVA has demonstrated that improved turbine designs, equipment upgrades, and systems optimization can lead to significant economic and environmental benefits – energy production was increased approximately 12% while downstream fish resources were significantly improved.
- Field-testing of some features of the Kaplan turbine Minimum Gap Runner design indicates that fish survival can be significantly increased, if conventional turbines are modified. The full complement of Minimum Gap Runner design features have not been implemented in a single turbine, so additional performance improvements are expected.

Commercialization and Deployment Activities

- Voith Siemens Hydro Power and the TVA have established a partnership to market environmentally friendly technology at hydropower facilities. Their products were developed in part by funding provided by DOE and the Corps of Engineers, as well as private sources.
- In a competitive solicitation, DOE accepted proposals for advanced turbine designs from Voith Siemens, Alstom, American Hydro, and General Electric Co., all of which are ready for field verification and testing to demonstrate improved environmental performance.
- Flash Technology is developing strobe lighting systems to force fish away from hydropower intakes and to avoid entrainment mortality in turbines. Implementation at more sites may allow improved environmental performance with reduced spillage.

Market Context

- Advanced hydropower products can be applied at more than 80% of existing hydropower projects (installed conventional capacity is now 78 GW); the potential market also includes 15-20 GW at existing dams (i.e., no new dams required for development) and more than 30 GW of undeveloped hydropower.
- Retrofitting advanced technology and optimizing system operations at existing facilities would lead to at least a 6% increase in energy output – if fully implemented, this would equate to 5 GW and 18,600 GWh of new, clean energy production.

2.3.11 GEOTHERMAL ENERGY

Technology Description

Geothermal energy is heat from within the Earth. Hot water or steam are used to produce electricity or applied directly for space heating and industrial processes. This energy can offset the emission of carbon dioxide from conventional fossil-powered electricity generation, industrial processes, building thermal systems, and other applications.

System Concepts

- Geophysical, geochemical, and geological exploration locates resources to drill, including highly permeable hot reservoirs, shallow warm groundwater, hot impermeable rock masses, and highly pressured hot fluids.
- Well fields and distribution systems allow the hot fluids to move to the point of use, and afterward back to the earth.
- Utilization systems may apply the heat directly or convert it to another form of energy such as electricity.

Representative Technologies

- Exploration technologies identify geothermal reservoirs and their fracture systems; drilling, reservoir testing, and modeling optimize production and predict useful lifetime; steam turbines use natural steam or hot water flashed to steam to produce electricity; binary conversion systems produce electricity from water not hot enough to flash.
- Direct applications use the heat from geothermal fluids without conversion to electricity.
- Geothermal heat pumps use the shallow earth as a heat source and heat sink for heating and cooling applications.
- Coproduction, the recovery of minerals and metals from geothermal brine, is being pursued. Zinc is recovered at the Salton Sea geothermal field in California.

Technology Status/Applications

- With improved technology, the United States has a resource base capable of producing up to 100 GW of electricity at 3¢-5¢/kWh.
- Hydrothermal reservoirs are being used to produce electricity with an online availability of up to 97%; advanced energy-conversion technologies are being implemented to improve plant thermal efficiency.
- Direct-use applications are successful throughout the western United States and provide heat for space heating, aquaculture, greenhouses, spas, and other applications.
- Geothermal heat pumps continue to penetrate markets for heating/cooling (HVAC) services.

Current Research, Development, and Demonstration

RD&D Goals

- By 2010, make geothermal cost effective at 3¢-5¢/kWh

RD&D Challenges

- Develop improved methodologies for predicting reservoir performance and lifetime.
- Find and characterize underground fracture permeability and develop low-cost, innovative drilling technologies.

- Reduce capital and operating costs and improve the efficiency of geothermal conversion systems.
- Develop and demonstrate technology for enhanced geothermal systems that will allow the use of geothermal areas that are deeper, less permeable, or dryer than those currently considered as reserves.

RD&D Activities

- DOE Office of Energy Efficiency and Renewable Energy promotes collaborations among laboratories, universities, states, and industry. Industry provides access to operating fields and well data, equipment and geothermal materials, and matching funds. Related activities are supported by DOE Office of Fossil Energy and Office of Science.

Recent Progress

- The DOE Geothermal Program sponsored research that won two R&D 100 Awards in 2003: Acoustic Telemetry Technology, which provides a high speed data link between the surface and the drill bit; and Low Emission Atmospheric Monitoring Separator, which safely contains and cleans vented steam during drilling, well testing, and plant start-up.
- A second pipeline to carry replacement water has been completed through the joint efforts of industry and Federal, state, and local agencies. This will increase production and extend the lifetime of The Geysers Geothermal Field in California. The second pipeline adds 85 MW of capacity.

Commercialization and Deployment Activities

- Costs at the best sites are competitive at today's energy prices – and investment is limited by uncertainty in prices; lack of new, confirmed resources; high front-end costs; and lag time between investment and return.
- Improvements in cost and accuracy of resource exploration and characterization can lower the electricity cost; demonstration of new resource concepts, such as enhanced geothermal systems, would allow a large expansion of the U.S. use of hydrothermal when economics become favorable.

Market Context

- Hydrothermal reservoirs have an installed capacity of about 2,400 MW electric in the United States and about 8,000 MW worldwide. Direct-use applications have an installed capacity of about 600 MW thermal in the United States. About 300 MW electric are being developed in California, Nevada, and Idaho.
- Geothermal will continue production at existing plants (2.2 GW) with future construction potential (100 GW by 2030). Direct heat will replace existing systems in markets in 19 western states.
- By 2015, geothermal should provide about 10 GW, enough heat and electricity for 7 million homes; by 2020, an installed electricity capacity of 20,000 MW from hydrothermal plants and 20,000 MW from enhanced geothermal systems.

2.4 NUCLEAR FISSION

2.4.1 EXISTING PLANT RESEARCH AND DEVELOPMENT

Technology Description

Currently, 103 commercial nuclear power plants generate 20% of U.S. electricity – with about 100 GWe installed capacity – emitting no greenhouse gases (GHGs). Through the Nuclear Energy Plant Optimization (NEPO), DOE is working with the nuclear industry to apply new technology to nuclear and nonnuclear equipment in existing plants, enabling them to produce more electricity by optimizing their operating lifetimes. If not renewed, most current nuclear power plant licenses will expire between 2005 and 2030. If these plants are shut down and replaced with fossil-based generation, CO_2 emissions will *increase* by more than 160 million metric tons carbon per year (MMTC/yr) by 2030 (assuming 208 gC/kWh). Extending the lifetimes and optimizing the generation of these plants for 20 more years will avoid more than 3,200 MMTC through several years beyond 2050.

The goal of this area of R&D is to increase the efficiency, reliability, and power generation of existing nuclear power plants; and to help make the economic and clean air benefits of the plants available through current and renewed license terms. In 2003, 16 nuclear units have received approval to extend their operating licenses to 60 years; 34 others have filed or announced their intent to file for license extensions; and most, or all, of the remaining plants are expected to follow suit.

System Concepts

- Improve availability and maintainability of nuclear plants.
- Provide technology to predict and measure the extent of materials damage from plant aging.
- Operate plants at higher power levels, based on more accurate measurement and knowledge of safety margins, reduced consumption of onsite electrical power, and power uprates.

Representative Technologies

- Prediction and monitoring of stress-corrosion cracking of reactor internals and steam generators, materials-cladding processes.
- Advanced technologies for online condition monitoring of conventional equipment (pumps, motors, valves, etc.) to minimize production losses from unplanned outages.
- Replacement of aging, hard-to-maintain safety system instrumentation with easy-to-maintain advanced, digital electronics.
- Materials measurement and diagnostic technologies to determine the condition and fitness of aged materials.
- Advanced core loading strategies; nuclear fuel and cladding research.
- Advanced power generation technologies to increase electrical output.

Technology Status/Applications

- Current technology does not adequately determine residual life; overly conservative margins may result in premature shutdown or refurbishment.
- Replacing major components (e.g., steam generators) may be prohibitively expensive; better techniques are needed.
- Some in-service valve testing technology is in place, but current technology fails to efficiently detect a significant number of failures.
- Technology development for condition monitoring is required for application to nuclear plants.
- Technology advances are needed to achieve future extended power uprates.

Current Research, Development, and Demonstration
RD&D Goals • Increase electrical generation capability from existing plants by achieving continued improvement in average industry capacity factors and developing break-through technologies for long-term operation. • Address the long-term effects of component aging; optimize efficiency; and improve plant reliability, availability, and productivity while maintaining high levels of safety. **RD&D Challenges** • Development and demonstration of new technologies to allow future extended power uprates. • Complete the DOE/nuclear industry R&D program for research on existing nuclear plant life extension and generation optimization technologies. **RD&D Activities** • The department and the electric utility industry's Electric Power Research Institute (EPRI) developed the *Joint DOE-EPRI Strategic Research and Development Plan to Optimize U.S. Nuclear Power Plants* to help the Federal government and private sector jointly identify, prioritize, and execute R&D. The plan, first issued in March 1998 and later updated in October 2000, is based on input from utilities, DOE national laboratories, the Nuclear Regulatory Commission (NRC), and other key stakeholders. Research funded under the NEPO program is consistent with this joint strategic plan. • A previous cooperative research and development agreement between DOE's Office of Nuclear Energy, Science, and Technology; and the Electric Power Research Institute started development of advanced electronics to replace Westinghouse safety-system components. • Activities to improve monitoring of the condition of nuclear power plants are supported by DOE's Offices of Nuclear Energy, Science, and Technology; and the Nuclear Regulatory Commission. • Advanced technologies are being applied to existing light water reactors and aging research, funded by DOE.
Recent Progress
• An initial industry decision was made to commercialize DOE electronics technology for replacing Westinghouse safety system components. • Nonintrusive evaluation of pressurized water reactor accumulator discharge check valves has reduced testing time and improved reliability. • Hydrogen water chemistry is used in boiling water reactors to control stress-corrosion cracking. • Electrical cable condition monitoring and aging management techniques.
Commercialization and Deployment Activities
• The NEPO program has made significant progress toward addressing many of the material aging and generation optimization issues that have been identified as the key long-term issues facing current operating plants. Examples of recent results from the NEPO program include the development of new electrical cable monitoring techniques for improved prediction of cable lifetimes; and the development of techniques to qualify smart transmitters to replace existing analog transmitters, which are less accurate and are difficult to maintain. • Advanced diagnostic techniques are gaining wider acceptance for evaluating the status of safety-related equipment. • Successful technology may not be sufficient to extend the life of all plants if adverse regulatory or economic factors dominate. • DOE/industry Sustainable Electric Partnership Agreement provides a basis for DOE/industry cooperation and ensures commercial deployment. • DOE/industry NEPO program partnership provides another basis to ensure commercial deployment of R&D successes. **Market Context** • Technologies to support improved operations and life extension have enhanced the economics of existing nuclear power plants and thus increased their market value.

2.4.2 NEXT-GENERATION FISSION ENERGY SYSTEMS

Technology Description

Electricity from nuclear power generates no greenhouse gas emissions. To the extent that next-generation nuclear fission energy systems can address prevailing concerns, nuclear power can continue to be an important part of a greenhouse gas emissions-free energy portfolio. Although evolutionary light water reactors of standardized design are now available – and have received Nuclear Regulatory Commission design certification and been constructed on schedule in Japan and South Korea – newer nuclear energy systems in the long term need to offer significant advances in the areas of sustainability, proliferation resistance and physical protection, safety, and economics. These newer nuclear energy systems are required to replace or add to existing light water reactor capacity and can be available starting in 2015.

To develop these next-generation systems, DOE has initiated the Generation IV Nuclear Energy Systems Initiative. Generation IV is an international effort, with participation by Argentina, Brazil, Canada, France, Japan, Republic of Korea, Republic of South Africa, Switzerland, the United Kingdom, and the United States. The *Generation IV Nuclear Energy Systems Technology Roadmap* was completed in December 2002. The completed roadmap has identified the six most promising fission energy systems for potential further development. In FY 2003, DOE and its international partners initiated preconceptual design studies, fuel and materials development, and energy conversion development on promising systems of interest, which will lead to demonstration and eventual deployment (with industry and international participation) of one or more systems.

System Concepts

- Advanced fission reactors and fuel cycles that will reduce the potential for proliferation of nuclear materials, provide economical electricity generation, and contribute to hydrogen generation, with minimal waste products.

Representative Technologies

- Gas-Cooled Fast Reactor (GFR).
- Lead-Cooled Fast Reactor (LFR).
- Molten Salt Reactor (MSR).
- Sodium-Cooled Fast Reactor (SFR).
- Supercritical-Water-Cooled Reactor (SCWR).
- Very-High-Temperature Reactor (VHTR).

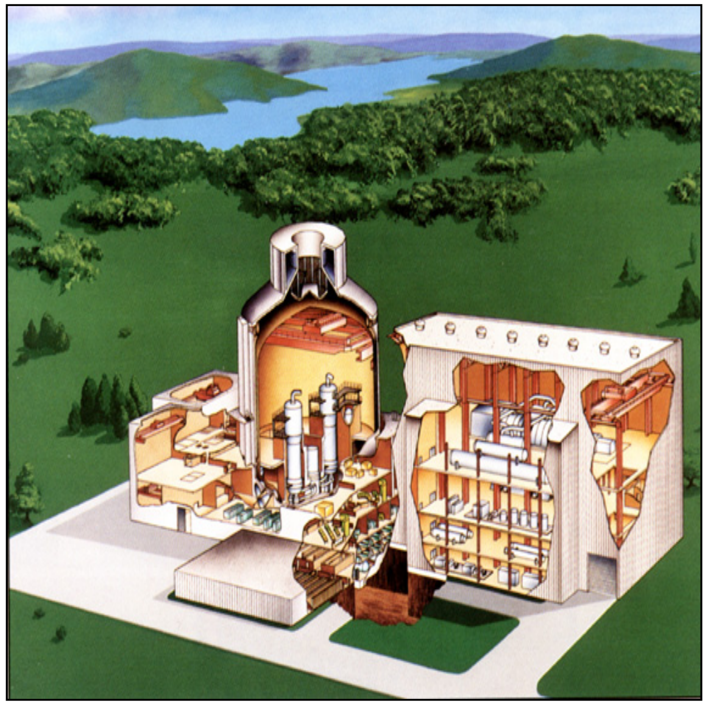
Technology Status/Applications

- Advanced fission reactors and fuel cycles: development is at advanced stage; demonstration is incomplete.
- High-temperature gas-cooled reactor development is focused on high-conversion efficiency through direct use of the high-temperature gaseous reactor coolant to power a gas turbine driving a generator (i.e., direct conversion), also capable of high-efficiency hydrogen production through electrolysis or chemical processes.
- Liquid metal-cooled reactors (both sodium and lead) have been successfully operated worldwide. Safety performance has been demonstrated, but economic performance needs improvement.
- Technologies for advanced fuel recycle and remote fuel refabrication have been developed in the laboratory, and some elements have advanced to pilot scale.
- Nuclear-assisted hydrogen production by means of thermochemical cracking of water is at the preconceptual design stage, requiring extensive development.
- Other advanced fission systems are at a preconceptual stage, requiring extensive development and irradiation testing of new fuel forms and high-temperature materials.
- Direct-cycle turbine technology requires development and demonstration.

Current Research, Development, and Demonstration
RD&D Goals • Generation IV research is focusing on reactors and fuel cycles that are safer, more economically competitive, more resistant to proliferation, produce less waste, and make better use of the energy content in uranium. **RD&D Challenges** • Demonstrate technology for advanced concepts. • Develop proliferation-resistant fuel-cycle concepts. • Develop safety, waste, and proliferation aspects of advanced fission reactors. • Conduct comprehensive R&D on advanced fission reactor concepts, relying heavily on international collaboration. **RD&D Activities** • Federally funded development of advanced reactors and fuel cycles has been resumed in the United States, through the Nuclear Energy Research Initiative, the Generation IV Nuclear Energy Systems Initiative, and the Advanced Fuel Cycle Initiative. • Advanced used fuel treatment technologies are under development through the Advanced Fuel Cycle Initiative.
Recent Progress
• Advanced light water reactors have received design certification from the Nuclear Regulatory Commission. • An advanced boiling water reactor, which was built in less than five years, is operating in Japan.
Commercialization and Deployment Activities
• Generation IV Nuclear Energy Systems are projected to be ready for commercial deployment in the timeframe of 2015 to 2030. **Market Context** • Indeterminate at this time. Potentially large international and domestic markets.

2.4.3 NEAR-TERM NUCLEAR POWER PLANT SYSTEMS

Technology Description



Electricity from nuclear power generates no greenhouse gas emissions. To the extent that deployment of near-term nuclear power plants can address prevailing concerns, nuclear power can continue to be an important part of a greenhouse gas emissions-free energy portfolio. In order to enable the deployment of new, advanced nuclear power plants in the United States in the relatively near-term – by the end of the decade – it is essential to demonstrate the untested federal regulatory and licensing processes for the siting, construction, and operation of new nuclear plants. In addition, other major obstacles (including the initial high capital costs of the first few plants and the business risks resulting from this and the regulatory uncertainty) must be addressed. Research and development on near-term advanced reactor concepts that offer enhancements to safety and economics is needed to enable these new technologies to be competitive in the deregulated electricity market, and support energy supply diversity and security.

The *Near-Term Deployment Roadmap* was issued in October 2001 and advises DOE on actions and resource requirements needed to support deployment of new nuclear power plants by 2010. The primary focus of the roadmap is to identify the generic and design-specific gaps to near-term deployment, to identify those designs that best promise to meet the needs of the marketplace, and to propose recommended actions that would close gaps and otherwise support deployment. This includes, but is not limited to, actions to achieve economic competitiveness and timely regulatory approvals.

System Concepts

- Advanced fission reactor designs that are currently available or could be made available with limited additional work to complete design development and deployment in the 2010 timeframe.

Representative Technologies

- Certified Advanced Light Water Reactor designs: ABWR, AP600, System 80+.
- Enhancements to certified designs with some engineering work already completed: AP1000, ESBWR.
- Gas reactor designs with significant engineering work already completed: PBMR, GT-MHR.
- Proposed designs from overseas with significant potential for near-term deployment in the United States: SWR-1000, ACR-700.

Technology Status/Applications

- All near-term deployment designs are well-defined concepts in varying stages of development. Most still need significant detailed engineering development and/or regulatory approval.

Current Research, Development, and Demonstration

RD&D Goals

- Demonstration of the untested regulatory processes for Early Site Permit (ESP) and combined Construction and Operating License (COL) processes.
- Industry decision to order a new nuclear power plant by 2005.
- Deployment of one or more new nuclear power plants in the 2010 timeframe.

RD&D Challenges

- Most R&D challenges remaining for near-term deployment options relate to advanced light water and gas reactors, including fuel development, characterization, manufacture, testing and regulatory acceptance; power conversion system design and testing, including resolution of uncertainties regarding materials, reliability, and maintainability; and fission reactor internals design and verification.

- Support resolution of the technical, institutional, and regulatory barriers to the deployment of new nuclear power plants in the 2010 timeframe, consistent with recommendations in *Near-Term Deployment Roadmap.*
- In cooperation with the nuclear industry, demonstrate the untested regulatory processes for Early Site Permit and combined Construction and Operating Licenses to reduce licensing uncertainties and attendant financial risk to the licensees.
- Provide for conduct of R&D to enable finalization and NRC certification of those advanced nuclear power plant designs that the U.S. power generation companies are willing to build.
- Provide for development and demonstration of advanced technologies to reduce construction time for new nuclear power plants and to minimize schedule uncertainties and associated costs for construction.

RD&D Activities

- Demonstration of regulatory processes for Early Site Permit and combined Construction and Operating Licenses.
- Development and NRC certification of advanced nuclear plant designs.
- Gas reactor fuel development and qualification.

Recent Progress

- Three near-term deployment designs have been certified by the Nuclear Regulatory Commission.
- The Advanced Boiling Water Reactor has been deployed successfully in Japan; Advanced Boiling Water Reactors are under construction in Taiwan.
- Three U.S. utilities plan to apply for NRC approval of sites for new nuclear plants.
- Reactor vendors are exploring NRC certification of advanced reactor concepts.
- The three cost-shared Early Site Permit (ESP) demonstration projects initiated with industry in FY 2002 continued with the plan for completed ESP applications to be submitted by the power-generating companies to NRC for review and approval.
- A nuclear power plant project cost and construction assessment to independently evaluate the cost, schedule, and construction methods of advanced nuclear plant designs, as well as identify promising improvements to the construction methods and techniques to support new nuclear power plant deployment in the 2010 timeframe was initiated.
- The advanced gas-cooled reactor fuel development and qualification activities initiated in FY 2001 continued.
- Fuel fabrication process development in laboratory-scale equipment as well as manufacture and characterization of the demonstration fuel, which will undergo irradiation testing, was initiated.

Commercialization and Deployment Activities

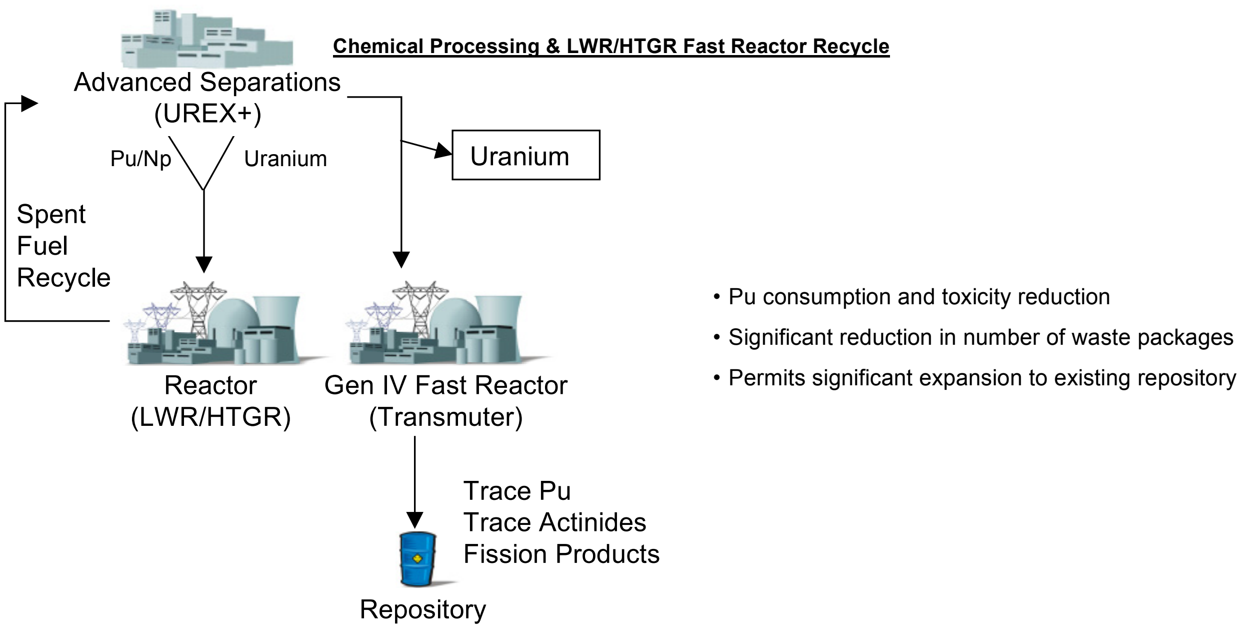
- At least two designs and perhaps more can be commercialized in the United States in the 2010 timeframe. Achieving this goal will require a major effort by industry and DOE to work together to resolve open issues and to share the one-time costs of closing both generic and design-specific gaps.

Market Context

- The focus of the market is in the United States. Due to the uncertainty regarding the impacts of deregulation, designs in the 100-300 MW_e range and the 1,000 MW_e-plus range are both required.

2.4.4 ADVANCED NUCLEAR FUEL CYCLE PROCESSES

Technology Description



Electricity from nuclear power generates no greenhouse gas emissions. To the extent that deployment of advanced nuclear fuel cycle processes can contribute to the success of next-generation fission systems, nuclear power can continue to be an important part of a greenhouse gas emissions-free energy portfolio. Current nuclear fission reactors operate in the United States with once-through fuel cycles and produce significant quantities of used or "spent" nuclear fuel. Several current designs for future fission reactors also rely on once-through fuel cycles. The planned disposal of spent nuclear fuel is in geologic repositories, and the accumulation of spent nuclear fuel raises public concerns about radiotoxicity, dose, and proliferation risk. Once-through fuel cycle technology also does not make optimal use of natural uranium resources. DOE activities under the Advanced Fuel Cycle Initiative aim at developing the technologies needed to dramatically reduce the waste stream from nuclear fission, thus lowering the potential environmental consequences, reducing the cost of geologic disposal, reducing the technical need for a second repository, and making better use of natural resources. These activities include transmutation research, in which the actinides and selected fission products in spent nuclear fuel are separated, stored, and potentially formed into fuels that can be bombarded by neutrons in reactors or accelerator driven systems, causing them to fission or transmute into shorter-lived or stable elements/isotopes. In the long term, these technologies may be assembled into advanced Generation IV nuclear systems that could result in decreased amounts of waste, while generating substantial amounts of energy.

System Concepts

- Advanced nuclear systems (fission reactors and accelerator-driven systems) that aim to reduce the lifetime of the waste from current-generation fission reactors to short times.
- Advanced nuclear systems that aim to extract the full energy potential of the spent nuclear fuel from current fission reactors, while reducing or eliminating the potential for proliferation of nuclear materials and technologies, and reducing the amount of waste produced.

Representative Technologies

- Spent-fuel treatment technologies that are proliferation resistant.
- Advanced fuel types for waste transmutation.
- Advanced fuel types for sustained nuclear energy.
- Accelerator-driven systems for rapid waste transmutation.
- Advanced reactors for sustained nuclear energy.

Technology Status/Applications

- Advanced fuel-cycle development has reached the laboratory scale-demonstration stage in some cases.
- Transmutation fuels are in early R&D stages.
- Development of accelerator-driven systems is at the preliminary R&D stage.

Current Research, Development, and Demonstration

RD&D Goals

- Prove design principles of spent-fuel treatment and transmutation technologies.
- Demonstrate the fuel and separation technologies for waste transmutation.
- Deploy Generation IV advanced fast spectrum reactors that can transmute nuclear waste.

RD&D Challenges

- Demonstrate performance of advanced fuel cycles.
- Demonstrate performance of advanced transmutation fuels.
- Demonstrate technology for advanced fission reactor concepts.
- Demonstrate feasibility and technology for accelerator-driven systems.

RD&D Activities

- Continued development and demonstration of aqueous and electrometallurgical spent-fuel treatment technologies.
- Development of transmutation fuels for Generation IV reactor systems.
- Development of technologies for accelerator-driven systems.

Recent Progress

- Hot demonstration of the UREX (Uranium Extraction) aqueous spent fuel treatment process.

Commercialization and Deployment Activities

- Disposal of spent nuclear fuel is a government activity in the United States. Similar spent-fuel treatment and transmutation technology development programs exist in France, Japan, and the United States. Development of treatment and transmutation technologies for use with advanced Generation IV fuel cycles will increase the acceptability of nuclear energy.
- Advanced Fuel Cycle Initiative has the potential to decrease the quantity and toxicity of nuclear waste, possibly eliminating the need for a second geologic repository.

Market Context

- Technologies to improve spent-fuel disposition increase the value of keeping existing nuclear power plants online as well as increase the likelihood for expanded new nuclear power capacity.

2.5 NUCLEAR FUSION

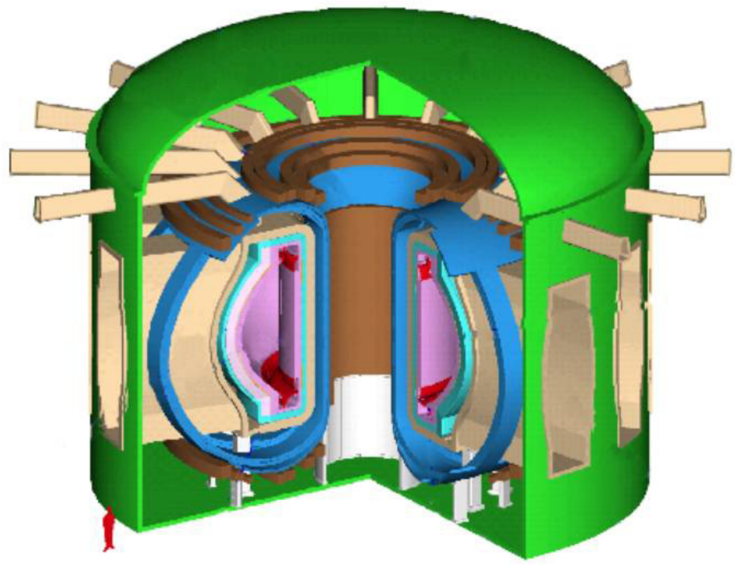
2.5.1 FUSION POWER

Technology Description

Magnetic fields or particle inertia are used to confine a hot plasma to produce fusion energy from deuterium/tritium fuel. Deuterium is abundantly available from water, and tritium can be produced from lithium within the fusion plant. The energy of the fusion reactions could be used to generate electricity and/or hydrogen at central power plants with no greenhouse gas emissions. Due to anticipated low fuel costs, electricity produced from fusion at off-peak hours could also be used to generate hydrogen at off-site fueling stations.

System Concepts

- Strong magnetic fields produced by, in some cases, superconducting coils confine plasmas with temperatures of several hundred million degrees Celsius. Twenty percent of the heat from the fusion reactions remains in the fuel to sustain its high temperatures; the rest is carried out by neutrons and is absorbed in a surrounding blanket that serves both as a heat source to produce power and as a medium for producing the tritium.
- Compressed fuel pellets ignite and burn, producing repetitive pulses of heat and neutrons in a reaction chamber. For some approaches, flowing molten salt walls in the chamber can serve as blankets.



Pictured above is the fusion-specific portion of a 1,000 MWe power plant, the result of a conceptual design study done to explore the scientific and technological issues associated with the possible reactor embodiments of fusion.

Representative Technologies

- Large, high-current-density superconducting magnets; deuterium ion beams (energies of 100–1000 keV); millimeter-wave high-power microwaves; high-power, radio-frequency sources and launchers; and particle fueling apparatus for magnetic fusion.
- Heavy ion beam accelerators, diode-pumped solid-state lasers or krypton-fluoride gas lasers, target fabrication technologies, and advanced chamber technologies are required for inertial fusion.
- Structural materials with low-activation properties will be required to fulfill the ultimate potential of fusion devices. Tritium generation and heat-recovery systems are other common nuclear system technologies required for both magnetic and inertial fusion.

Technology Status/Applications

- Moderate-sized magnetic confinement fusion experiments, with plasmas at temperatures needed for power plants, have produced more than 10 MW of fusion power, and more than 20 MJ per pulse.
- A facility is being designed through an international project, which will support scientific experiments and engineering tests for magnetic fusion burning plasma that is near commercial power plant scale (500 MW of fusion power, 500-2500 sec pulse length).
- The physics of subignited targets has been advanced with glass lasers, and underground test results have resolved certain feasibility questions of high gain for power plants.
- The target physics of ignition and high gain, using glass lasers, are objectives of the National Ignition Facility, now under construction.
- Dramatic advances have been made in the understanding and control of magnetically confined plasmas, allowing improved designs of confinement systems and increased confidence in extrapolations to power plant scale.

Current Research, Development, and Demonstration

RD&D Goals

- Accelerate the advance of scientific understanding of fusion plasmas.
- Determine the approaches and configurations for both magnetic and inertial fusion that will take the best advantage of the newest scientific insights.
- Establish the technological basis for an efficient, low-cost ion beam using an induction accelerator; develop high-average-power, durable and cost-effective solid-state and gas laser systems; and demonstrate useful gain from compression and burn of National Ignition Facility targets.
- Qualify low-activation materials that meet structural and compatibility criteria.

RD&D Challenges

- Develop magnetic geometries optimal for heat containment that at the same time (1) minimize technical complexity, (2) maximize fusion power density for good economics, and (3) operate in a continuous mode.
- Understand target requirements for high gain; reduce the development cost of candidate drivers; and develop long-life chambers and low-cost pellet targets.
- Develop low-activation materials that also meet structural and compatibility criteria.

RD&D Activities

- Coordinated worldwide magnetic fusion experimental and theoretical efforts center on configuration improvements. Fusion technology and materials development is also being pursued internationally.
- The United States has joined Europe, Japan, Canada, China, and Russia to develop plans for construction of a magnetic fusion-burning plasma science and engineering test facility (called ITER), which is to be capable of operation for 500–2,500 sec with fusion power level of 500 MW.
- Inertial fusion efforts are concentrated on driver, chamber, and pellet manufacturing technologies.
- The National Ignition Facility project, funded by the National Nuclear Security Administration, will provide information on high-gain, single-shot pellet burn experiments for inertial fusion energy.

Recent Progress

- More than 10 MW of fusion power was produced in magnetically confined plasma for about 1 second, using deuterium-tritium fuel.
- Improved understanding of plasma stability and turbulence has led to improved plasma performance in existing facilities and improved configuration designs for the future.
- Results from underground tests in the United States have resolved fundamental questions of feasibility of high gain for efficient fusion power plants.
- Results from the NOVA laser at Lawrence Livermore National Laboratory have confirmed the validity of computer models used to predict ignition and gain in the National Ignition Facility.
- Vanadium alloys show promise as a low-activation structural material in magnetic fusion devices, and liquid walls for inertial fusion chambers promise to avoid life-limiting radiation damage.

Commercialization and Deployment Activities

- Large central-station, electrical-generating plants could be commercialized late in the second quarter of the 21st century; the timescale depends on a sustained international effort and success in that R&D.
- Fusion power plants would replace aging and polluting power generators and fill a potential multibillion-dollar market sector.
- Many technologies developed for fusion are used in the commercial sector. Prominent are plasma processing for etching semiconductor chips, hardening of metals, thin-film deposition, and plasma spraying and lighting applications. Other applications from this research include medical imaging, heat-removal technologies, destruction of toxic waste, X-ray lithography and microscopy, micro-impulse radar, precision laser cutting, large-scale production of precision optics, and high-power microwave and accelerator technologies.
- Emphasize fusion science, concept improvement and alternative approaches, and development of materials.
- Recognize increasing importance of international cooperation as a means of building major facilities.

Market Context

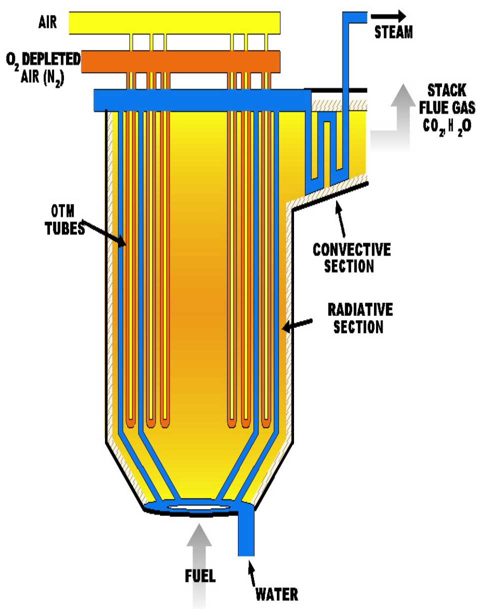
- Large potential market in the United States and throughout the world.

3.0 CAPTURING AND SEQUESTERING CARBON DIOXIDE

3.1. GEOLOGIC SEQUESTRATION

3.1.1 CO_2 CAPTURE AND SEPARATION

Technology Description



Oxyfuel Technology

Integrates air separation, using O2 Transport Membrane (OTM) and oxygen combustion

Fossil- and biomass-based energy conversion processes convert hydrocarbon materials (i.e., substances consisting mostly of carbon and hydrogen) into carbon dioxide and water while releasing energy. The goal of CO_2 capture and separation is to produce relatively pure CO_2 from these processes, preferably at pressures suitable for storage or reuse.

System Concepts

- *Post-combustion capture*. A chemical or physical separation process extracts CO_2 from the flue gas of a conventional air-fired combustion process. CO_2 is present in concentrations ranging from 3% to 12%. The focus is on technology for retrofitting or repowering existing power plants and industrial processes.
- *Oxy-fuel combustion*. Pure oxygen rather than air is charged to the combustion chamber, producing a flue gas of CO_2 and water. A portion of the CO_2 is recycled and mixed with the oxygen to absorb heat and control the reaction temperature.
- *Precombustion decarbonization*. The hydrocarbon feedstock is gasified to produce a synthesis gas made up primarily of hydrogen and carbon dioxide. The CO_2 is separated from the hydrogen before it is combusted or charged to a fuel cell.
- There are other advanced-system concepts in which fuel processing and CO_2 capture are integrated into a single stage using, for example, membranes or reduction-oxidation agents.

Representative Technologies

- The conventional technology for post-combustion capture (removing CO_2 from flue gas) is amine scrubbing. A solution of amine and water is contacted with flue gas. The amine and the CO_2 undergo a chemical reaction forming a rich amine that is soluble in the water. The rich amine solution is pumped to a desorber where it is heated, reversing the reaction and releasing pure CO_2 gas. The recovered amine is recycled to the flue-gas contactor.
- Other technologies for post-combustion capture include cryogenic distillation, polymer membranes, ceramic membranes, carbon absorbents, sodium absorbents, hydrides, and lithium silicate.

Technology Status/Applications

- Amine systems are used in numerous industrial applications to capture CO_2 from flue gas for use as a commodity chemical. Cryogenic and carbon absorbent systems have been built commercially.
- Other post-combustion capture technologies are being developed at the laboratory and pilot scale.

Current Research, Development, and Demonstration

RD&D Goals

- In the long term, reduce the cost of capture so that it increases the cost of energy services by 10% or less.
- By 2005, reduce the cost of capture by 50% in retrofit applications. Attainment of 2005 goals will be estimated based on technology performance in pilot-scale proof-of-concept demonstrations.
- Conduct large-scale demonstration of new technology by 2010.

RD&D Challenges

- CO_2 exists in air-combustion flue gas at low concentration, 3-12 volume percent.
- Flue gas contains reactive impurities that can adversely affect CO_2 capture systems.
- Transport and/or storage systems may require highly pure CO_2 product.
- Loss of CO_2 temperature and pressure across the capture system.

RD&D Activities

- Laboratory-scale experiments with advanced amines, ceramic membranes, high-temperature polymer membranes, vortex gas/liquid separator, ammonium bicarbonate, carbon absorbents, and electrochemical pumps.
- Pilot-scale tests with a novel oxy-fuel boiler, a CO_2/water hydrate process, a sodium-based CO_2 sorbent, and a metal reduction-oxidation power generation process.

Recent Progress

- During a short three-year period, a strong portfolio of research projects has been developed with more than 40% private-sector cost-share.
- The international community has been successfully engaged through participation in the International Energy Association Greenhouse Gas Programme, the CO_2 Capture Project with the European Commission and other international participants, and other collaborations with Canada, Australia, and Japan.

Commercialization and Deployment Activities

- Roughly 15 Mt/yr of CO_2 is captured from anthropogenic emissions sources in the United States and used as a commodity chemical.

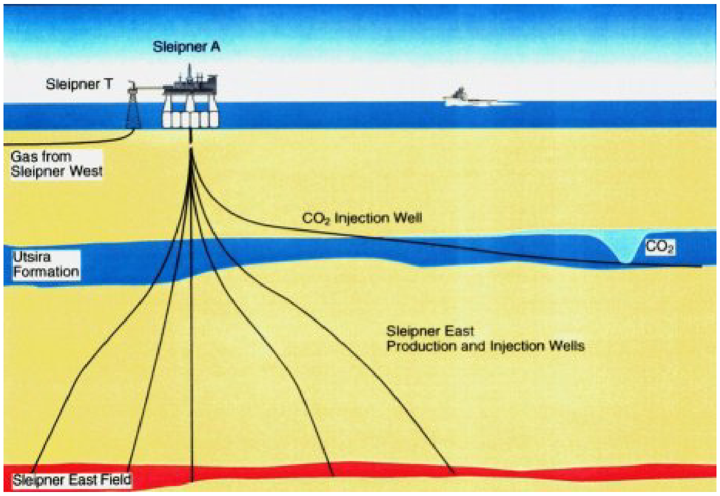
Market Context

- Development of approaches for economically decarbonizing fossil fuels will allow the carbon-free production of electricity and hydrogen, and will take advantage of an existing fossil fuel infrastructure that accounts for more than 80% of the energy consumed in the United States and internationally.

3.1.2 CO_2 STORAGE IN GEOLOGIC FORMATIONS

Technology Description

Sleipner North Sea Project



Large amounts of CO_2 (about a billion tons per year) may need to be stored as a part of a future global atmospheric stabilization strategy. CO_2 can be injected into depleting oil wells and unmineable coal-bearing formations to enhance resource recovery. A portion of the CO_2 remains underground, although current industry practices are geared strongly toward minimizing the CO_2 left underground – and little or no attention is paid to the CO_2 that is not recovered. R&D is focused on revamping conventional enhanced oil recovery and enhanced coalbed methane processes so that they can serve a dual purpose: resource recovery and CO_2 storage. Saline formations, organic-rich shale beds, and other nonconventional geologic structures have potentially enormous CO_2 storage capacities. Research is focused on learning more about these formations and developing the capabilities needed to use them as CO_2 repositories.

System Concepts

- CO_2 is captured from a large point source of anthropogenic emissions, transported, and injected into a depleting oilwell, unmineable coal seam, saline formation, depleting gas well, shale formation, or other geologic structure amenable to CO_2 storage.
- Storage may entail geochemical reactions that tend to form carbonates in silicic host rock, enhancing containment.
- In an oil well, the CO_2 decreases the viscosity of the oil, enabling more of it to be recovered. A portion of the injected CO_2 remains stored in a reservoir as a free gas, brine or oil solution, or carbonate.
- In a coal bed, CO_2 displaces methane absorbed onto the surface of the coal, enabling it to be recovered. The CO_2 remains absorbed on the coal and, thus, is securely stored.
- Components in the CO_2 stream (e.g., sulfur, nitrous oxides, nitrogen) could have a positive impact on certain storage applications.

Representative Technologies

- Natural gas storage in saline aquifers provides relevant capability.
- Technologies will borrow extensively from the petroleum industry in the areas of drilling simulation; completion of injection wells; processing, compression, and pipeline transport of gases; operational experience of CO_2 injection for enhanced oil recovery; and subsurface reservoir engineering and characterization.

Technology Status/Applications

- The Mount Simon reservoir underlying Illinois, Indiana, Michigan, Kentucky, and Pennsylvania has been approved for industrial waste disposal and underlies a region with numerous fossil energy power plants.

- Industry has experience with more than 400 wells for injecting industrial wastes into saline formations.
- The petroleum technology is readily adaptable to subsurface CO_2 storage.

Current Research, Development, and Demonstration

RD&D Goals

- Develop domestic CO_2 underground storage repositories capable of accepting around a billion tons of CO_2 per year.
- Demonstrate that CO_2 storage underground is safe and environmentally acceptable.
- Demonstrate an effective business model for CO_2 enhanced oil recovery and enhanced coalbed methane, where significantly more CO_2 is permanently stored than under current practices.
- Develop publicly accepted monitoring protocols.

RD&D Challenges

- Develop the capability to inject CO_2 into saline formations with low permeability.
- Harness geochemical reactions to enhance containment.
- Develop injection practices that preserve cap integrity.
- Develop an understanding of the CO_2 properties of shales and other unconventional hydrocarbon-bearing formations.
- Develop the ability to track CO_2 transport.
- Develop field practices that optimize CO_2 storage and resource recovery.
- Develop the ability to predict the CO_2 storage capacity and potential resource recovery of a particular formation.
- Develop the ability to track the fate and transport of injected CO_2.
- Develop a better understanding of the chemistry of coal and CO_2, and conduct comprehensive R&D program on all physical and chemical aspects of CO_2 interactions with reservoir phases.

RD&D Activities

- Study geochemical reactions involving CO_2 in a laboratory.
- Study the natural analogs of geochemical CO_2 conversion. Study rock samples from CO_2 bearing geologic formations to better understand in situ geochemical/geobiological reactions.
- Develop CO_2 tracking technology, e.g., sonic, chemical tracers.
- Study CO_2 transport in the Sleipner Vest gas field, via the International Energy Agency's Greenhouse Gas Programme.
- Novel injection techniques to increase CO_2 storage in saline formations.
- CO_2 storage in coal beds. ARI and industry consortium, commercial-scale field demonstration in the San Juan Basin; Consol – horizontal drilling, Alabama geologic survey, screening model for Black Warrior.
- CO_2 storage in oil reservoirs. Weyburn, reservoir mapping, West Pearl Queen, CO_2 monitoring and simulation.

Recent Progress

- Major saline formations underlying the United States have been identified.
- Initiated a pilot-scale test of CO_2 storage in a depleted oil reservoir.
- Initiated several field tests with key industrial companies participating and providing cost-share: Consol Inc. CBM,-Appalachia ARI, CBM-San Juan Basin; Strata Production C. – Permian Basin; Pan Canadian Resources EOR-Canada.

Commercialization and Deployment Activities
• Since 1999, Statoil has been injecting CO_2 at a rate of 1 Mt/yr into the Sleipner Vest gas field in a sandstone aquifer 1,000m beneath the North Sea. • About 70 oil fields worldwide use CO_2 for enhanced oil recovery. • Another project uses CO_2 from Dakota Gasification for enhanced oil recovery in the Weyburn field in Canada. CO_2 is transported via pipeline. • The pipeline enables extensive use of CO_2 for enhanced coal bed methane recovery in the San Juan basin. • There are plans for using CO_2 for enhanced oil recovery in Kansas, using CO_2 from ethanol production. **Market Context** • Development of approaches for economically decarbonizing fossil fuels will allow the carbon-free production of electricity and hydrogen, and will take advantage of an existing fossil fuel infrastructure that accounts for more than 80% of the energy consumed in the United States and internationally.

3.1.3 NOVEL SEQUESTRATION SYSTEMS

Technology Description
In the long term, CO_2 capture can be integrated with geologic storage and/or conversion. Many CO_2 conversion reactions are attractive but too slow for economic chemical processes. **System Concepts** • Using impurities in captured CO_2 (e.g., SO_x, NO_x) or additives enhances geologic storage. This is a possible opportunity to combine CO_2 emissions reduction and criteria pollutant-emissions reduction. • Conducting reactions on CO_2 while it is being stored underground can alleviate the problem with slow kinetics. • Rejected heat from electricity generation and CO_2 compression can help drive CO_2 conversion process. **Representative Technologies** • Capture of CO_2 from flue gas and algal conversion to biomass. • Capture of CO_2, storage in a geologic formation, and in situ biological conversion to methane. **Technology Status/Applications** • Conceptual.
Current Research, Development, and Demonstration
RD&D Goals • Demonstrate viable chemical or biological conversion approaches at the laboratory scale. • Develop robust conceptual designs for integrated capture, storage, and conversion systems. **RD&D Challenges** • CO_2 conversion reaction kinetics are slow, energy requirements are high. • For biological in situ CO_2 conversion, must provide food and remove waste. • Truly novel concepts may be required to meet the ultimate “stretch” goals of the program. Technology breakthroughs could come from concepts associated with areas not normally related to traditional energy technologies (e.g., nanotechnology). Tapping areas where current researchers do not have an energy mindset will require new approaches for soliciting proposals for R&D projects. **RD&D Activities** • Laboratory and pilot-scale experiments with biological and chemical conversion. • Conceptual studies of integrated systems and in situ CO_2 conversion.
Recent Success
• Several cost-shared research projects have been initiated.
Commercialization and Deployment Activities
• None.

3.2. TERRESTRIAL SEQUESTRATION

3.2.1 LAND MANAGEMENT

3.2.1.1 CROPLAND MANAGEMENT AND PRECISION AGRICULTURE

Technology Description

Cropland management practices can increase the amount of carbon stored in agricultural soils by increasing plant biomass inputs or reducing the rate of loss of soil organic matter to the atmosphere as CO_2. Precision agriculture is a form of site-specific management used to increase productivity. This approach can be adapted for improving soil carbon sequestration through a customized carbon sequestering management plan.

System Concepts

- Each production system will have its own particular set of practices that optimize carbon sequestration while maintaining profitable crop production.
- Precision agriculture can be used to develop the most appropriate suite of technologies for specific sites.
- Most agricultural soil management practices that promote carbon sequestration provide additional environmental and yield benefits.
- Use of genetically modified crops to enhance yields and reduce fertilizer use.

Representative Technologies

- Conservation tillage, especially no-till.
- Residue management.
- Reducing fallow.
- Cover crops.
- Nutrient management.
- Manure and organic matter additions.
- Water management.
- Erosion control.
- Apply advanced information technologies (e.g., global positioning systems, remote sensing, computer modeling) for efficient application of management treatments.
- Herbicide-tolerant crops that advance conservation tillage.
- Genetically modified crops that increase utilization of soil nutrients and/or fertilizer.
- Technologies that increase agricultural productivity (e.g. by increasing yields, minimizing crop losses, minimizing spoilage and increasing shelf life, because each would minimize area under cultivation).

Technology Status/Applications

- Each of these technologies and management practices has been researched and implemented for purposes other than carbon sequestration (for soil conservation, erosion control, and crop yield increases).
- Soil carbon data has been collected from hundreds of long-term field studies and used to estimate the soil carbon sequestration potential of different management practices.
- Additional studies are underway to explicitly investigate the potential of various management practices to sequester soil carbon.
- Technical support is available on how to implement these technologies for conservation and yield-enhancing purposes.
- Specialized equipment for implementing management practices (no-till drills, global positioning systems, etc.) is commercially available.

Current Research, Development, and Demonstration

RD&D Goals

- Quantify the carbon sequestration potential of each technology and management practice for various crop production systems, climates, and soils.
- Develop the combinations of practices that optimize soil carbon sequestration, crop production, and profits for various crop production systems; soil types; and geographical areas.
- Determine the applicability of precision agriculture for enhancing carbon sequestration.

- Develop decision support tools for farmers, other land managers, and policy makers that provide guidance for land-management decisions. For example, create databases that answer questions about how changing from one land-use practice to another will affect carbon sequestration, production, and profits.

RD&D Challenges

- Measuring and monitoring procedures need to be improved for more accurate determination of cropland soil carbon status.
- Increasing cropland soil carbon without increasing emissions of other greenhouse gases, especially nitrous oxide and methane.
- Research on the effect on carbon sequestration of specific management practices, climate and weather factors, soil properties, and cropping systems is needed to develop recommendations and improve models and decision support tools.

Recent Progress

- Research programs have been established in the USDA (Carbon Cycle Component of Agriculture Research Service's Global Change National Program), Consortium for Agricultural Soils Mitigation of Greenhouse Gases, DOE Office of Fossil Energy, and U.S. Geological Survey to conduct research on soil carbon sequestration.
- More data are becoming available to improve the quantification of the cropland carbon sequestration.
- Preliminary models and decision support systems have been developed.
- Research on precision agriculture has been initiated.

Commercialization and Deployment Activities

- Carbon sequestration markets are being developed.

Market Context

- Ranges from 10%-80 % of cropland acreage.

3.2.1.2 CONVERTING CROPLANDS TO RESERVES AND BUFFERS

Technology Description

Converting croplands to other less-intensive land uses such as conservation reserve and buffer areas increases soil carbon because soils are not subjected to tillage and other disturbances that lead to soil carbon losses.

System Concepts

- Conversion of croplands to reserves and buffers provides environmental benefits by removing potentially degradable land from production, but competes with crop production needs and markets.
- Reserves receive minimal long-term management and may be converted back to cultivation.
- Soil carbon can be rapidly lost if reserves or buffers are converted back to cultivation.
- Reduce land under cultivation, which then would directly or indirectly free up land for conservation purposes.

Representative Technologies

- *Conservation Reserve Program*. Converts cropland in environmentally sensitive areas to grass or forest land for a contractual time period (e.g, 5-15 years).
- *Riparian Buffers.* Land adjacent to streams is converted from cropland into grass and forest land.
- Technologies that increase agricultural productivity (e.g. by increasing yields or minimizing spoilage and increasing shelf life, because each would minimize area under cultivation.

Technology Status/Applications

- Almost 34 million acres of land have been entered into the Conservation Reserve Program as of 2002.

Current Research, Development, and Demonstration

RD&D Goals

- Quantify the carbon sequestration potential of buffer and reserve programs for various climates and soils.
- Develop the combination of practices (e.g., plant species, siting, establishment practices) that optimize carbon sequestration and minimize production losses for various types of reserves and buffers.
- Develop decision support tools for farmers, other land managers, and policy makers to inform which areas to put into reserves and the relative costs and benefits of different land conservation approaches, both in terms of carbon sequestration and production.

RD&D Challenges

- Improve measuring and monitoring procedures for more accurate carbon status.
- Determine the effects of conservation reserves on non-CO_2 greenhouse gases.
- Develop the optimal combination of practices for each system for each area of the country and soil type.
- Develop better models and decision support systems.

Recent Progress

- Estimates of the potential for reserve and buffer area soils to sequester soil carbon have been published and provide a baseline for future activities.
- Ongoing programs have been established in USDA to promote and assist in buffer and conservation reserve programs.
- Preliminary models and decision support systems have been developed.

Commercialization and Deployment Activities

- USDA has an established Conservation Reserve Program and riparian buffer program.
- Technical support is available from USDA on how to implement technologies and practices.

Market Context

- The market for implementing land conservation through reserves and buffers will be driven by other conservation priorities such as erosion control and water quality, and crop commodity prices.

3.2.1.3 ADVANCED FOREST AND WOOD PRODUCTS MANAGEMENT

Technology Description

Advanced forest and wood products management represent large carbon sequestration opportunities that can also produce other environmental benefits, such as improved water quality and habitat. Advanced technology is also needed to improve forest and wood product management in these areas: (1) data collection, assimilation, and analysis, (2) design, development, and management of forest systems, and (3) deployment of acceptable operations. Information systems are needed for collecting and using increasingly detailed site-specific data. Traditional silvicultural tools need to be integrated with newer technologies to better design and manage forest production. In addition, these systems provide for improved understanding, control, and manipulation of woody tree growth, resource requirements and acquisition, and microbial processes that control carbon, water, and nutrient flows. Energy-efficient, low-impact systems will be developed and used to apply treatments optimized to achieve specific resource outcomes. Durable wood products in use and wood disposed of in landfills can provide a mechanism to allow forestlands to continually add to and increase the amount of sequestered carbon. Advances in developing wood products, substitutions, recycling technologies, and wood waste management provide pathways to increase carbon sequestration. These systems provide an integrated capability to improve environmental quality while enhancing economic productivity by increasing energy efficiency, optimizing fertilization and other site treatments, and conserving and enhancing soil and water resources.

System Concepts

- Global positioning, measurement infrastructure, and remote and in situ sensors for soil, plant, and microclimate characterization and monitoring.
- Process-based growth models, data, and information analysis.
- Variable-rate application control systems and smart materials for prescription delivery.
- Advanced management systems for wood products in use and in landfills and advanced wood products development.
- Low-impact, energy-efficient access and harvest systems.

Representative Technologies

- Integrated forest carbon dynamics, inventory, modeling, and prediction systems.
- Global positioning satellites and ground systems, satellite and aircraft based remote sensing, in situ electrical, magnetic, optical, chemical, and biological sensors.
- Advanced information networking technologies; autonomous control systems; selected and designed genetic plant stock; materials responsive to soils, plants, moisture, pests, and microclimates.
- Biological and chemical methods for plant and microbial process manipulation.
- Wood product development, substitution, and management pathways.

Technology Status/Applications

- Many first-generation precision technologies can be used in silvicultural systems, especially in plantations with little modification. Application to mixed-age and/or mixed-species forest types will require additional research. LIDAR and RADAR remote-sensing methods are being tested for 3-D imaging of forest structure.
- Information management and networking tools; rapid soil monitoring and characterization sensors; tree stress and growth sensors; systematic integration of all technologies are not yet available for application to silvicultural projects.
- Understanding of soil nutrient processes exists in the forestry, energy, and university research communities.
- The capability exists for genetic characterization performance testing of plant stocks, developing smart materials, and methods for microbial manipulation.

Current Research, Development, and Demonstration

RD&D Goals

- Technologies that improve silviculture operation efficiencies and reduce energy consumption from road building to milling processes and transportation.
- Economic and biophysical modeling to better understand the economics of achieving certain GHG mitigation goals through tree planting and improved forest management.

- Remote and field deployed sensors/monitors and information management systems for accurate, real-time monitoring and analysis of plant growth, soils, water, fertilizer, and pesticide/herbicide efficiency.
- Smart materials for prescription release.
- Advanced fertilizers and technologies to improve fertilizer efficiency and reduce nitrogen fertilizer inputs.
- Methods of manipulating system processes to increase efficiency of nutrient availability and uptake to increase CO_2 uptake and sequestration and reduce emissions.
- Wood product management and substitution strategies.
- Initial systems models and prototype operation on major plantation types by 2007.
- Deploy first-generation integrated system models and technology by 2010.

RD&D Challenges

- Site-specific silviculture requires advances in rapid, low-cost, and accurate soil nutrient and physical property characterization; real-time water and nutrient demand characterization, photosynthesis and allocation characterization, and insect and pest infestation characterization; autonomous control systems; and integrated physiological model and data/information management systems, as well as efficient, low-impact access and harvest systems.
- Smart materials that will release chemicals based on soil and plant status depend on breakthroughs in materials technology.
- Improved understanding of forest processes is required to support development of management systems.
- Couple plant physiology and soil process models and improving the temporal resolution of process representation.
- Improve understanding of the pathways by which methane is produced and consumed in soils, and by which nitrate is reduced to gaseous nitrogen, which is required to support scaling trace gas emissions.
- Research on sensors, information sciences, materials, and above- and below-ground forest processes.

RD&D Activities

- Efforts are underway in both public and private sectors.
- Sponsors include USDA, universities, forest industry, DOE, and National Aeronautics and Space Administration. Principle funding is from USDA, Forest Service, and forest industry.

Recent Progress

- Improved planting stock with better quality wood formation and resistance to insects and diseases.
- Management systems for the efficient production of wood and other valuable products.
- Research programs are in place that can (1) provide an inventory of carbon stocks; (2) understand biological processes; (3) model and predict climate impacts and management strategies, and (4) develop effective, low-cost management systems.
- Partnerships have development among government, university, and private research organizations to better understand, develop, and implement good management practices for carbon sequestration.
- The USDA and DOE are formally collaborating in the Biobased Products and Bioenergy research program to develop more ways to store carbon or use renewable bioenergy to offset carbon emissions.

Commercialization and Deployment Activities

- High-quality planting stock is commercially available.
- Fertilization systems for irrigation and nutrient delivery to individual trees are commercially available.

Market Context

- Development of energy-efficient, low-impact equipment for all forest operations.
- Market for improved planting stock for feedstock production.
- Market entry for resource-efficient durable wood products as substitutions for more energy-intensive products in building.
- Expansion of wood energy feedstocks.
- Potential demand for carbon accounting in forest and wood product production nationally and internationally.
- The market for energy-efficient forest production systems is substantial, nationally and internationally.

3.2.1.4 GRAZING MANAGEMENT

Technology Description

Most grazing land soils can sequester carbon with alternative management technologies and practices. These practices increase the amount of carbon in the soil by increasing biomass production and reducing the amount of carbon lost to erosion. The production of methane by domestic ruminants also can be reduced. Methane production depends on the quality of forage ingested and the efficiency of the digestive process – and can be reduced with improved diet and the use of supplements. These practices increase production efficiency while reducing methane emissions. Environmental and production benefits are high in all cases.

System Concepts

- Increasing carbon storage on grazing lands depends on implementing management technologies (e.g. fire, grazing, seeding) to achieve an appropriate mix of plants that optimize the use of available sunlight, water, and nutrients in biomass production.
- Pasturelands use more fertilizer and water than rangelands, and mesic rangelands have a relatively high sequestration potential.
- Nitrous oxide emissions from fertilizer application on pastures can be dramatically reduced by split applications or applications when plants are actively growing.
- Reduction of methane production by ruminant animals has been demonstrated in grazing systems where improved diet quality and herd management practices have been implemented. In addition, organisms in grassland soils decompose methane into the less-potent greenhouse gas CO_2 and water.

Representative Technologies

- Alternative grazing practice.
- Livestock herd management.
- Vegetation management.
- Water management.
- Erosion control.

Technology Status/Applications

- Each of these technologies has been researched and implemented for purposes other than carbon sequestration, primarily conservation.
- These technologies have generally been demonstrated to be economically feasible.
- Some soil carbon data has been gathered while these practices were investigated for their conservation and yield benefits.

Current Research, Development, and Demonstration

RD&D Goals

- Construct quantitative models that describe site-specific interactions among grazing systems, vegetation, soil and climate, and the effects on greenhouse gas dynamics.
- Develop and optimize the combination of practices that maximize carbon sequestration for various grazing systems and geographical areas.
- Develop decision support tools for ranchers, technical assistance providers, and policy makers to inform the relative costs and benefits of different grassland management scenarios for carbon sequestration and other conservation benefits.
- Demonstrate and refine decision-support tools through pilot projects.

RD&D Challenges

- Develop and implement measurement and monitoring technologies and protocols with sufficient site specificity and acceptable cost-benefit ratios.
- Determine the effectiveness of practices and systems in sequestering carbon.
- Quantify the effects of land and livestock management on carbon sequestration and CO_2, methane, and nitrous oxide emissions across a variety of climates, soils, and production systems.

Recent Progress
• Estimates of the potential for range and pastureland soils to sequester soil carbon have been published and provide a baseline for future activities. • Development of the Pasture Land Management System (PLMS) decision-support tool, a joint project of EPA, National Resources Conservation Service, and Virginia Tech. • Research programs already have been established in the USDA Agricultural Research Service, Natural Resources Conservation Service, Land Grant Universities, DOE, national labs, and U.S. Geological Survey to study soil carbon sequestration. • New technologies for the measurement of greenhouse gas fluxes have been developed.
Commercialization and Deployment Activities
• USDA has provided technical assistance to landowners for implementing these technologies. • Commercial application of grazing land restoration has been successful but is limited in extent. **Market Context** • Virtually 100% of rangeland and grazing lands could increase carbon storage.

3.2.1.5 RESTORATION OF DEGRADED RANGELANDS

Technology Description

Degraded rangelands have low levels of soil carbon and diminished potential for biomass production to increase storage, but represent potentially large carbon sinks. Degradation is usually the result of inappropriate management, especially during extended periods of drought or unusual weather events. Symptoms of degradation include poor soil cover, dominance of undesirable species, low soil quality, or, in the extreme, topsoil erosion. In many arid and semi-arid rangelands, the cost of restoring land may far exceed the potential returns from livestock production. In addition, restoration technologies are unreliable in environments where precipitation is unpredictable. In more mesic areas, many rangelands are occupied by invasive species, which may be native or exotic. Technologies for managing invasive species to increase carbon storage in rangelands are expensive and require significant investment as well as careful post-treatment management.

- Increasing carbon storage on degraded arid and semi-arid rangelands depends on reestablishing vegetation in areas that have lost productivity.
- In many cases, soil may be intact, but beneficial microbial activity has been lost and must be restored simultaneously with vegetation reestablishment.
- In more mesic areas, rangeland degradation is due largely to the dominance of invasive species. The association between increased competition of shrubs and carbon fluxes and other greenhouse gas emissions in rangelands is poorly understood and very difficult to manage.

Representative Technologies

- Reestablishment of vegetation.
- Vegetation management.
- Restoring soil function.

Technology Status/Applications

- Each of these technologies has been researched and implemented for purposes other than carbon sequestration, primarily to prevent erosion and conserve soil.

Current Research, Development, and Demonstration

RD&D Goals

- Gain reliable understanding of the relationship between soil microbes and vegetation establishment and growth in arid and semi-arid areas.
- Develop low-cost, reliable technologies for the restoration of vegetation on degraded arid and semi-arid rangelands.
- Improve decision support for the application of low-cost technologies, such as fire, to control invasive species and to reduce greenhouse gas emissions from mesic rangelands.
- Develop seed production technology to produce low-cost seeds for reestablishing desired rangeland species. Currently costs are high and seed supply is limited for many cultivars.
- Develop new risk management and liability tools for use in prescribed burning systems on rangelands.

RD&D Challenges

- Measuring and monitoring procedures need to be improved for accurate, efficient, and low-cost determination of range and pasture land soil carbon status and determination of the effectiveness of carbon sequestration practices.
- Integrate complex and multisource data to develop better models and decision support systems.
- Develop more accurate estimates of the impacts of these management practices on soil carbon, particularly for the purpose of monitoring carbon sequestration following management adjustments.
- Develop new technologies to restore semi-arid and arid rangelands suffering from degradation, including soil-quality microbe interactions.

Recent Progress

- Estimates of the potential for range and pastureland soils to sequester soil carbon have been published and provide a baseline for future activities.
- Research programs already have been established in the USDA Agricultural Research Service, Natural

Resources Conservation Service, Land Grant Universities, DOE, national labs, and U.S. Geological Survey to study soil carbon sequestration. • New technologies for the measurement of greenhouse gas fluxes have been developed. • New herbicide technologies and fire management practices have the potential to reduce the high costs associated with pretreating restoration sites.
Commercialization and Deployment Activities
• While current costs of rangeland restoration are high, restoration is likely to be economically feasible if there is demand for carbon sequestration. • Currently, the cost of most seeds is high for species and varieties that are needed in grazing land restoration. • USDA has provided technical assistance to landowners for implementing these technologies.

3.2.1.6 WETLAND RESTORATION, MANAGEMENT, AND CARBON SEQUESTRATION

Technology Description

Wetlands, including coastal zones, estuaries and marshes, northern tundra and peatlands, total about 2.8 x 10^9 ha, about 7% of the Earth's land surface and 11.6% of the United States. Wetlands present an important opportunity for carbon sequestration and greenhouse gas offsets by virtue of their potential for restoration using known and innovative land management methods. Equally important is protection of wetlands in northern and temperate latitudes from carbon loss with global warming. Because they are inherently highly productive and accumulate large below-ground stocks of organic carbon, restoring lost wetlands and protecting those that remain clearly represents an immediate and large opportunity for enhancing terrestrial carbon sequestration.

System Concepts

- Wetlands are inherently among the most productive ecosystems on earth, with 7% of total land area contributing 10% of global net primary productivity.
- Climatic condition is the single most important factor in determining success in protecting carbon stored in existing wetlands. Fire, permafrost melt, sea-level rise and more frequent droughts will significantly affect wetlands.
- Carbon sequestration can be enhanced through application of proven engineered wetlands technology.

Representative Technology or Practices

- Restoration of riparian zones, estuaries and tidal marshes, mangrove forests, bottomland hardwood forests and other wetland systems.
- Management of periodically flooded rice fields and floodplains.
- Protection of existing wetlands, in particular, peatlands, bogs, and other northern latitude wetlands that might otherwise become large sources of gaseous carbon with global warming.

Technology/Practice Status and Application

- Limited data exist as to the actual quantification of sequestered carbon by wetland type and location.
- Wetland restoration has centered on wildlife habitat, water quality improvement, erosion control, shoreline restoration, but not carbon sequestration.
- Efforts to manage northern wetlands in danger of becoming massive sources of carbon to the atmosphere do not exist.

Current Research, Development, and Demonstration

RD&D Goals

- Evaluate the extent to which various management practices on restored wetlands have enhanced carbon sequestration.
- Delineate and quantify carbon stocks in U.S. wetlands by region and type.
- Assess the vulnerability of wetland carbon stocks to human activity and climate change.
- Develop and demonstrate integrated management strategies for wetland carbon sequestration.

RD&D Challenges

- Quantify carbon accrual in wetlands to enable better estimates of their potential for carbon sequestration in coming decades.
- Identify cost-effective management approaches and technologies to mitigate loss of carbon from wetlands in northern latitudes.
- Construct and verify models that couple hydrology, ecosystem processes and carbon sequestration.
- Devise workable fire management techniques for wetlands that are compatible with wildfire suppression strategies.

RD&D Activities

- Ongoing research to evaluate wetland restoration methods.
- Demonstration projects are ongoing in select regions, including the lower Mississippi River valley and delta with mixed results. It has proven difficult to recreate native wetland vegetation assemblages.
- New demonstration projects with industry, including DOE-sponsored work with the Tennessee Valley Authority, have recently been initiated with limited results to date.

Recent Progress
• Wetland loss and degradation has been recognized and new programs implemented to regulate development activities that adversely affect wetland functions. Loss of wetlands in the 1990s was 80% lower than the 1980s. • The U.S. Department of Transportation has established a goal of replacing 1.5 acres for every acre of wetland impacted within 10 years.

3.2.1.7 CARBON SEQUESTRATION ON RECLAIMED MINED LANDS

Technology Description

Hundreds of thousands of hectares of lands are disturbed by extracting minerals, particularly coal, in the United States annually. Topsoils are generally removed prior to mining, resulting in loss of soil organic matter. Stockpiling of the topsoil until it is needed for reclamation of the mined lands also results in a loss of soil organic matter through decomposition with only limited inputs. These degraded lands have a significant potential to sequester carbon once revegetated to grasslands, pastures, cropland, or forest.

System Concepts

- Climatic condition is the single most important factor in determining revegetation success.
- Nearly 1.6 million acres in the Unites States have been affected by mining operations. The soils at these abandoned mining sites only marginally support regrowth of trees and vegetation in the absence of direct management, resulting in erosion and runoff into receiving tributaries.
- Carbon sequestration by these mined lands can be enhanced with organic amendments such as biosolids, sawmill residues, feedlot wastes, and other organic or inorganic byproducts that result in enhanced nutrient status or improved physical characteristics of the restored soil.

Representative Technology or Practices

- Grassland, cropland, and forest restoration on reclaimed or abandoned mine lands.

Technology/Practice Status and Application

- Limited data exist as to the actual quantification of sequestered carbon by reclaimed mined lands.
- These lands should have the potential to sequester carbon at a rate similar to degraded croplands.
- Organic residues have been used on reclaimed mine lands, generally to dispose of the residue rather than consider its benefits in carbon sequestration.

Current Research, Development, and Demonstration

RD&D Goals

- Quantify carbon sequestration on reclaimed mined lands to enable better estimates of the potential of this large land area to sequester carbon.
- Evaluate the extent to which various management practices on reclaimed mined lands enhance carbon sequestration (i.e., measure the effects of organic and inorganic residues, grazing, plant biodiversity, and various shrubs and trees on soil carbon).
- Establish the role of various plant community attributes in carbon sequestration in semi-arid regions of the United States.
- Partner with private organizations and the public sector to sequester carbon and restore impacted lands.
- Develop demonstration projects that promote carbon sequestration and other collateral benefits as primary goals of mine reclamation.

RD&D Challenges

- Establish a sequence of studies across variable climatic zones to adequately address the soil variables, plant community attributes, and response of amendments to the various climatic conditions and management scenarios.

RD&D Activities

- Ongoing research in the eastern U.S. mining regions evaluates the impacts of planting trees to reclaim mined lands and provides estimates of the potential carbon sequestration from this practice.
- Researchers are revising growth and yield models to determine the optimal time of harvest for maximum carbon sequestration.

Recent Progress

- Community-based environmental groups are working with coal and utility companies to reclaim impacted lands, forming successful partnerships.

3.2.2 BIOTECHNOLOGY

3.2.2.1 BIOTECHNOLOGY AND SOIL CARBON

Technology Description

Biotechnology can be used to affect soil carbon by altering the chemical composition of plants and that of microorganisms that control plant decomposition. Plant chemical composition affects the amount of carbon transformed into more stable organic matter (such as humus) when plant biomass decomposes in the soil. Soil microorganisms determine the soil carbon compounds that are formed during residue decomposition.

System Concepts

- Roots and wood that have relatively high lignin content are more readily converted into stable soil organic matter than are plant components with high cellulose and hemicellulose content. Cellulose and hemicellulose are more readily decomposed by soil microbial respiration and released to the atmosphere as CO_2.
- Soil microorganisms that control plant decomposition also produce chemical precursors to stable organic compounds. Thus, genetic modifications that increase soil microorganism production of these chemical precursors could potentially affect soil carbon content.
- Use of genetically modified crops to enhance yields and reduce fertilizer.

Representative Technologies

- Plants already have been modified using biotechnological methods for herbicide resistance, to produce an insecticide, and to produce vitamin A precursors.
- Microorganisms have been bioengineered to produce novel compounds (e.g., insulin) and to biodegrade recalitrant compounds present in hazardous wastes.
- Herbicide tolerant crops that advance conservation tillage.
- Genetically modified crops that increase utilization of soil nutrients and/or fertilizer.
- Technologies that increase agricultural productivity (e.g., by increasing yields or minimizing spoilage and increasing shelf life, because each would minimize area under cultivation).

Technology Status/Applications

- Biotechnology has successfully produced modified plants and microorganisms, but it has not been used to modify plants or microorganisms to enhance soil carbon sequestration.
- This technology may be better suited for biomass/bioenergy crops than traditional food and feed crops because of the close compatibility between plant characteristics and desired biomass/bioenergy crop properties.

Current Research, Development, and Demonstration

RD&D Goals

- Identify the traits needed in plants and microorganisms to increase soil carbon sequestration capacity.
- Determine the feasibility of using biotechnology to modify the traits of plants and microorganisms that can affect soil carbon sequestration.
- Develop systems for monitoring nontarget environmental affects associated with plant modifications.
- Develop methods to incorporate genetically modified plant and microorganisms into cropland and conservation reserve and buffers systems.
- Develop guidance for farmers, other land managers, and policy makers for using carbon sequestration biotechnology products.

RD&D Challenges

- Because biotechnology has not yet been used to enhance soil carbon sequestration, the feasibility of this approach is unknown. In particular, specific genetic traits affecting carbon sequestration capacity need to be evaluated to determine whether few or many genes are involved and how modifications to these traits might also impact crop yields.
- Estimate the costs of bioengineered plants and microorganism, which may be prohibitive for farmers, ranchers, and other managers.
- Determine whether modified microorganisms can compete with native microflora.
- Address the general concern of introducing genetically modified organisms into ecosystems because of their potential to disrupt natural ecosystem processes.

Recent Progress
• Biotechnology has been used to successfully modify plants and microorganisms for other purposes.
Commercialization and Deployment Activities
• Both private companies and public research agencies have biotechnology products in commercial markets. • Regulatory procedures are in place for release of genetically modified organisms. • The private sector will support the development of carbon sequestration biotechnology if the market is large enough. **Market Context** • Difficult to estimate until feasibility research is conducted.

3.2.3 IMPROVED MEASUREMENT AND MONITORING

3.2.3.1 TERRESTRIAL SENSORS, MEASUREMENTS, AND MODELING

Technology Description

Agricultural lands (cropland, pasture, rangeland) represent potentially large and cost-effective sinks for atmospheric carbon, if management technologies can be applied in the right place at the right time. Management to increase carbon sequestration requires the development of more sophisticated, lower-cost measurement systems and models for integrating multiple data sources into a decision-making context.

System Concepts

- In the past, management of soil carbon and greenhouse gas (GHG) emissions has not been a primary management goal in agriculture. Consequently, efforts to develop rigorous quantification systems at multiple scales (local, regional national) are relatively recent, but are rapidly developing.
- Methods exist to accurately and precisely measure soil carbon and GHG concentrations and fluxes. However, most conventional methods were developed for local measurements. Plot and field applications and numerous samples must be analyzed for accurate and precise values.
- Models (particularly computer simulations) of soil carbon and GHG dynamics exist and several are in widespread use and have been extensively tested against research data. Their development and use in inventories, policy assessment, and decision-support environments is only recent.
- Emergence of new sensing technologies (i.e. laser, infrared, multispectral video) and computing power capable of handling large amounts of information has spawned a new generation of instruments, databases, and computer models.
- There is a rich collection of resource data on factors determining soil carbon and GHG dynamics in croplands, e.g., survey data on management practices, crop areas and yields, soil maps, land cover, and irrigation. Much of the data is spatially referenced and can be used to drive stimulation models and interpolate/extrapolate measurements. Similar data exists for grazing lands, with the exception of type, distribution, and extent of different management practices for which information is currently sparse.

Representative Technologies

- Instruments to measure GHG fluxes among soils, plants, animals, and the atmosphere.
- Models to integrate spatial and temporal variability into a decision context.
- Easily accessible, interactive distribution systems of quantification technologies that integrate measurement and modeling approaches.

Technology Status/Applications

- New sensors, instruments, measurement systems, models, and distribution systems are emerging, but integrated systems of information collection, retrieval, management, manipulation, and processing to aid decision making in complex and diverse agricultural environments have yet to be developed.
- Integrated information management and the physical sciences now have the capacity to provide vastly improved information to land managers and policy makers to improve the amount of carbon stored in grazing land soils.

Current Research, Development, and Demonstration

RD&D Goals

- Develop a new generation of sensors and instruments to measure GHGs and their fluxes in situ across a wide variety of agricultural ecosystems.
- Develop cost-effective soil carbon probes for in situ measurement of soil carbon content (as opposed to fluxes) that can be made both before and after implementation of management changes to validate impacts on sequestration.
- Determine time and cost-efficient sampling and monitoring designs to support national inventories and project level GHG mitigation activities.
- Combine measurement technologies and ecological process models to make reliable predictions (and verify them) regarding the impact of management on GHG dynamics.
- Integrate near real-time climate information into process models as a driver.

- Distribute site-specific information to farmers, ranchers, and technical assistance providers to aid in making more realistic decisions.

RD&D Challenges

- High spatial and temporal variability results in very complex situations that must be measured and modeled. Data sources will be multisource and large.
- Successful implementation will require substantial improvements in the ability of field staff and land managers (farmers and ranchers) to use complex information.

Recent Progress

- Laser-induced breakdown spectroscopy instrument to measure soil carbon in situ for less than 10% of the lab costs of other methods with comparable reliability.
- Mid-range infrared spectroscopy to measure soil carbon and forms.
- Near-infrared spectroscopy technology and Nutritional Balancer software to accurately predict livestock diet quality based on fecal analysis.
- Biophysical models have been developed to integrate spatial and temporal variability in soils into a predictive framework for making estimates of changes in soil carbon in response to climate and management.
- Satellite and low-altitude remote-sensing technologies have been developed that can quantify cropland and grassland features at a spatial resolution of less than 0.5 m^2.
- Internet distributed site-specific information systems that integrate near real-time weather predictions, land condition, and land-cover classes have been developed. Such tools provide ready access to information used in developing decision tools and in dynamic models as inputs.
- Decision-support systems are being developed that can integrate information to evaluate implications of various management decisions.

Commercialization and Deployment Activities

- Markets in precision agriculture and decision-support consultation are potentially large.
- Technical basis of instruments, models, and information systems is proven, but their systematic deployment to solve complex problems remains unexplored.

3.2.3.2 MEASURING AND MONITORING SYSTEMS FOR FORESTS

Technology Description

Forest systems provide a significant carbon sink and can contribute to GHG emissions. To mitigate GHG effects, advanced technology is needed to measure and monitor forest and wood product processes, pools, and fluxes to better manage these systems to reduce and mitigate emissions, and to enhance carbon sinks. Measurement systems should be integrated using a multitiered approach combining national inventories, remote sensing, land-based measurements, and intensive monitoring on experimental sites. Additional profiles on measuring and monitoring systems for greenhouse gases in general can be found under "Enhancing Capabilities to Measure and Monitor Emissions."

System Concepts

- GHG (fluxes and pools) inventory and measurement systems are a collage of measurements, covering broad temporal and spatial scales, methods, and technologies. No current inventory system provides the comprehensive coverage across scales needed to understand and manage GHG across the United States.
- An integrated approach is needed that combines national inventories, remote-sensing data, regional and site studies and measurements, experimental data, and modeling capabilities into a comprehensive observational and analysis system.
- Technology advances are needed in (1) enhanced remote-sensing data collection and analysis, (2) expansions and enhancements of extensive inventories systems for large-scale, landscape, and integrated resource measurements, (3) in situ instrumentation and monitoring systems for intensive monitoring, (4) specialized measurement and characterization systems for soils, and (5) integrating measurements and data.
- Global positioning and inertial measurement infrastructure, and remote and in situ sensors for soil, plant and microclimate characterization and monitoring

Representative Technologies

- The USDA Forest Service's Forest Inventory and Analysis Program and the Natural Resources Conservation Services' National Resources Inventory provide the basis for a national carbon inventory and annual changes in carbon pools for forest, pastures, and croplands.
- Wide range of technology such as global positioning systems, satellite and aircraft based remote sensing, in situ electrical, magnetic, optical, chemical, and biological sensors, and scientific instruments.

Technology Status/Applications

- LIDAR and RADAR remote-sensing methods are being developed and tested for 3-D imaging of forest structure. Additional work is needed to integrate remote and land-based measurements.
- Low-cost, portable, real-time measurement systems are not available for soil monitoring and other in situ measurements.

Current Research, Development, and Demonstration

RD&D Goals

- Reduce uncertainty associated with the national carbon inventory by improving coverage of national inventories and analyses of changes.
- Develop understanding of underlying processes of biological and ecological processes in order to develop improved monitoring systems and use systems to validate models for mitigation actions.
- Improve and develop low-cost, portable, real-time sensors and measuring systems for in situ measurements.
- Provide integration and systems design of remote sensing and ground-based carbon pool and GHG fluxes measurements technology using multitiered system.

RD&D Challenges

- National inventory systems were not designed for carbon and other GHG measurements and have not been adequately supported to develop complete wall-to-wall, comprehensive inventories of carbon pools and fluxes among the pools and atmosphere.
- There is little understanding of forest soil processes in the storage and allocation of carbon. This information is paramount for the development of management systems and practices that enhance carbon sequestration.

- The broad range of required scales, cover types, and ecosystems will require the development of (1) remote sensing integrated with other measurements at various levels of coverage, duration, and intensity, and (2) low-cost, robust measurement systems that can effectively be used at different scales. Sites covered need to be expanded as part of extensive monitoring and intensive measurement systems.
- A great wealth of information and data will be acquired by enhanced measurement and monitoring systems. Advances are needed in the technology to manage, process, translate, analyze, and transform this information into predictive and decision-making tools.
- Develop measuring and monitoring systems for carbon pools in wood products in use and in landfills.

RD&D Activities

- Efforts are underway to improve carbon inventory systems and reduce the uncertainty of our national inventory.
- Improvements are being made in remote sensing, senor, instrumentation, and measuring system technology through Federal, university, and private collaboration.
- Current technology needs to be more fully deployed; and new, innovative technology should be piloted and demonstrated to accelerate deployment.

Recent Progress

- The USDA Forest Inventory and Analysis Program assesses the U.S. forest structure and condition and is the basis for our nation's carbon inventory in concert with information provided by the National Resource Inventory. Periodic national carbon inventories have been produced using this data.
- The AmeriFlux network is being completed, which will improve the understanding of carbon pools and fluxes in large-scale, long-term monitoring areas and intensive experimental sites.
- Research programs are in place that can (1) provide inventory of carbon stocks, (2) understand and quantify biological processes, (3) model and predict climate impacts and management strategies, and (4) develop effective, low-cost management systems.
- Partnerships have developed among government, university, and private research organizations to improve greenhouse gas measurements.

Commercialization and Deployment Activities

- Global positioning systems are currently in use and can provide geo-references for carbon measurements.
- Current technology is not fully deployed; efforts are needed to demonstrate and increase the efficiency of such technologies.
- Specialized remote sensing technology is being developed and will be deployed in the near term for the measurement of greenhouse gas emissions and carbon stocks.
- A comprehensive, integrated, multiple-tier measuring and monitoring system needs to be fully developed and deployed.

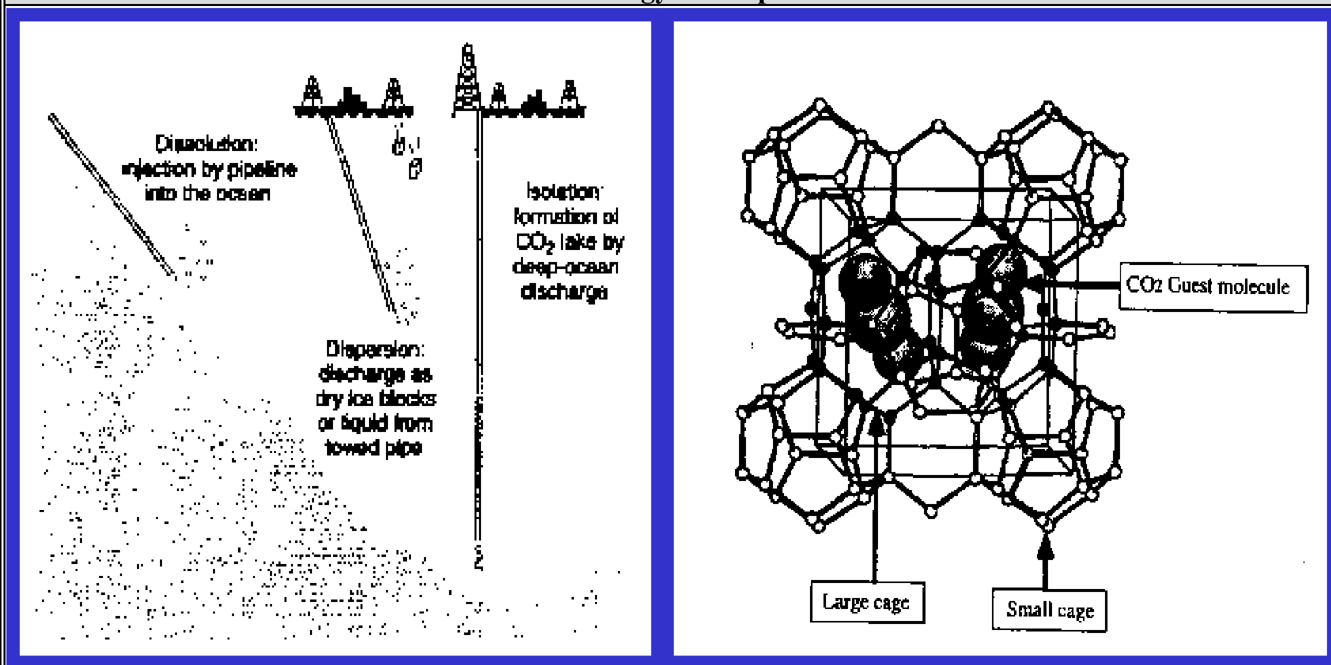
Market Context

- Improved technology for carbon measurements can provide security in credit trading.
- Enhanced measurement systems can provide input for the optimal design, deployment, and management of forest and wood product systems that will provide additional carbon sequestered and ancillary benefits.

3.3 OCEAN SEQUESTRATION

3.3.1 OCEAN SEQUESTRATION – DIRECT INJECTION

Technology Description



Sketch of various ocean CO_2 disposal options (left). Structure of a CO_2 hydrate (right).

Ocean sequestration technologies strive to reduce carbon emissions by injecting captured CO_2 into the ocean, rather than releasing it into the atmosphere. The captured CO_2 is concentrated, and then pressurized into a liquid state. The physical chemistry of CO_2 is such that at high pressure and low temperatures (which exist at depth in the ocean), the CO_2 molecule reacts with seawater wrapping itself in a cage of water to form a solid compound much like ice (clathrate). This reaction profoundly changes its behavior. However, there are significant environmental questions that need to be examined.

System Concepts

- CO_2 is captured from a large point source of anthropogenic emissions, transported, and injected into the ocean via pipeline or tanker.
- CO_2 molecule reacts with seawater wrapping itself in a cage of water to form a solid compound much like ice (clathrate).

Representative Technologies

- Technologies will potentially be borrowed from the petroleum industry in the areas of drilling simulation and wells; processing, compression, and pipeline transport of gases; and operational experience of CO_2 injection.

Technology Status/Applications

- The injection technology is technically ready for adaptation for mid- to deep-ocean injection. However, technology is not ready for deployment. This is due to insufficient data detailing hydrate interactions with marine community structure, as well as knowledge gaps about physical and chemical behavior concerning dispersion and transport of hydrate plume by ocean hydrology.

Current Research, Development, and Demonstration

RD&D Goals

- Demonstrate that CO_2 direct injection is safe and environmentally acceptable.
- Improve global circulation simulation with more accurate biology modules.

RD&D Challenges

- Develop field practices that optimize CO_2 direct-injection retention times.
- Develop the ability to predict plume effects on marine organisms.
- Develop the ability to track the fate of direct injected CO_2.
- Develop a better understanding of the CO_2 chemistry in ocean waters, and its effects on indigenous organisms, e.g. hypercapnia (effects of elevated CO_2 levels), and acidification of plume waters (depressed pH).

RD&D Activities

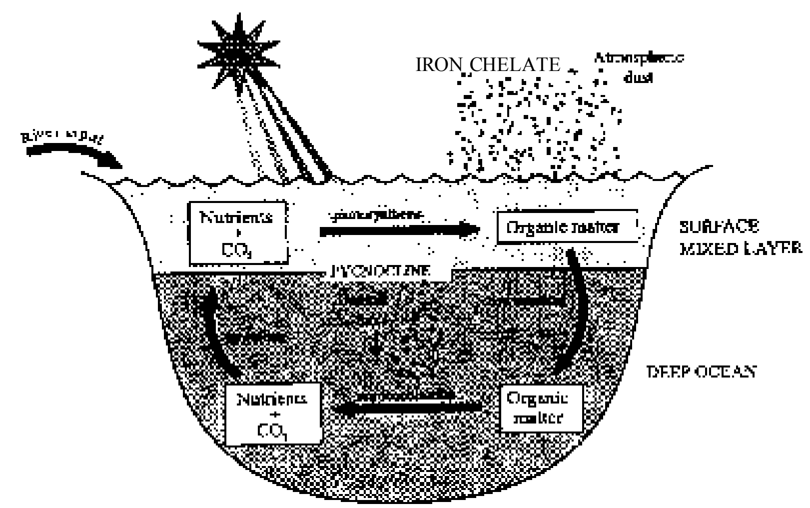
- Key DOE activities are targeted to determine physical, chemical and biological impact of direct injection.
- Conduct an appropriate-scale field experiment to adequate assess unit operations and potential impacts on marine environment at a sufficient scale downstream of injection zone.
- Formulate future experiments to evaluate community effects (long term) and the total impact on the ecology of multiple regions of deep oceans.
- Develop other small-scale field experiments to understand fundamental biogeochemical cycles.
- Current expenditures for field experiment estimated to be $6 million.

Recent Progress

- A survey cruise of Hawaiian biology occurred during the summer of 1999.
- Small-scale release (one liter) at 3,600 m off the California coast demonstrating hydrate formation.
- Properties of hydrate formation determined in lab utilizing high-pressure, low-temperature reaction vessels.
- Conducted 10-day cruise off Loihi seamount (Hawaii) during December 2002, to determine effect of natural analogues of CO_2 on amphipod community in vent waters.

3.3.2 OCEAN SEQUESTRATION – IRON FERTILIZATION

Technology Description



CONCEPT OF IRON FERTILIZATON

It is hypothesized that the rate of carbon dioxide fixation by microscopic plants called phytoplankton that live in the surface waters of the oceans may be limited by the availability of iron. In particular, field experiments in high nutrient, low chlorophyll (a measure of plant biomass) ocean waters such as the Southern Ocean and the Equatorial Pacific have shown that addition of iron increased the rate of removal of carbon dioxide through the process of photosynthesis. The carbon dioxide has thus been incorporated into plant biomass (phytoplankton), some of which will sink to deeper waters (export) where it may be sequestered for a period of time. Industry has developed a strong interest in using iron fertilization as a potentially low cost technology to offset carbon dioxide emissions. Many fundamental questions, however, remain as to the long-term effectiveness and potential environmental consequences of this carbon sequestration strategy.

System Concepts

- Iron chelate "fertilizer" is mixed into the ocean via vessel propellers. The release stimulates phytoplankton bloom.
- The phytoplankton bloom increases the rate of carbon fixation or photosynthesis, thus reducing the levels of carbon dioxide dissolved in the surface waters. Having converted carbon dioxide to plant biomass, some of the phytoplankton will sink to deeper waters where the carbon will be sequestered.

Representative Technologies

- Technologies will be borrowed extensively from the unit operations of the maritime industry and existing instrumentation systems.

Technology Status/Applications

- Three previous research demonstrations have been performed. The Southern Ocean Iron Fertilization Experiment (SOFEX) occurred in January-February 2002. This research, which was cofunded by the National Science Foundation and the Department of Energy, aims to quantify carbon export – that is, how much carbon sinks to deeper waters, after fertilization with iron. The major goal is to quantify the extent of export production of carbon.

Current Research, Development, and Demonstration

RD&D Goals

- Determine if iron-induced phytoplankton blooms result in the vertical flux (transport) of carbon from the surface waters (export production) to the deep waters.

RD&D Challenges

- Determine the overall short-term environmental consequences of release of iron as iron chelate.
- Determine the long-term consequences of iron enrichment on the surface water community, midwater community, and ocean processes.
- Determine the best proxy for carbon.
- Quantify the efficiency of the long-term storage of carbon.

RD&D Activities
• Continue data reduction from SOFEX cruise. • Determine magnitude of carbon export from surface layer from SOFEX. • Prepare for proposal selection from current solicitation.
Recent Progress
• Previous cruises of research vessels IRONEX I and II, and SOIREE, confirmed the stimulation of phytoplankton bloom by the addition of iron chelate.

4.0 REDUCING POTENTIAL FOR CLIMATE EFFECTS OF NON-CO_2 GREENHOUSE GASES

4.1 METHANE EMISSIONS FROM ENERGY AND WASTE

4.1.1 ANAEROBIC AND AEROBIC BIOREACTOR LANDFILLS

Technology Description

Landfill bioreactor cell, Yolo County, California

In recent years, bioreactor landfills have gained recognition as a possible innovation in solid-waste management. The bioreactor landfill is generally defined as a municipal solid-waste landfill, operated to transform and more quickly stabilize the readily and moderately decomposable organic constituents of the waste stream by enhancing microbiological processes. There are currently two bioreactor processes – anaerobic and aerobic. Hybrids employ both methods. The primary difference between the two is that, in anaerobic bioreactors, a key objective is to enhance the generation of landfill gas (i.e., methane), by minimizing oxygen infiltration, over a shorter period of years; whereas, in aerobic bioreactors, the objective is to minimize landfill gas generation overall by introducing oxygen into the waste mass. Both methods utilize leachate recirculation and/or supplemental moisture addition as a means to control and enhance moisture levels within the landfill, thereby increasing decomposition.

Current Research, Development, and Demonstration

RD&D Goals

- The first commercial full-scale anaerobic and aerobic bioreactor technology was operational in 2002. The goal is to have three-five commercial full-scale demonstration units operational by the close of 2004.
- Environmental, public-health impacts, and design and operational issues need to be further evaluated.
- Undertake a program of market penetration 2006–2010.

RD&D Challenges

- No long-term, full-scale commercial application demonstrated.
- Environmental, public-health impacts, and design and operational issues need to be addressed.
- A regulatory barrier to the deployment of the bioreactor landfill is the Resource Conservation and Recovery Act (RCRA) Subtitle D that prohibits the addition of liquids to a waste management unit from outside the unit (40 CFR 258.28). Supplemental liquid addition is critical to the operation of the bioreactor landfill.
- The construction and operation/maintenance costs associated with bioreactor landfills are not fully known.

RD&D Activities

- At the present time, bioreactor landfills are in the early stages of full-scale field testing. In the United States, early work on anaerobic bioreactors began in the mid-1980s at landfills in Sonoma County and Mountain View, California.
- As of July 2003, approximately six anaerobic bioreactor projects (including hybrids) are in various stages of deployment or demonstration. Approximately two aerobic bioreactor projects are in various stages of deployment or demonstration. The Environmental Protection Agency (EPA) Project XL program is currently implementing and evaluating five bioreactor landfills and developing a database to track and record information on bioreactor landfills. EPA is funding the development of a bioreactor operations training manual and course.
- In 2001, DOE's National Energy Technology Lab funded a study of the Yolo County Pilot Bioreactor Landfill Demonstration (9,000-ton test cell and 9,000-ton control cell) to study new ways to capture greenhouses gases from the bioreactor landfill.

Recent Progress

- Results from the Yolo County pilot-scale demonstration project showed production of landfill gas in the anaerobic cell was more than six times that of the normal range expected. A tenfold increase in methane recovery rate was observed compared to conventional landfills, which suggest a tenfold reduction in interval of methane generation. The biodegradation rate of the waste was increased thus decreasing the waste stabilization and composting time (5-10 years) relative to what would occur within a conventional landfill (30 or more years).
- Benefits include:
  - Subtitle D established a "dry tomb" sanitary landfill approach to municipal solid-waste disposal, where waste is placed and maintained in dry conditions to minimize potential leachate and gas generation and release. A concern of the "dry tomb" landfill is that the waste may pose a threat to public health and the environment well beyond the prescribed 30-year postclosure maintenance period because the natural decomposition process is retarded. Should the "dry tomb" landfill containment be compromised, significant generation and release of leachate and gas could occur well beyond the postclosure maintenance period. In a bioreactor landfill, controlled quantities of liquid are added and circulated through waste to accelerate the natural biodegradation and composting process of the waste. The bioreactor landfill process may significantly increase the biodegradation rate, such that the waste may be stabilized in a relatively short period of time (5-10 years).
  - Reduction in air-pollutant emissions, especially criteria pollutants and methane early in the decomposition process when landfill gas is collected and combusted.
  - The anaerobic bioreactor may increase gas yields to favor more economical utilization projects in the earlier years of the landfill life while reducing the greenhouse gas burden in the subsequent years. Gas generation during conventional landfilling techniques occurs over long periods of time (more than 30 years).
  - Aerobic technology (i.e., methane elimination) could become a prime candidate technology for landfills in the United States and elsewhere that cannot generate landfill gas in sufficient quality or quantity to economically recover the associated energy. In addition, the technology also could be considered as a follow-on technology for energy-recovery projects at landfills that are no longer producing methane at economically valuable levels.

Commercialization and Deployment Activities
• Several companies, including the largest waste management company in the United States, are working with states and the EPA to demonstrate bioreactor technology. **Market Context** • Municipal solid-waste landfills represent the largest human-made source of methane emissions in the United States (approximately 32%), and account for approximately 55% of waste disposal. • All new municipal solid-waste landfills constructed in the United States are potential markets. • Based on the preliminary findings from several bioreactor demonstration projects, landfill gas recovery costs on a $/MMBtu basis will be lower for a bioreactor landfill than for a conventional landfill. The cost reduction could be 25%-50%, depending on how bioreactor costs are allocated.

4.1.2 CONVERSION OF LANDFILL GAS TO ALTERNATIVE USES

Technology Description

Landfill gas to compressed natural gas vehicle refueling station, Los Angeles, California

Conversion to compressed natural gas (CNG) and liquefied natural gas (LNG): Use of landfill gas to produce CNG and LNG for vehicle use has gained interest because: (1) it provides an alternative use for landfill gas projects that cannot use all of the gas recovered; and (2) increasingly stringent diesel emission regulations require use of alternative fuel vehicles. Use of CNG and LNG has been recognized for its environmental benefits because it is a cleaner-burning fuel relative to gasoline and diesel fuel, especially for NO_x and particulate matter (PM) emissions.

Pipeline quality gas and CO_2 production: Since landfill gas is about half CO_2 and half methane, separation of these two gases can generate two separate sources of revenue – commercial CO_2 and pipeline-quality (high-Btu) methane. Since methane is the chief constituent of natural gas, the methane from landfills, once cleaned and processed, can be fed into existing natural gas distribution networks. CO_2 separated from landfill gas can be processed to high-purity (food grade) liquid CO_2, coalbed, oil and gas enhancement; wastewater treatment; dry cleaning; or for the production of dry ice; or to promote plant growth in greenhouses.

Conversion to methanol and ethanol: Landfill methane has been successfully converted to methanol and ethanol, both renewable fuels that produce fewer emissions than gasoline. Landfill gas can be converted to methanol and ethanol for use as a chemical feedstock, hydrogen production, or as a vehicle fuel or fuel additive.

System Concepts

- *Conversion to CNG/LNG:* In general, to produce LNG from landfill gas, the removal of corrosive trace impurities is accomplished through the use of phase separators, coalescing filters, and impregnated\non-impregnated activated carbon adsorbents. Next, a zeolite adsorbent removes remaining polar molecules (specifically water) to a concentration of a few parts per million. Oxygen also must be removed at this point, if present in more than trace quantities. The resultant gas then enters a cryogenic purifier where the carbon dioxide is separated out, leaving a high-grade LNG product consisting of 90%-97% methane. The remainder of the LNG is dissolved nitrogen. Conversion to CNG is a similar process and therefore not addressed here.
- *Pipeline quality gas production:* Landfill gas must be processed to increase its energy content and to meet strict standards for oxygen, hydrogen sulfide, moisture, carbon dioxide, and non-methane organic compounds. The landfill gas also must be free of environmentally unacceptable substances and must be pressurized to the pressure of the pipeline to which the gas production facility is interconnected.
- *Conversion to methanol and ethanol:* Nearly all methanol produced today is made from natural gas. Ethanol is produced primarily from biomass feedstocks. Landfill gas is an alternative, renewable feedstock.

Representative Technologies

- *Conversion to CNG/LNG:* Thermal regenerative purification system.
- *Pipeline quality gas production:* At least three processes are employed to upgrade landfill gas to pipeline quality – membrane separation process, molecular sieve (pressure swing adsorption), and absorption process using a liquid solvent.
- *CO_2 production:* Triple-point crystallization and the use of cold liquid carbon dioxide.
- A CO_2 wash technology removes contaminants from landfill gas. The resultant clean stream of methane and CO_2 can be used as medium Btu gas or can be further refined into products such as CNG/LNG production, pipeline quality gas, and methanol.

Technology Status/Applications

- *Conversion to CNG/LNG:* To date, three landfill-gas-to-CNG projects have been successfully demonstrated worldwide. Los Angeles County, California, has operated a CNG project at Puente Hills Landfill for more than five years. The CNG plant produces 3,500 psi natural gas equivalent as fuel for several pieces of landfill equipment (e.g., water truck). The first landfill-gas-to-LNG pilot plant recently completed initial performance testing at the Hartland Landfill in Victoria, British Columbia (Canada). By 2004, the first four commercial landfill-gas-to-LNG production and fueling facilities are planned for landfills in California (2), Pennsylvania (1), and Texas (1).

- *CO_2 production:* Triple-point crystallization has been demonstrated. Use of cold liquid carbon dioxide is under development.
- *Pipeline quality gas production:* At least eight projects that convert landfill gas to high-Btu (pipeline-quality) gas are currently in operation throughout the United States. An additional three projects are currently under construction and planned.
- Conversion of landfill gas to methanol and ethanol for use as a vehicle fuel or as a chemical feedstock has been investigated in the United States since the early 1980s.

Current Research, Development, and Demonstration

R&D Goals

- *Conversion to CNG/LNG:* Monitor performance of LNG conversion technology application on landfill gas and converted vehicle performance; development of distribution/fueling infrastructure.
- *Pipeline quality gas production*: Develop cost-effective separation technology applications.
- *CO_2 production*: Evaluate and demonstrate technologies for producing commercial carbon dioxide.
- When technologically feasible and cost competitive, LFG could offset natural gas consumption for the production of methanol and hydrogen.

RD&D Challenges

- *Conversion to CNG/LNG*: No commercial-scale, landfill-gas-to-LNG facility is currently operational. Major drawbacks to using CNG in motor vehicles include the limited driving range of vehicles because of fuel storage capacity constraints. For both CNG and LNG, another limitation has been the availability of fuel dispensing facilities. In addition, the cost to convert vehicles from diesel to CNG/LNG is prohibitive.
- *Pipeline quality gas production*: The cost of the landfill gas clean-up technologies is such that this application is only feasible at the largest landfills (which produce greater quantities of landfill gas), where economies of scale can make projects cost-effective.
- *CO_2 production*: Costs to recompress the CO_2; the need to remove trace contaminants to meet purity requirements for food-grade use; and nontechnical hurdles, such as public perception of a food product developed from landfill gas.
- The major obstacle facing methanol and ethanol production from landfill gas has been the overall economics of the conversion technology and lack of suitable markets for the end product.

RD&D Activities

- *Pipeline quality gas production*: As of July 2003, two studies are currently under development to investigate pipeline gas production at a small landfill in West Virginia, and the production of hydrogen from a landfill in Florida for NASA's Kennedy Space Flight Center (i.e. Space Shuttle fuel).
- *CO_2 production*: Field tests were conducted on producing commercial CO_2 from landfill gas at the Al Turi Landfill in Goshen, New York, with a grant from DOE's Federal Energy Technology Center. A DOE Small Business Innovation Research grant helped fund a demonstration project to convert landfill gas into methane for fuel cell electric generation and pure carbon dioxide to stimulate greenhouse crop growth. Brookhaven National Laboratory is supporting a study that will remove landfill gas contaminants and produce approximately 24,000 gal/day of LNG and 85 ton/day of liquid CO_2 from 4 million scfd of raw LFG.

Recent Progress

- *Pipeline quality gas production:* At least eight projects that convert landfill gas to high-Btu (pipeline-quality) gas are operating in the United States.
- *CO_2 production:* Klickitat Public Utility District in Oregon will generate carbon offsets by use of landfill gas to produce green electricity. The project is expected to produce 2.1 MW of electricity and 13 ton/day of CO_2

while removing contaminants such as sulfur compounds, volatile organic compounds, and siloxanes.

- Under a recently completed Small Business Innovation Research Phase II grant from DOE, Acrion Technologies, Inc., successfully demonstrated the Liquid CO_2 Wash Process with a pilot-scale system at the Al Turi Landfill in Goshen, New York.
- The first commercial-scale application of the Liquid CO_2 Wash Process is under development at a landfill in Ohio.

Commercialization and Deployment Activities

- Currently, few companies manufacture the landfill-gas-to-LNG conversion technology.
- Commercial technologies exist for upgrading LFG to high Btu gas production; however this application is only feasible at the largest landfills.
- Available methanol and ethanol conversion technology is limited.

Market Context

- Conversion of landfill gas to LNG or CNG may be ideally suited for small- to medium-scale landfills, especially with existing gas collection systems. Municipalities and private-sector companies that maintain medium- and heavy-duty vehicles (buses, trash collection, postal service, etc.) – especially in metropolitan areas – represent important markets.
- Commercial CO_2 markets include food and beverage and other industrial applications.
- Pipeline gas and hydrogen production from large landfills.

4.1.3 ELECTRICITY-GENERATION TECHNOLOGIES FOR LANDFILL GAS

Technology Description

Several emerging alternative electricity-generating technologies have significant potential for landfill gas. *Fuel cells* and *microturbines* are technologies that are available in small incremental capacities, have short lead times from planning to construction, and have lower air emissions than other, larger-scale, generation technologies. The modularity of these technologies makes them ideal for use on landfill gas; by adding or removing units, project size can be adjusted to match landfill gas production. *Stirling-Cycle engines* – closed-cycle "hot air" engines – are adaptable for use with landfill gas, are highly efficient, and have low emissions as compared to reciprocating engines. The *Organic Rankine Cycle (ORC)* engine is a process that uses an organic fluid (rather than steam) in a closed cycle to convert thermal energy into mechanical energy resulting in essentially no air emissions. The ORC may represent a technically feasible alternative for electrical generation using landfill gas.

Three 30-kW microturbines are in use at a landfill in Burbank, California, to generate electricity.

System Concepts

- Fuel cells generate electricity through an electrochemical process in which the energy stored in a fuel is converted directly into electricity, thus avoiding the need for combustion. These units can run on hydrogen that is produced from the methane content in landfill gas and use oxygen from the ambient air. Landfill gas cleanup is an important issue as fuel cells employ catalysts that could be fouled by trace compounds in landfill gas.
- The microturbine is a derivative of the much larger combustion turbines employed in the electric power and aviation industries. Microturbines spin at much faster speeds than traditional combustion turbines.
- Both fuel cells and microturbines generate a significant amount of thermal energy that can be easily captured for use (i.e., hot water/steam), thus increasing the total efficiencies of these units.
- In the Stirling engine, gas is contained in a continuous, closed volume that is divided into hot and cold regions. The size of the volume is periodically varied to compress and expand the gas. Heating and cooling are accomplished by periodically transferring working gas between the hot and cold regions. Since the engine derives its heat from an external source, almost any type of fuel (e.g., landfill gas) or combustible material can be used.

Representative Technologies

- Microturbines currently on the market use air bearings rather than traditional mechanical bearings in order to reduce wear. Combustion air and fuel are mixed in a combustor section, and the release of heat causes the expansion of the gas. Hot gas is sent through a gas turbine that is connected to a generator. Units are normally equipped with a recuperator that heats combustion air using turbine exhaust gas in order to increase the unit's overall efficiency. Combustion air is compressed using a compressor that is driven by the gas turbine. Use of landfill gas requires gas compression.

Technology Status/Applications

- Several types of fuel cells using different electrolytes are either available or under development. The four basic electrolyte types are: (1) phosphoric acid, which is commercially available and has been demonstrated commercially on landfill gas; (2) molten carbonate, which has also shown promise for landfill gas use; (3) solid oxide; and (4) proton exchange membrane (polymer-membrane).
- The microturbine is a recently commercialized technology. As of July 2003, six microturbine projects (3 megawatts) are operational, and four additional projects are under construction.
- Since January 2003, the first successful demonstrations of 2-25 kW and 10-25 kW Stirling-Cycle engines using landfill gas are operational at two landfills in Michigan.

Current Research, Development, and Demonstration

RD&D Goals

- Evaluate and demonstrate use of landfill gas as a fuel source for fuel cells and appropriate and cost-competitive cleanup technologies.
- Demonstrate long-term performance of microturbines on landfill gas, improve component corrosion protection, and develop larger microturbines.
- Demonstrate Stirling-Cycle engine at additional landfills; and evaluate technical, economic, and environmental considerations by 2004.
- Demonstrate first organic rankine cycle engine use at a landfill by 2004.

RD&D Challenges

- For fuel cells, developing cleanup technologies for landfill gas that are adequate but not cost prohibitive.
- For microturbines, dealing with potential fouling and failure of the turbine unit from silica or other components in landfill gas, and potential corrosion and excessive wear of components due to constituents found in landfill gas. In addition, microturbines are not currently cost competitive with traditional reciprocating engines. The total cost of power production, based on net power output and assuming retirement of the capital cost during 10 years at an interest rate of 10%, would be $0.07–$0.14/kWh ($0.04-$0.06 for recip. engine).
- High cost to develop and demonstrate Stirling engine and organic rankine engine; no commercial-scale units have been designed or demonstrated.
- Continued testing and commercialization of fuel cell and microturbine technologies.
- Technologies/processes to pretreat landfill gas prior to introduction to fuel cells and microturbines.
- Development of larger microturbines (i.e., greater than 75 kW).
- Development of larger Stirling engines and continuing to test Stirling and organic rankine cycle technologies.

RD&D Activities

- EPA-funded phosphoric acid fuel cell demonstration on LFG in California; the same system was also demonstrated in Connecticut. DOE/EPRI funded a molten carbonate fuel cell on LFG; EPA funded a study to evaluate LFG cleanup technologies for use with fuel cells; and a DOE small-business innovative research grant funded a demonstration converting LFG to methane for fuel cell use.
- Three microturbine demonstration projects with landfill gas have been completed since October 1999 – a 75-kW unit in New Mexico and California, and a 30-kW unit in California. In 2000, EPA funded a demonstration of a microturbine on landfill gas in Oregon. In 2001 and 2002, EPA funded two additional microturbine demonstration projects in Virginia and Vermont to test new microturbine technologies.
- Today, one manufacturer is developing commercially viable Stirling engines versions for landfill application (up to 250 kW).
- Since 1999, the Salt River Project (led by DOE and a municipal utility located in Phoenix, Arizona) is demonstrating the operation of the first thermal hybrid electric sundish. This technology combines solar thermal heliostats and a Stirling cycle engine using landfill gas (dual “fuel” Stirling cycle engine).

Recent Progress

- A phosphoric acid fuel cell is currently operating on landfill gas from the Braintree, Massachusetts, landfill.
- Microturbines have been demonstrated to operate on landfill gas with a low methane content, and have demonstrated NO_x emissions less than one-tenth those of the best performing reciprocating engines
- Demonstration of the first thermal hybrid electric sundish (combines solar and Stirling cycle engine using landfill gas) has been running successfully since 1999.
- Since January 2003, the first successful demonstrations of 2-25 kW and 10-25 kW Stirling cycle engines using landfill gas are operational at two landfills in Michigan.

Commercialization and Deployment Activities
• Phosphoric acid fuel cells are commercially available today, and many are installed worldwide. Most are using fuels other than landfill gas, but this type of fuel cell has been successfully demonstrated on landfill gas. Molten carbonate fuel cells have been operated on landfill gas – as well as a variety of other fuels – and this type of fuel cell looks particularly promising for landfill gas application due to its tolerance of CO_2 . • As of July 2003, two companies manufacture and sell landfill gas microturbines. Five commercial microturbine projects (3 megawatts) fired by landfill gas have been operational since January 2002. • One landfill gas pilot-plant study has been conducted for Stirling technology, and no organic rankine cycle pilot projects are planned. This may be due to resistance to "new" technology (even though the technology has been operating successfully in other applications) and current economic factors of electrical generation. **Market Context** • A market for these technologies exists wherever there is a need for electricity generation capacity. Hundreds of thousands of landfills and open dumps exist worldwide, all of which generate some amount of methane.

4.1.4 ADVANCES IN COAL MINE VENTILATION AIR SYSTEMS

Technology Description

Lean fuel turbine running off of ventilation air methane and drained gas. (Courtesy of Energy Developments Ltd.)

Ventilation air methane equipment (Megtec Vocsidizer) in Australia. (Courtesy of BHP Billiton Ltd).

Gassy underground coal mines emit more than 35 million tonnes (metric tons) of CO_2 equivalent (MtCO2e) of methane through their ventilation shafts. Until recently, because of the very low concentration (typically below 1%) of methane in ventilation air, coal operators had no technically proven option to recover this gas for its energy value. However, during the past decade, technologies have been developed and adapted that offer the promise of mitigating most of these emissions at low cost. One family of technologies being developed is the catalytic and thermal flow reversal reaction of ventilation air methane. These technologies may use up to 100% of the methane from ventilation shafts, and the byproduct heat may be used for the production of power or to satisfy local heating needs. Another prospective technology allows for the direct use of air mixed with down to 1% methane to produce power in gas turbines. This approach may require enriching the concentration of the air flow but may be a lower capital cost means of producing power.

System Concepts

Flow Reversal Reactors

Both catalytic and thermal-flow reversal technologies employ the principle of regenerative heat exchange between a gas and a solid bed of heat-exchange medium. Ventilation air flows into and through the reactor in one direction, and its temperature increases until the methane is oxidized. Then the hot products of oxidation lose heat as they continue toward the far side of the bed, until the flow is automatically reversed.

- Thermal reactors operate above the auto-ignition temperature of methane (1,000ºC). Catalytic reactors reduce the auto-ignition temperature significantly.
- Both types of reactors produce heat, which, through use of heat exchange technologies, may be transferred for local heating needs or for the production of power in steam or gas turbines.

Lean Fuel Turbines

- Some lean-fuel turbine concepts employ catalysts to aid the combustion.
- Others take place in an external combustor without catalysts but at a lower temperature than with normal turbines.
- Depending on the methane concentration, these technologies may use ventilation air for more than 80% of all fuel if concentrations are high, or less than 20% with low concentrations.

Representative Technologies

- Thermal-flow reversal reactors require a higher auto-ignition temperature that may require more sophisticated heat-exchange technologies.

- Catalytic flow reversal reactors have a lower auto-ignition temperature that may make heat exchange less costly, but they require catalyst material.
- Lean-fuel turbines under development include microturbines and larger scale turbines.
- Ancillary uses for ventilation air methane exist, such as the use of some ventilation air methane as the combustion air for power projects. This approach is technically straightforward and commercially proven, but the greenhouse gas reduction potential is limited.

Technology Status/Applications

- The Environmental Protection Agency (EPA) has identified and evaluated two specific flow reversal reaction technologies. Based on laboratory and field experience, both technologies may sustain operation with ventilation air with methane concentrations as low as 0.1%.
- These reactors have been applied for oxidation of volatile organic pollutants and have been successfully tested at small scale with ventilation air methane. Both thermal and catalytic flow reversal technologies may be used for the simple oxidation of methane (reducing methane emissions); and for the heat product, which may be used for production of power or direct heating.
- The EPA is working with technology vendors to identify viable lean fuel turbines and to improve their applicability for real-world ventilation air methane projects and identifying sites and partners for field demonstration. The EPA is also exploring an array of technologies for the use of ventilation air methane.

Current Research, Development, and Demonstration

RD&D Goals

- First commercial-scale field unit to demonstrate oxidation-only in 2003 and 2004.
- First commercial-scale field unit to demonstrate oxidation and heat recovery (power) in 2004 and 2005.
- A program of market penetration to be undertaken 2005-2010, ultimately leading by the end of the program to the majority of ventilation air methane emissions mitigated.

RD&D Challenges

- No commercial-scale unit has been designed or demonstrated.
- Heat-recovery technologies must be adapted from other industries for application at mine ventilation shafts.
- Safety design issues need to be addressed.

RD&D Activities

- Several technology developers/vendors are working with the coal industry, EPA, and DOE to develop the first commercial-scale projects.
- Tests are underway in Australia for the oxidation and heat recovery (via hot water) of a small, noncommercial-scale unit.
- EPA is providing technical support for technology vendors in identifying markets, performing safety analyses, and supporting project development.
- EPA and DOE are working with CONSOL Energy, a large coal operator, to demonstrate thermal oxidation of ventilation air methane using Megtec's Flow Reversal Reactor.

Recent Progress

- A project in Australia commercially employed ventilation air methane as feed air in internal combustion engines. The ventilation air methane provided approximately 7% of the total energy for the project at nominal cost.
- Tests prove that flow-reversal reactors can successfully sustain reactions down to a methane concentration in air of 0.1%.
- Small-scale demonstrations at coal mines have shown that ventilation air methane can be safely deployed at noncommercial scale, and that heat recovery is technically viable.

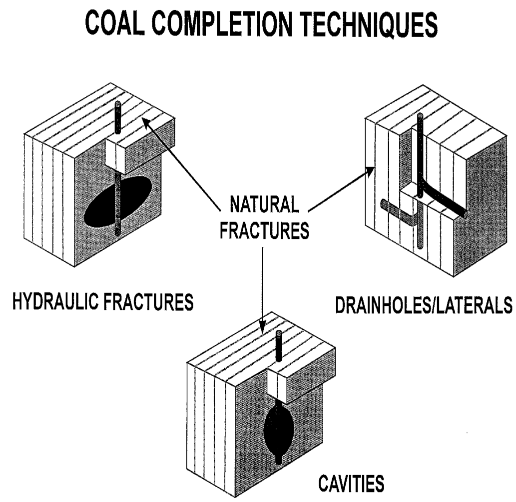
Commercialization and Deployment Activities
• Project vendors and developers are working with coal operators to develop ventilation air methane projects in the United States. **Market Context** • Majority of emissions in the United States at fewer than 30 very gassy ventilation shafts. • Heat recovered likely will interest power generators. Potential for more than 450 MW of power production available. • Markets for these technologies exist worldwide in countries with gassy coal seams and coal mining industries such as Australia, Canada, China, India, Mexico, Ukraine, Russia, and Poland.

4.1.5 ADVANCES IN COAL MINE METHANE RECOVERY SYSTEMS

Technology Description

In-mine directional drilling.

Vertical drainage in advance of mining.



Coal mine methane (CMM) is liberated into underground coal mines – as coal seams are mined – and vented out of the mine to provide a safe working environment. Where ventilation air cannot adequately control these emissions, mine operators utilize a CMM drainage system. Drainage systems consist of boreholes drilled into the coal seams and adjacent strata, and equipment is used to extract and collect CMM. Dependent on geologic, reservoir characteristics, and mine layout, CMM can be recovered in advance of mining or after mining has occurred. State-of-the-art CMM drainage techniques are now available to mine operators. Advances in steerable motors and stimulation techniques have increased the ability to recover CMM far in advance of actual mining operations. This allows operators to recover a higher percentage of the total methane in coal seams. The most promising technologies either necessitate fewer wells to produce more gas or increase the recovery efficiency of surface wells or underground boreholes. This CMM, much of which is high quality, presents many alternatives for utilization and markets.

System Concepts

- Boreholes are drilled into the coal seams and adjacent gas-bearing strata vertically or horizontally from the surface or from within the mine, depending on geologic, reservoir, and mine design and conditions.
- Various drilling technologies are employed to promote the release of the CMM.
- Gathering systems are used to collect and vent the CMM or distribute the gas to a specific use such as a natural gas pipeline. CMM recovered through drainage systems would have otherwise been vented through mine ventilation systems.

Representative Technologies

- Directional drilling systems that enable fewer wells to contact the same quantity of coal.
- Advanced stimulation techniques that use injection of a second gas such as nitrogen to improve recovery.

Technology Status/Applications

- Directional drilling, applied in conjunction with flexible coiled tubing and high pressure water jets, has been downscaled and applied to coalbed methane reservoirs.
- Operators also have demonstrated and commercialized slant-hole directional drilling, which involves the drilling of a guided surface hole that intersects the targeted coal seam and continues drilling within the bounds of a coal seam.

- Recent innovative methods for enhancing the recovery of methane from coalbeds by injection of second gases such as nitrogen are being tested. Carbon dioxide, while potentially attractive for unmineable seams, is not appropriate for coalbed methane development associated with mining because CO_2 is a hazard in the underground mining environment. Further work regarding the use of nitrogen is required.
- Computer simulation has suggested various configurations of in-mine directionally drilled boreholes and surface vertical wells to optimize CMM drainage approach.

Current Research, Development, and Demonstration

RD&D Goals

- Refined directional drilling technologies to improve the application in friable coal seams, increase drilling depths, and reduce the cost of drilling.
- Application of in-mine hydraulic fracturing techniques.
- Additional data supporting nitrogen injection as a cost-effective alternative for improving recovery efficiencies.
- In-mine application of nitrogen-injection techniques.
- Use of other inert gases as a second gas for injection into mined coal seams.
- New drilling techniques that could improve recovery of coalbed methane.
- Further applications of surface oil and gas drilling, as well as completion technologies and their application for in-mine CMM recovery.

RD&D Challenges

- Must locate demonstration projects at coal mines to clearly establish greenhouse gas reductions, but the number of very gassy mines in the United States is limited to about 30-40 coal mines.
- Must develop products that the mining community considers a help rather than a hindrance.
- Must directly link gas recovered to methane emissions avoided. Total coal mine methane emissions (ventilation air methane and drained emissions) does not increase due to improved drainage technologies; rather, ventilation air emissions decrease when drained gas emissions increase. Must consider this when assessing total methane emissions at a specific project.

RD&D Activities

- Several U.S. companies have developed directional drilling techniques, both vertical and horizontal, which are currently being evaluated.
- Use of CO_2 and nitrogen have been laboratory tested and/or field tested by private industry and research institutes.
- U.S. government funding has focused on gas utilization techniques, rather than recovery enhancement.

Recent Progress

- Reports indicate that directional drilling and injection of a second gas have demonstrated drainage efficiencies of 50%-90%.
- Slant-hole drilling has been used successfully to date at the SASOL Secunda Operations in South Africa. SASOL Secunda has drilled in excess of 100,000 meters of the surface to in-seam wells, regularly reaching target depths of up to 2 km. Dallas-based CDX Gas has successfully commercialized a surface directional drilling technique called the "Pinnate" multilateral drainage networks, and a dual-well drilling and production system.
- Nitrogen tests appear to be successful, but results are confidential.
- If the national, industry-wide drainage efficiency at underground mines increased from the current average of 34%-50%, then the United States could realize an additional 8 $MtCO_2e$ emissions reductions.

Commercialization and Deployment Activities
• Projects in the United States are currently employing directional drilling on a limited basis. • Carbon dioxide injection has been used for enhanced oil production for quite some time, and is being evaluated by the Alberta Research Council and an international consortium of Canadian and U.S. organizations. The results are confidential at this point. CO_2 injection does not appear appropriate for coal mine applications, however. • Nitrogen injection to enhance methane recovery from mineable coal seams needs demonstration. **Market Context** • Gassy coal mines in the United States, where improved gas recovery efficiencies will yield greater coal mine productivity and natural gas for use or resale are potential markets for this technology. • Additional gas recovered likely will interest gas users such as gas marketers, power generators, etc. • Markets for these technologies exist worldwide in countries with gassy coal seams and coal-mining industries such as Australia, Canada, China, India, Ukraine, Russia, and Poland. • Beyond carbon reductions, market for these products will be found in the exploration and production sector of the natural gas industry.

4.1.6 MEASUREMENT AND MONITORING TECHNOLOGY FOR NATURAL GAS SYSTEMS

Technology Description

Handheld infrared remote imaging spectrometer for fugitive gas leak detection.

Hi-Flow™ Sampler to measure emission rates.

There are approximately 300,000 miles of pipeline in the U.S. natural gas transmission network. Along this network, compressor stations – with up to 2,500 separate components each – leak millions of dollars worth of methane into the atmosphere every year. In addition, there are more than 700 gas-processing facilities that lose an estimated 30 billion cubic feet of gas each year. Through the use of effective leak detection and measurement technology as part of a directed inspection and maintenance program, methane emissions can be reduced significantly.

System Concepts

- Advanced leak detection and measurement technologies enable quick and cost-effective detection and quantification of fugitive methane leaks.
- Directed inspection and maintenance programs employ these technologies through the collection of screening and measurement data through comprehensive surveys in the first year. Information gathered on equipment with high leak rates is then used to direct surveys and prioritize cost-effective leak repair efforts in subsequent years. Because leak surveys and repairs are better focused and more accurate, they can be conducted less frequently, thereby reducing operation and maintenance costs.

Representative Technologies

- The Gas Technology Institute (GTI) has developed an advanced measurement technology known as the Hi-Flow™ Sampler. This technology is unique because it measures actual emission rates from sources that traditionally were not easily measured. The Hi-Flow™ utilizes a variable-rate induced-flow sampling system that provides total capture of the emissions from a leaking component. The instrument is designed to ensure total emissions capture, and prevent interference from other nearby sources. A dual-element hydrocarbon detector (i.e., catalytic-oxidation/thermal-conductivity), measures hydrocarbon concentrations in the captured air stream ranging from 0.01% to 100%. A background sample-collection line and hydrocarbon detector allows the sample readings to be corrected for ambient gas concentrations. A thermal anemometer monitors the mass flow rate of the sampled air-hydrocarbon gas mixture, and a mass rate is then calculated.
- GTI (in cooperation with Pacific Advanced Technology) is also developing advanced leak-detection technology. One of the emerging technologies is the IMSS camera, a handheld infrared remote imaging spectrometer for fugitive gas leak detection. It detects species by comparing differential absorption spectra. The device can detect low flow and underground methane leaks from a maximum of 300 feet away but is more effective at a distance of around 50 feet or less.

Technology Status/Applications

- Traditional leak measurement technologies are currently available. Advanced technologies, like the Hi-Flow Sampler, are in the demonstration and deployment stage.
- Advanced imaging technology for leak detection is still in the development and demonstration phases. Next-generation technology may provide the ability to both detect a leak and quantify the emission rate.

Current Research, Development, and Demonstration

RD&D Goals

- Complete the development of advanced measurement technologies like the Hi-Flow™ and ensure broad deployment throughout the industry.
- Advance the development of imaging technology for methane leak detection and facilitate demonstration.

RD&D Challenges

- No commercial-scale unit designed or demonstrated.
- Safety design issues need to be addressed.

RD&D Activities

- Advanced measurement technologies already are being demonstrated. Additional research to enhance this technology is underway.
- Identification and adaptation of new technologies for real-time remote optical leak detection, quantification, and speciation is underway. Preliminary testing indicates the ability to image low-flow conditions and under-ground methane leaks.
- The Kansas State University National Gas Machinery Laboratory and EPA's Natural Gas STAR Program are collaborating on a study to demonstrate the cost-effective use of measurement technology to reduce methane leakage from natural gas production and processing facilities.

Recent Progress

- As part of a cooperative R&D effort among the EPA, the Gas Technology Institute, and the natural gas industry, the effectiveness of utilizing the Hi-Flow™ Sampler measurement technology to reduce methane leakage at three gas-processing plants was evaluated. The value of natural gas losses at the surveyed sites was approximately $2.2 million, substantially offsetting the cost of the surveys.
- Preliminary testing of the IMSS technology for leak detection has been successful. In a recent test conducted by PAT, IMSS successfully imaged leaks as small as 0.01 cubic feet per minute in ambient conditions, using either a building or the sky as background.

Commercialization and Deployment Activities

- Both the IMSS camera and Hi-Flow™ Sampler are not yet available for commercial applications. Prototype versions of the Hi-Flow™, however, already have been used by several large transmission companies.

Market Context

- Gas transmission and processing companies are most likely to be interested in these technologies. Gas distribution and production companies, however, are also likely to be potential consumers.

4.2. METHANE AND NITROUS OXIDE EMISSIONS FROM AGRICULTURE

4.2.1 ADVANCED AGRICULTURAL SYSTEMS FOR N_2O EMISSION REDUCTION

Technology Description

No-tillage cropping system in irrigated agriculture to reduce Net global warming potential (A.D. Halvorson, USDA-ARS, Fort Collins, CO)

Low fertilizer nitrogen-use efficiency in agricultural systems is primarily caused by large nitrogen losses due to leaching and gaseous emissions (ammonia, nitrous oxide, nitric oxide, nitrogen). It is axiomatic then that most strategies that increase the efficiency use of fertilizer nitrogen will reduce emissions of N_2O and probably NO. In general, nitrogen oxide emissions from mineral and organic nitrogen can be decreased by management practices that optimize the crop's natural ability to compete with processes where plant-available nitrogen is lost from the soil-plant system, and/or by directly lowering the rate and duration of the loss processes. Strategies to increase the overall efficiency of nitrogen are therefore necessary to decrease nitrogen oxide emissions. Advanced agricultural systems are a group of technologies that can be applied to this goal. These systems enable a process of collecting and using increasingly detailed, site-specific information in conjunction with traditional farm-management tools, and applying the best available information to better manage individual farming operations. These systems conceptually provide for improved understanding, control, and manipulation of the soil/plant/atmosphere environment to match nutrient, water, pesticide, and other inputs for crop production demand, which will increase efficiency of nutrients and decrease gaseous and leaching losses. These systems provide an integrated capability to improve environmental quality while enhancing economic productivity by increasing energy efficiency, optimizing fertilizer and other chemical applications, and conserving soil and water resources. Most system concepts for reduction of GHG emissions are, however, theoretical and remain untested.

System Concepts

- Precision agriculture – global-positioning infrastructure and remote and in-situ sensors for soil, crop, and microclimate characterization; this practice includes variable rate water, fertilizer, and pesticide application in space and time.
- Cropping system models, data and information analysis, and management tools.
- Control-release fertilizer and pesticide delivery to match crop demand and timing of pest infestation.
- Biological and chemical methods for manipulating soil microbial processes to increase efficiency of nutrient uptake, suppress N_2O emissions, and reduce leaching.
- Best-management practices to limit nitrogen gas emissions, soil erosion, and leaching.
- Soil-conservation practices utilizing buffers and conservation reserves.
- Recycling of livestock manure.
- Plant breeding to increase nutrient-use efficiency and decrease demand for pesticides and energy consumption.

Representative Technologies

- Global-positioning satellites and ground systems, satellite- and aircraft-based remote and in-situ electrical, magnetic, optical, chemical, and biological sensors.
- Advanced artificial intelligence and information networking technologies; autonomous control and robotics systems; soil/ crop moisture, pest and microclimate responsive (smart) materials.
- Control-release fertilizers and pesticides.
- Nitrogen transformation inhibitors.
- Livestock waste delivery systems.
- Best-management practices.
- Genetically engineered plants that are resistant to herbicides or specific pests.

Technology Status/Applications

- Many first-generation precision agriculture technologies are available; in 1998, used on about 14% of farms.
- Information management and networking tools; rapid soil-characterization sensors; selected crop stress, yield, and quality sensors; and a systematic integration of all technologies for all major cropping systems are not yet at technical performance levels and require field testing.
- Strong understanding of soil microbiology and soil processes and relationships exist in the agriculture, energy, and university research community.
- Capability exists for the development of control-release materials and biological process inhibitors.
- Best-management practices are in place in many production sectors.

Current Research, Development, and Demonstration

RD&D Goals

- Precision agriculture technologies that improve production efficiencies and reduce energy consumption.
- Remote and field-deployed sensors/monitors and information-management systems for accurate, real-time monitoring and analysis of crops, soils, water, fertilizer, and agricultural chemicals use/efficiency to meet the fertilizer and energy reduction goals.
- Smart materials for prescription release utilized in major crops.
- Advanced fertilizers and technologies to improve fertilizer efficiency and reduce nitrogen inputs.
- Methods of manipulating soil microbial processes to increase efficiency of nitrogen use.
- Deployment of first-generation integrated system models, technology, and supporting education and extension infrastructure.
- Genetically designed major crop plants to utilize fertilizer more efficiently.
- Complete transition of first-generation system development to the private sector.
- Full utilization of best-management practices.

RD&D Challenges

- Precision agriculture in general requires advances in rapid, low-cost, and accurate soil nutrient and physical property characterization; real-time crop water need characterization; real-time crop yield and quality characterization; real-time insect and pest infestation characterization; autonomous control systems; and integrated physiological model and massive data/information management systems. All of these require a full understanding of the spatial and temporal dynamics that occur within a field.
- Smart materials that will release chemicals based on soil and crop status depend on modest breakthroughs in materials technology.
- Improved understanding of specific soil microbial processes is required to support development of methods for manipulation and how manipulation impacts greenhouse gas emissions.
- Models that represent accurate understanding of plant physiology must be coupled with models that represent soil processes such as decomposition, nutrient cycling, gaseous diffusion, water flow, and storage to understand how ecosystems respond to environmental and management change.
- Detailed and simultaneous examination of biogeochemical reactions that occur in near-surface groundwater is required to improve understanding of nutrient cycling, GHG emissions, and degradation of contaminants.
- Improved understanding of agro-ecosystem management on nitrogen cycling and GHG emissions.
- Development of plant varieties that increase nutrient use efficiency.
- Conduct direct basic and applied research effort on sensors, information sciences, materials, and microbial processes.
- Apply whole-systems engineering and integration to effectively develop and guide program formulation and implementation to include the concept of whole system net GHG emissions.

RD&D Activities

- Complementary efforts are underway in both public and private sectors.
- Sponsors include USDA, DOE, NASA, universities, state agencies, commodity groups, and sensor and satellite developers – the principal funding comes from USDA.

Recent Progress
• High-resolution satellite imagery can identify stress and disease in some crops at 1-to-2-m resolution. • Research programs have related reflectance spectra to disease or nutrient status. • Control-release formulations for fertilizers and pesticides are in use. • Rf-link deployable field sensors exist for ground moisture monitoring. • On-farm use of yield-monitoring equipment is increasing. • Commercial sensors for sensitive, precise, and rapid analysis of GHGs are now marketed. • Best-management practices are in place for many crops and regions of the country. • Genetically modified crop varieties are being used that are resistant to specific herbicides or pests.
Commercialization and Deployment Activities
• Global-positioning systems, geographic information system software for parameter mapping, remotely sensed imagery, selected field monitors, and selected variable rate control systems for seed, fertilizer, and chemical applications are commercialized and in application in the United States, Canada, Australia, and Europe. • Slow-bleed release pesticides are available commercially. • Nitrogen transformation inhibitors are available commercially, and were applied to approximately 10% of corn acres in 1996. Inhibitor application increased net revenue $8-$20/acre. • Control-release fertilizers are produced and used mainly in horticultural and ornamental crops. **Market Context** • Market for technologies exists not only in the United States but worldwide. In developing countries dependent on agriculture, the market for improved agricultural systems is substantial.

4.2.2 METHANE REDUCTION OPTIONS FOR MANURE MANAGEMENT

Technology Description

Construction of a complete mix anaerobic digestion system

The livestock and poultry industry produces large quantities of manure each year. Pollutants from improperly managed waste can damage the environment in terms of water, air, and health quality. Methane and other gases are produced when manure is managed under anaerobic conditions typically associated with liquid or slurry manure-management systems such as lagoons, ponds, tanks, and basins. Methane reduction and other environmental benefits can be achieved by utilizing a variety of technologies and processes including aeration processes to remove and stabilize some pollutant constituents from the waste stream; anaerobic digestion system that collect and transfer manure-generated off-gases to energy producing combustion devises (such as engine generators, boilers, or odor-control flares); and solids-separation processes to remove some pollutant constituents from the waste stream.

System Concepts

- *Anaerobic digestion* provides a high level of manure treatment that mitigates water and other air pollution by biologically stabilizing (treating) influent waste materials and capturing methane emissions. Captured gas can then be combusted to produce electricity, heat, or vehicle fuel. Anaerobic digestion technologies can be applied at various scales (i.e., farm or centralized) and require separate effluent storage and a gas use device. Centralized anaerobic digestion technologies can be cost-effectively integrated into high-density livestock regions, where a number of farms would transfer manure to a dedicated processing facility. Centralized systems can produce very large power outputs (1-20 MW) depending on the manure volume and quality. Comparatively centralized systems can use technologies with greater complexity, because these plants typically have a professionally trained team available to operate the system.
- *Separation processes*, typically used in dairy operations, remove particulate matter from manure handled as liquid or slurry through gravity, mechanical, or chemical methods. These processes create a second waste stream that must be managed using techniques different from those already in use to manage liquids or slurries. Separation processes offer the opportunity to stabilize solids aerobically i.e., to control odor and vermin propagation.
- In *aeration processes*, oxygen is transferred to a liquid primarily by mechanical equipment. The equipment serves to a) provide the oxygen needed by the microorganisms to oxidize the organic matter and b) keep the solids in suspension by mixing. A residual-dissolved oxygen concentration of at least 1-2 mg/L is an indicator that the rate of oxygen transfer is adequate to satisfy this oxygen demand aerobically for livestock waste. This requirement is usually met by large pumps operating in the range of about 50-125 HP.

Representative Technologies

- *Centralized digester technologies* include both mesophilic and thermophilic mixed digesters and other advanced environmental processes such as reverse osmosis and gas compression. Thermophilic digesters operate at high temperatures (140ºF). Mesophilic operate at lower temperatures (about 105ºF) and have greater process stability. Currently available combustion devices include medium-BTU reciprocating engines with heat recovery (cogen), turbines, boilers, absorption cooling, and furnaces. Flares also can be used to control odor and other air emissions in nonenergy applications. Emerging technologies include microturbines, sterling engines, and fuel cells.
- *Farm-scale digesters* are typically simpler systems operating at ambient and mesophilic temperatures and include mix, plug, and inground covered systems.

- *Separation process technologies* include gravity separation (shallow pits where solids settle and liquids run off to a treatment lagoon), mechanical separators (use external energy sources to remove solids), and flocculation or precipitation (chemical additions are used to help precipitate particulate and colloidal materials).
- A variety of *aeration process technologies* exist, including aerobic digestion (a suspended growth process operating at ambient temperature), autoheated aerobic digestion (utilizes heat released during the microbial oxidation of organic matter to raise process temperature above ambient levels), sequencing batch reactors (combine the conventional activated-sludge treatment process with secondary settling/clarification in a single tank), attached-growth processes (trickling filters, rotating biological contactors, and packed bed reactors use inert media to stabilize organic matter and limit organic loading rates), and composting (a solid-waste treatment process that requires oxygen and appropriate carbon:nitrogen ratios to heat and stabilize waste material.)

Technology Status/Applications

- There are currently about 50 farm-scale anaerobic digesters producing heat and about 30 million kWh of electricity per year with currently available technologies at U.S. dairy and swine farms. A small number of farms also flare gas for odor control and GHG reductions. There are no centralized anaerobic digesters operating in the United States, although Europe has several of these systems.
- Separation is typically used in the dairy industry to remove nonbiodegradable material from treatment lagoons, but is rarely applied to managing wastewater from swine facilities because swine solids are small, heavy, tend to mat, and hold water. Additional equipment and management is required to maintain adequate air infiltration for aerobic conditions.
- Aeration processes are basically applied to low-strength and dilute waste streams due to energy requirements. Their use has been limited for livestock liquid and slurry waste streams.

Current Research, Development, and Demonstration

RD&D Goals

- Develop new types of digesters with reduced costs and biological efficiencies. A number of private companies are developing and testing newer gas combustion devices for medium-BTU gases.
- Modification to under-slat floors in swine buildings to separate solid and liquid fractions and chemical additions applied to swine manure.
- Develop, apply, and evaluate aeration process performance for manure waste streams. Identify appropriate pollution-control methods for confined livestock facilities.

RD&D Challenges

- Current R&D on anaerobic digestion technologies is done at bench or pilot scales. These processes often are operationally complex at commercial scales. This complexity may be justified under a centralized operating structure because dedicated expertise is available to control system processes. Continued work in this area needs to identify regional areas with greatest opportunity to implement this approach relative to farm distances, manure-handling method, and frequency of collection.
- Utility policies toward independent power producers impede development of digestion technologies for power generation. Increasing operational reliability and efficiency of electrical production equipment and increasing the number of equipment providers is needed. Controller logic for electrical-producing gas uses and digester type also is required.
- Improved separation processes need to be demonstrated at commercial-scale farms where operations are more complex.
- Challenges for the use of aeration processes for primary manure treatment today include high investment and operating costs (including energy) of treating waste streams aerobically. Aeration processes also increase the volume of residual solids depending on the operating conditions necessitating removal and additional management. Aeration may also volatilize 30%-90% of the nitrogen as N_2 or N_2O, which contribute to global warming and other environmental problems.

RD&D Activities

- EPA Region 9 is working with California to evaluate the feasibility of a centralized anaerobic project.
- USDA and DOE are currently funding research, development, and demonstration projects under the Biomass Research and Development Act of 2000. There are a number of projects focusing on technologies to generate energy from animal waste, convert biomass to hydrogen, and develop innovative biorefinery processes.

Recent Progress

- EPA's AgSTAR Program provides project development tools, performance evaluations, and general digester information. AgSTAR also collaborates with a number of state programs and various Farm Bill sections to expand the use of appropriate anaerobic digestion processes and gas uses. AgSTAR products and expertise have been used in the majority of animal waste digestion systems currently in operation.
- Currently, dairy manure handled as liquid and slurry is generally separated. Some dairies blend solids with other organic materials and market "brand" name compost materials for the nursery and home garden market.
- Aeration processes may be feasible for secondary or tertiary treatment of livestock waste, where greater pollution control is desirable – or to further reduce nitrogen availability for crop uptake.

Commercialization and Deployment Activities

- Currently, centralized digestion applications are being identified and some are in operation. The opportunities, however, may be limited because of farm distances and manure-handling practices. Biosecurity issues also may reduce the potential of this approach. Emerging gas-use technology development is limited for farm-scale anaerobic digesters because commercial applications have not been in operation long enough to make a performance determination by designers and vendors. However, applications at larger scales (such as landfill gas) will be relevant for centralized systems.
- There are several manufacturers and suppliers of mechanical separator equipment. USDA provides design guidance for gravity separators and technical resources to farms requesting assistance.
- A number of manufacturers and suppliers of aeration processes are available because it is used in municipal and industrial waste treatment. A number of low-rate aeration processes are emerging but have limited application because the dissolved oxygen requirements for microbial populations to oxidize organic matter are not met.

Market Context

- Cost-sharing and appropriate energy policies for independent power production could increase market penetration.

4.2.3 ADVANCED AGRICULTURAL SYSTEMS FOR ENTERIC EMISSIONS REDUCTION

Technology Description

Enteric emissions of methane from animals are a byproduct of digestion that are exhaled or eructated by the animals. It is a natural process, and the amount of methane is dependent on the animal's digestive system and the amount and type of feed consumed. Any reductions in this energy loss will increase nutritional efficiency – therefore the goal of much nutrition research has been to reduce this energy loss, while increasing production or nutritional efficiency. There are a number of strategies that can be used, including increased digestibility of forages and feeds; feeding grain rather than forages; providing feed additives that may tie up hydrogen in the rumen and inhibit the formation of methane by rumen bacteria; improving production efficiency; and modification of bacteria in the rumen. Many production practices are currently used that reduce methane; when used individually or in conjunction with each other, the practices may lower the loss of methane energy up to one half. These have not only global change benefits but may have significant economic benefits as well. Most system concepts for reducing methane emissions are, however, theoretical, and considerable research and development are required.

System Concepts

- High-grain diets: Feeding of high-grain diets to reduce methane emissions and increase animal production efficiency, without contributing to the animal health problems that are typically associated with high-grain diets.
- Ruminal fermentation time: Methane is released from the rumen where feed is fermented in an aerobic environment. The shorter the period of time feed remains in the rumen, the less carbon is converted to methane. Residence time in the rumen can be shortened by increasing the digestibility of feed grains or forages and by feeding of concentrated supplements.
- Alternate hydrogen acceptors: Addition of unsaturated edible oils in feed may be used to reduce methane emissions by sequestering hydrogen making it unavailable for methanogens.
- Use of feed additives: Ionophores are feed additives that inhibit the formation of methane by rumen bacteria. Considerable research is needed in maintenance of effectiveness for long periods and for delivery systems to grazing cattle.
- Improvement in production efficiency: Any practice that increases productivity per animal reduces methane emissions. Animal technologies that increase productivity include BST to increase milk production, growth regulators for beef cattle to enhance lean and reduce fat, genetic improvement of animal performance, genetic improvement of pasture and other feedstuffs potential, improved animal feed-handling practices, improved pasture nutritional and water management, and earlier marketing of animals.
- Enhancing ruminal acetogens: Acetogens are a group of rumen microbes that produce acetic acid from hydrogen and carbon dioxide rather than methane. They exist in the rumen as a minor species, predominate in the gut of some termites, and may be important in the lower gut of several animal species. Developing methods to make them more competitive in the rumen or transferring the acetogenesis genes to already successful ruminal organisms could be very helpful to animal efficiency and the environment.
- Modification of bacteria in the rumen: Alteration of ruminal microbes may lead to significant reduction in methane emissions; however, considerable research is needed to genetically produce microbes that can compete with natural microbes for sustained periods.

Representative Technologies

- Improved feed and forage management and treatment practices to increase the digestibility and reduce residence digestion time in the rumen, such as using improved feed grains and forage, increased surface area of the feeds, addition of fiber sources, treatment of the feeds/forages to increase digestibility, and appropriate use of concentrated supplements.
- Best-management practices for increased animal reproduction efficiency.
- Use of growth promotants and other agents to improve animal efficiency and enhance lean meat production.

Technology Status/Applications

- First-generation precision agriculture technologies are available and have been used on as many as 14% of farms by 1998.

- Rapid soil characterization sensors; selected forage stress, yield, and quality sensors; integration of global positioning systems to enhance selected needed areas of forage systems for enhanced selected management; and a systematic integration of all technologies for all major pasture and forage systems are not yet at technical performance levels required for field application.
- Strong understanding of animal physiology exists in the agriculture, energy, and university research areas.
- Research is required for the development of control-release materials and biological process inhibitors.
- Extensive use is made of animal and feed technologies in dairy- and beef-feeding systems; however, adequate techniques for uniform and effective delivery systems are needed in grazing systems.
- Best-management practices are in place in many production sectors.

Current Research, Development, and Demonstration

RD&D Goals

- Precision agriculture technologies that will improve forage and feedstuffs production efficiencies and increase digestibility.
- Remote and field-deployed sensors/monitors and information management systems for accurate, real-time monitoring and analysis of forage and crops, soils, water, fertilizer, and agricultural chemical use/efficiency to improve animal production efficiency.
- Smart materials for prescription release of feed additives under pasture or grazing systems.
- Genetic improvement of forages to increase productivity and digestibility.
- Methods of manipulating ruminal microbial processes to sequester hydrogen making it unavailable to methanogens.
- Deployment of first-generation integrated system models, technology and supporting education, and extension infrastructure.
- Genetically design forages to increase digestibility, reduce fertilizer requirements, provide chemicals for increased digestibility, and provide appropriate nutrients to enhance acetogen competitiveness.
- Genetically design bacteria that can compete with natural microbes for sustained periods.
- Full utilization of best-management practices.

RD&D Challenges

- Precision agriculture requires advances in rapid, low-cost, accurate plant, soil-nutrient, and physical property characterization; real-time crop and forage water requirements characterization; real-time crop and forage yield and quality characterization; real-time insect and pest infestation characterization; autonomous control systems; and integrated physiological model and comprehensive and user-friendly data/information-management systems.
- "Smart" materials that will release chemicals and feed additive doses under special conditions.
- Improved understanding of specific rumen microbial processes is required to support development of methods for making engineered microbes competitive with natural rumen microbes.
- Models that represent accurate understanding of the relationship of animal digestion and plant physiology must be coupled with models that represent soil-plant growth relationships. These models also must consider the changing global climate.
- Genetic engineering of sustainable competitive microbes that will produce acetic acid for the reduction of CO_2 with hydrogen.
- Development of plant varieties that increase nutrient-use efficiency while enhancing digestibility.
- Conduct direct basic and applied research effort on animal physiology, sensor development, material and feed additive research, and microbial processes research.

RD&D Activities

- The principal funding for this type research comes from the USDA and the animal-support industries. Others include the EPA, universities, state agencies, commodity groups, and instrumentation developers.

Recent Progress
• High-resolution satellite imagery can be used to identify water and nutrient stress and disease in some forage systems at 1-to-2 m resolution. • Success has been observed under grazing in the use of ionophores, which are widely used in the beef industry. • Control-release formulations for fertilizers and pesticides are in use, which improve forage productivity and digestibility. • Animal productivity per unit of methane emissions has steadily increased under managed conditions in the past 30 years. • On-farm use of yield-monitoring equipment is increasing. • Commercial sensors for sensitive, precise, and rapid analysis of greenhouse gases are in development and being marketed. • Best-management practices are in place for many crops and animal-management systems and regions of the country.
Commercialization and Deployment Activities
• Global-positioning systems, geographic information system software for parameter mapping, remotely sensed imagery, selected field monitors, and selected variable rate-control systems for seed, fertilizer, and chemical applications are commercialized and in application in the United States, Canada, Australia, and Europe. All of these systems may be used for increasing productivity and digestibility of forages. • Mitigated-release fertilizers and pesticides are available commercially. • Ionophores are widely used in the beef-feeding industry to increase productivity – but better delivery systems are needed. • Current precision agriculture technology is proven to be cost effective about 50% of the time, with poor reproducibility. • The infrastructure in place for agricultural production will support economical new technologies; however, the cost to compete with traditional technologies may initially be high until technology integration is complete.

4.3 EMISSIONS OF HIGH GLOBAL-WARMING POTENTIAL GASES

4.3.1 SEMICONDUCTOR INDUSTRY: ABATEMENT TECHNOLOGIES

Technology Description

Figure 1. Litmas Blue Plasma Abatement Device

Figure 2. Hitachi Catalytic Oxidation System

Semiconductor manufacturers perform plasma etching and cleaning processes that use gaseous chemicals including perfluorocarbons (e.g., CF_4, C_2F_6 and C_3F_8), nitrogen trifluoride (NF_3), HFC-23 (CHF_3), and sulfur hexafluoride (SF_6). Collectively termed high global-warming potential (GWP) gases, these chemicals are potent greenhouse gases; one metric ton of SF_6 is equivalent to 23,900 Mt of carbon dioxide in terms of its potential effect on global warming. In addition, many high GWP gases have extremely long lifetimes in the atmosphere (3,000-50,000 years). For the past 15 years, through international efforts to decrease ozone-depleting substances in the atmosphere, industry has been engaged in activities to reduce emissions and find alternatives.

One method of decreasing the emissions of high GWP gases from the semiconductor industry is to abate the emissions before they reach the atmosphere. Abatement of high GWP gases from the exhaust gas stream in semiconductor processing facilities may be achieved by two mechanisms: 1) thermal destruction and 2) plasma destruction. Thermal destruction technology may be applied to chamber-cleaning and etching processes within a fab (a local point-of-use [POU] application) or fab wide (an end-of-pipe [EOP] application). A POU device controls emissions as they emerge from an individual tool, while an EOP device is installed further “downstream,” where it can abate emissions from a group of tools – or the entire fab – prior to the exhaust reaching the stack. Two thermal destruction technologies are being pursued: combustion systems and catalytic systems. In plasma-based systems, plasmas are formed from the effluent stream from etch or clean processes using either radio frequencies (low pressure streams) or microwaves (streams at atmospheric pressure). Destruction of high GWP gases that use plasmas offer system designers a broad range of conditions: oxidizing, reducing, and combinations of oxidizing and reducing conditions.

System Concepts

- In POU applications, thermal-destruction systems may be configured to accept exhaust from multiple etch/chemical vapor deposition chambers. High GWP emissions are oxidized in a natural gas-fired burner or over an electrically heated catalyst before the combustion products are removed by the on-site waste treatment systems.

- Burner and catalytic systems require pretreatment of inlet streams to reduce the loads of unused deposition/etchant gases and particles that can block burners or clog catalysts.
- Hydrofluoric acid formed in thermal destruction systems may be removed via POU scrubbers to prevent exceeding scrubber design limits.
- Plasma abatement technologies rely on the basic idea that larger exhaust molecules are broken into fragments in the plasma and then recombine in new ways, in the presence of other fragments formed from the dissociation of other gases added to the plasma, to form a new set of exhaust gases that may then be removed by existing waste-treatment systems.
- Plasma abatement systems for high GWP gases typically require very little floor space, because they are mounted off the floor directly on the foreline to the dry pump that feeds exhaust to scrubbing systems.

Representative Technologies

- The Edwards TPU 4214 (oxidation with advanced burner technology) is applicable for all high GWP emissions.
- The Hitachi system (catalytic oxidation technology) is applicable to CF_4, C_2F_6, c-C_4F_8, and SF_6.
- Investigators at Texas A&M patented an approach that used radio frequency and microwave surface wave plasmas. They now favor microwave technology that has proven more effective and holds the potential for exploiting low-cost magnetron technology.
- Litmas, Inc., has two systems. The first, “Blue,” uses an inductively coupled radio frequency plasma source to transform high-GWP exhaust gases from etchers. The second technology from Litmas, “Red,” transforms the exhausts from plasma-enhanced chemical vapor deposition chambers using microwaves.
- AMAT’s Pegasys™ POU unit integrates cold-plasma abatement technology with popular etchers, which makes the abatement unit transparent to process engineers.

Current Research, Development, and Demonstration

RD&D Goals

- To lower high GWP emissions from waste streams by more than 99%, while minimizing (1) NO_x emissions to levels at or below emissions standards, (2) water use and burdens on industrial wastewater-treatment systems, (3) fabrication floor space, (4) unscheduled outages and (5) maintenance costs.
- To apply plasma technology to develop a cost-effective POU abatement device that lowers exhaust stream concentrations of high GWP gases by two to three orders of magnitude from etchers and plasma-enhanced chemical vapor deposition chambers; and transforms those gases into molecules that can be readily removed from air emissions using known scrubbing technologies.

RD&D Challenges

- Optimal combustion conditions to achieve destruction efficiencies for all high GWP gases, minimal energy consumption, and water use.
- In low-pressure applications, convincing skeptical process engineers that back-streaming from the plasma system does not threaten etch-process performance.
- Achieving more than 99% destruction efficiencies for all high GWP gases, particularly CF_4 and SF_6.
- Develop a cost-effective POU abatement device that lowers exhaust-stream concentrations of high GWP gases by two to three orders of magnitude, and transforms these gases into molecules that can be removed with current scrubbing technologies.

RD&D Activities

- Evaluations/reviews of approximately 13 thermal-destruction systems have been completed. Evaluations and demonstrations performed under fabrication operating conditions with Litmas and Texas A&M plasma systems produced favorable results.

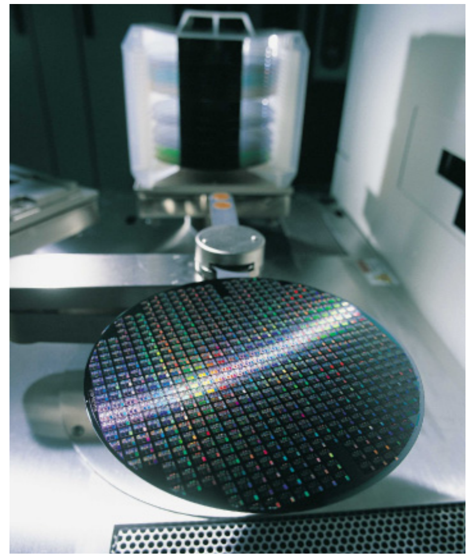
Recent Progress

- The Edwards TPU 4214 (oxidation with advanced burner technology) achieves more than 99% destruction efficiency.
- The Hitachi system (catalytic oxidation technology) achieves destruction efficiencies of more than 99% for CF_4, C_2F_6, c-C_4F_8 and SF_6.

• Litmas, Inc., reports emission reductions from 97% to 99% for its "Blue" POU device. • AMAT's capacitively coupled device (Pegasys II™) claims typically more than 95% reduction in emissions. • Recent reports indicate that the surface wave device offers emissions reductions of more than 99% for a large range of tested waste streams. • The Pegasys and Litmas radio frequency POU units appear affordable, with reasonable capital and operating costs, assuming that the existing hydrofluoric acid scrubber system (including ductwork) can handle the increase in hydrofluoric acid from these abatement units. • The AMAT and Litmas radio frequency POU units have a small footprint, are easy to install, and are applicable to 200- and 300-mm etch tools.
Commercialization and Deployment Activities
• The Edwards TPU 4214 is the only thermal-destruction device in commercial use and represents a favored POU solution for chemical vapor deposition cleaning processes. • AMAT's and Litmas' systems are commercially available and reported in use. • AMAT's (Pegasys II™) interfaces with AMAT's 200 and 300mm dielectric oxide etchers. • Litmas' "Blue" technology has successfully completed long-term impact tests on etch process performance. • Litmas' "Red" technology reported by Litmas to be in use on plasma-enhanced chemical vapor deposition chambers. • There are no reports of commercial application of the surface wave plasma device. Research continues at Texas A&M. **Market Context** • Thermal and plasma destruction technologies can have broad applicability across the semiconductor industry.

4.3.2 SEMICONDUCTOR INDUSTRY: SUBSTITUTES FOR HIGH GWP GASES

Technology Description



PFCs, HFCs, NF_3, and SF_6 are used to construct intricate semiconductor products on silicon wafers such as this one. (Reprinted with permission of Greenleaf Publishing.)

Semiconductor manufacturers perform plasma etching and cleaning processes that use gaseous chemicals including perfluorocarbons (e.g., CF_4, C_2F_6 and C_3F_8), nitrogen trifluoride (NF_3), HFC-23 (CHF_3), and sulfur hexafluoride (SF_6). Collectively termed high global-warming potential (GWP) gases, these chemicals are potent greenhouse gases; one metric ton of SF_6 is equivalent to 23,900 Mt of carbon dioxide in terms of its potential effect on global warming. In addition, many high GWP gases have extremely long lifetimes in the atmosphere (3,000-50,000 years). For the past 15 years, through international efforts to decrease ozone-depleting substances in the atmosphere, industry has been engaged in activities to reduce emissions and find alternatives. One method of decreasing the emissions of high GWP gases from the semiconductor industry is to substitute a different chemical or process for the high GWP gases. Replacing high GWP gases with environmentally benign substitutes for chemical vapor deposition clean and dielectric etch processes is a preferred option when viewed from the perspective of EPA's pollution prevention framework. Alternatives to the high GWP gases, such as SF_6, CF_4, C_3F_8, c-C_4F_8, and C_2F_6, are sought. To significantly lower emissions of high GWP gases, investigators seek gases that do not have high GWPs (and, if they do, are eliminated during the production process) and do not form byproducts with significant GWPs, particularly CF_4 and CHF_3. Important etch process performance criteria are etch rate, etch profile, etch selectivity, and control of the critical dimension. In this option, investigators seek alternative highly fluorinated compounds that either are not high GWP gases themselves or are highly utilized during plasma etching and do not form byproduct high GWP emissions.

System Concepts

- Replacements are not favored if they increase cleaning times (which adversely affects fabrication productivity), form high GWP byproducts such as CF_4 and CHF_3, or pose new health and safety hazards.
- In dielectric etch processes, fluorine is required to etch the desired features into the dielectric materials, and carbon is required to passivate newly etched surfaces by gas formation of C_xF_y polymers that are then deposited to retard etching. Generally accepted models state that the boundary between net etching and deposition is a function of the fluorine:carbon ratio in the discharge. Plasmas rich in fluorine favor etching over deposition and those rich in carbon favor deposition over etching.

Representative Technologies

- Replacing C_2F_6 with C_4-compounds, e.g., switching to c-C_4F_8 and c-C_4F_8O
- Replacing C_2F_6 with NF_3 using in situ plasma cleaning.
- Replacing C_2F_6 with a remote fluorine source that dissociates NF_3 in an upstream plasma source.
- Replacing C_2F_6 with ClF_3.
- Hydrofluorocompounds, unsaturated fluorocompounds and iodofluorocompounds are attractive etch gas candidates because they have lower GWPs.
- C_3F_8 is a potential drop-in replacement for C_2F_6 in some chemical vapor deposition clean and etch processes because its high utilization during etch may offset its high GWP.
- Using NF_3, a high-GWP gas with high process utilization, in mixtures of a noble gas with unsaturated hydrocarbons of varying degrees. Examples of unsaturated hydrocarbons are ethyne or acetylene (C_2H_2), ethylene (C_2H_4), propyne (C_3H_4) and ethane (C_2H_6).

Current Research, Development, and Demonstration
RD&D Goals • To identify the *chemical* and *physical* mechanisms that govern chemical vapor deposition chamber cleaning and etching with perfluorocarbons and non-perfluorocarbons as well as govern process performance so that emissions of high GWP gases may be significantly reduced without either adversely affecting process productivity or increasing health and safety hazards. **RD&D Challenges** • Developing conceptual models that guide the identification of candidate substitutes and substitute classes. • Finding substitutes that do not form CF_4 (or other high-GWP gases such as CHF_3). • Finding substitutes that do not require costly process requalification. **RD&D Activities** • Evaluations at the Massachusetts Institute of Technology (MIT) simulated process conditions, and at semiconductor facilities (with participation of equipment manufacturers and gas suppliers) actual representative process conditions (AMD, Motorola, and Texas Instruments). • Discovery of the in situ dilute NF_3 cleaning process. • Development of the remote NF_3 cleaning process.
Recent Progress
• Use of C_3F_8 will reduce high GWP emissions, in terms of carbon dioxide equivalent, by 60% relative to the standard C_2F_6 process. • A switch to C_4 -fluorocarbons reduces emissions by 90% relative to the standard C_2F_6 process. • Industry familiarity with the use of fluorocarbon compounds, excellent process performance and chemical cost savings make these alternatives attractive options. c-C_4F_8 is already in widespread fabrication use for high-density plasma oxide etching, reducing the usual procedures for chemical and supplier qualification by the industry. • NF_3 dilute clean process reduces high GWP emissions by 85% relative to the standard C_2F_6 process. • Remote NF_3 cleaning process reduces high GWP emissions by more than 99% relative to standard C_2F_6 process.
Commercialization and Deployment Activities
• C_3F_8 is reported in commercial applications at fabricating facilities owned by AMD, Motorola, and Texas Instruments. • IBM and Novellus have commercialized and deployed dilute NF_3 cleaning processes. • AMAT and ASTeX have deployed remote NF_3 cleaning processes. • The etch gas research underway, and completed thus far, is described as proof-of-concept. There are no reports of commercial use. **Market Context** • Identification of a cost-effective PFC substitute could have wide applicability in the semiconductor industry.

4.3.3 SEMICONDUCTORS AND MAGNESIUM: RECOVERY AND RECYCLE

Technology Description

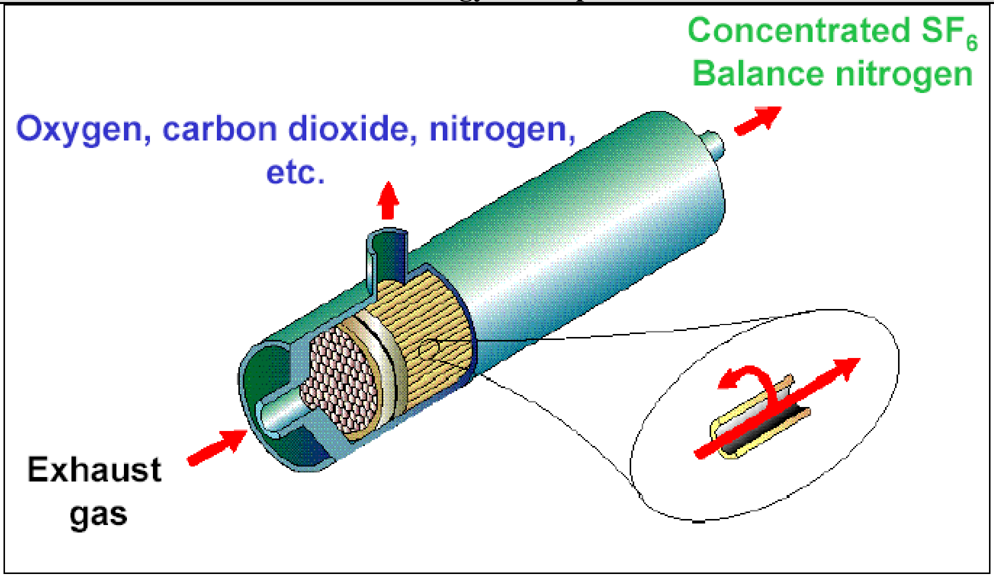


Figure 1. Diagram of Air Liquide's high GWP membrane separation technology.

The magnesium and semiconductor industries use and emit significant quantities of high global-warming potential (GWP) gases (e.g., SF_6, CF_4, C_2F_6 and C_3F_8). High GWP gases such as perfluorocarbons (PFCs) and SF_6 are potent greenhouse gases; one metric ton of PFCs is equivalent to 6,500-9,200 Mt of carbon dioxide in terms of its potential effect on global warming; SF_6 is the equivalent of 23,900 Mt of carbon dioxide. In addition, these compounds have extremely long lifetimes in the atmosphere (3,000-50,000 years). For the past 15 years, through international efforts to decrease ozone-depleting substances in the atmosphere, industry has been engaged in activities to reduce emissions and find alternatives.

One method of decreasing the emissions of high GWP gases from these industries is to recover and recycle these chemicals. Three recovery-and-recycle technologies are being investigated and evaluated: membrane separation, cryogenic capture, and pressure swing absorption.

System Concepts

- These technologies may be designed to treat exhaust streams from large magnesium firms and semiconductor processes.
- All recovery-and-recycle technologies require exhaust pretreatment to remove corrosives (such as hydrofluoric acid) and particles and moisture from the exhaust gas stream.
- The remaining PFCs and/or SF_6 are recovered, concentrated, and "bottled." On-site bottled PFCs may be either mixtures or highly purified. Captured SF_6 may be reused on-site for magnesium melt protection.

Representative Technologies

- Praxair/Ecosys and Edwards: cryogenic capture.
- Air Liquide and Air Products: membrane separation.
- MEGASORB and BOC: pressure swing.

Current Research, Development, and Demonstration

RD&D Goals

- To develop and demonstrate a cost-effective, universally applicable recovery-and-recycle technology (all fabrication facilities and all high GWP gases) that can yield "virgin"-grade high GWP gases for semiconductor fabrication or magnesium plant reuse or sufficiently pure high GWP gases for further use or purification elsewhere.

RD&D Challenges

- Development of a method for universal pretreatment.
- Capital and operating costs are high relative to other alternatives to reduce emissions, and only appear justifiable when recovery-and-recycle systems are applied to large portions of waste streams of large fabricating facilities or plants.
- As other high GWP emission-reducing technologies are considered and implemented, the viability of recovery-and-recycle systems and further investigation of those systems is reduced. This occurs because as high GWP gas concentrations in waste streams become lower, the technical challenges for separation and repurification increase as does the cost.

RD&D Activities

- Six systems have been tested at fabrication facilities, which demonstrated that cryogenic capture and membrane separation show promise.
- Air Liquide's membrane technology underwent an extended a successful evaluation at a U.S. primary magnesium producer – demonstrated 41% reduction in SF_6 emissions.
- DuPont is investigating the requirements for collecting, repurifying, and/or disposing of C_2F_6.

Recent Progress

- The Praxair/Ecoys (cryogenic capture) system has shown emission-reduction capabilities of up to 99% for C_2F_6, CHF_3, and SF_6, and up to 75% for CF_4.
- The Edwards (cryogenic capture) system has shown capture efficiencies that exceed 90%.
- Both the Air Liquide and the Air Products systems (membrane separation) have capture efficiencies of 96%-98% for C_2F_6, CF_4, and SF_6, when NF_3 and CHF_3 were first removed. Recovery efficiencies for NF_3 and CHF_3 varied between 30% and 60%, with CHF_3 being as low as about 30%.
- The MEGASORB and BOC systems (pressure swing) have shown low capture efficiencies, approximately 1% for the BOC system.

Commercialization and Deployment Activities

- Both cryogenic capture and membrane separation technologies have received encouraging press reports from chip manufacturers. However, there are no published reports of commercial use.
- Unpublished reports indicate that Intel is using Air Products' membrane separation technology in at least one fabricating facility.
- DuPont has expressed its intention to provide to the industry a disposition offering for recovered C_2F_6-containing mixture – an offer that includes repurification of C_2F_6 to virgin-grade specifications and, potentially if necessary, off-site destruction.

Market Context

- Recover-and-recycling technologies are only applicable for large facilities, such as large fabs, primary magnesium producers, or very large magnesium-casting companies.

4.3.4 ALUMINUM INDUSTRY: PERFLUOROCARBON EMISSIONS

Technology Description

Primary aluminum production is the largest source of emissions of perfluorocarbons in the United States. Mitigation technologies and measures cannot only reduce emissions, but they also can improve process efficiency. (Reprinted with permission of Greenleaf Publishing.)

Aluminum is produced through the electrolytic reduction of alumina (AL_2O_3). The electrolytic Hall-Héroult process was adopted in the late 19th century, and continues as the process in commercial use today. Producing aluminum by the conventional electrolytic cell process requires a large amount of energy and produces significant emissions of greenhouse gases. The Hall-Héroult process results in direct emissions of CO_2, due to the consumption of the carbon anode, and also perfluorocarbon emissions. Within the electrolytic bath, the alumina is dissolved in a mixture of molten cryolite (Na_3AlF) and aluminum fluoride (AlF_3). Perfluorocarbon emissions are formed as intermittent byproducts within the aluminum smelting pot as the result of operational disturbances called anode effects. Anode effects occur when there is an over-voltage disturbance of the smelting process and are triggered when alumina levels in the pot decline below a critical level. During these events, the fluorine from the cryolite bath reacts with the carbon anode to form tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6). Primary aluminum production is the largest source of emissions of perfluorocarbons in the United States. Greenhouse gas emission reduction measures not only reduce perfluorocarbon and other greenhouse gas emissions, but they also can improve process efficiency. The United States is one of the largest global producers of primary aluminum and, as of 2000, there were 11 U.S. companies that produced primary aluminum.

System Concepts

- Current efforts to reduce perfluorocarbon emissions from primary aluminum production focus on using the most efficient smelting processes to reduce the frequency and duration of anode effects. Perfluorocarbon reduction potential varies by smelter technology with point-feed technology the most efficient – and Søderberg technology the least efficient. Another concept, now in the research and development phase, involves replacing the carbon anode with an inert anode. Doing so would completely eliminate process-related perfluorocarbon and CO_2 emissions.

Representative Technologies

- Currently available perfluorocarbon mitigation technologies and practices include computerized controls and point-feeder systems, as well as improved operating practices that minimize the frequency and duration of anode effects and associated emissions. When using the Hall-Héroult process, perfluorocarbon emission reductions could be achieved through retrofitting existing cells, converting older technologies, and using advanced technologies. Emerging technologies include use of the inert anode mentioned above.

Technology Status/Application

- Computerized controls, point-feeder systems, and improved operator practices vary in their cost-effectiveness and ability to reduce emissions. Further research regarding anode effects could yield additional cost-effective emissions reductions. The Department of Energy, through its Industries of the Future strategy, supports research and development of the inert anode. Being noncarbon, the inert anode would eliminate PFC emissions. Laboratory, pilot-scale, and commercial-scale testing of inert anodes is currently underway.

A commercially viable design is expected by 2005. Commercialization can be expected by 2010-2015. Use of the inert anode technology will most likely be in conjunction with wetted cathode technology as part of an advanced technology cell. The advance technology cell is a combination of an inert anode, which would not be consumed during electrolysis, and a cathode with a stable surface, which would reduce electricity requirements.

Current Research, Development, and Demonstration

RD&D Goals

- If successful, the nonconsumable, inert anode technology would have clear advantages over conventional carbon anode technology, including energy efficiency increases, operating cost reductions, elimination of perfluorocarbon emissions, and productivity gains.

RD&D Challenges

- A number of critical technology barriers prevent the aluminum industry from the targets it has identified for inert anode technology. These challenges represent the difference between present-day carbon anode technology and the current state of nonconsumable anode technology. Challenges include:
  - Demonstration of "viable" inert materials for use in fabricating the anodes, including fabricating candidate materials in large sizes, and the means for scaling up the fabrication processes.
  - Basic knowledge of the operation of nonconsumable anodes.
  - Validation of the potential for full-scale process improvement.
  - Computer modeling to address retrofitting issues.

RD&D Activities

- DOE is leading the effort in producing inert anode technologies.

Recent Progress

- Use of the most efficient aluminum processing technologies, such as point-feed technology, has resulted in reducing perfluorocarbon emissions from U.S. primary aluminum production by more than 40% since 1990.

Commercialization and Deployment Activities

- High-efficiency smelting technologies (e.g., point-feed technology) and options for retrofitting the Hall-Héroult process are commercially available. A commercially viable inert anode design is not expected to be available until 2005.

Market Context

- Retrofit capability is a key issue with inert anode technology. If the new technology is technically and economically successful – but, ultimately, cannot be retrofitted to existing cells – it will still be considered a success. However, the ability to retrofit would be considered a major benefit, and would improve the technology's economics.

4.3.5 ELECTRIC POWER SYSTEMS AND MAGNESIUM: SUBSTITUTES FOR SF_6

Technology Description

Figure 1. Molten Mg with SF_6 cover gas.

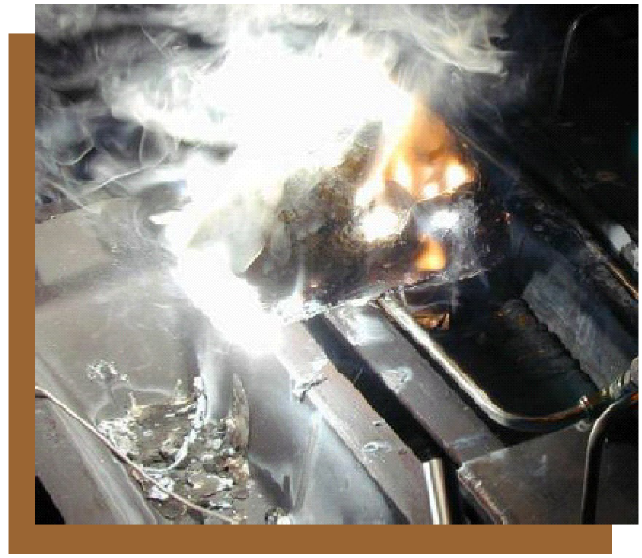


Figure 2. Molten Mg <u>without</u> protective cover gas.

Electric Power Systems: Sulfur hexafluoride (SF_6) is a favored insulating agent for high-voltage electric power system equipment because of its dielectric strength and arc-suppression capabilities. Use of other insulating media has been researched and some have been used, especially in medium- and low-voltage applications. Historically, several other media were used (e.g., air, vacuum, oil) before the advent of SF_6, some of which remain in use today in certain applications.

Magnesium Industry: Magnesium metal producers and casters use SF_6 mixed with dry air and/or CO_2 as a cover gas to prevent oxidation and burning of the molten metal. About 5% to 20% of the SF_6 is believed to react with the metal surface, preventing oxidation, while the remainder escapes to the atmosphere. The magnesium casting machine operators need to have access to the surface of the magnesium melt. Therefore, a tightly sealed system is difficult to engineer and maintain. Recognizing that some gas will escape, a highly attractive technology option involves use of a gas other than SF_6 with better environmental characteristics. The challenge is to isolate a substitute with low or no global-warming potential that satisfies the magnesium industry's melt protection performance and safety requirements.

System Concepts

- Electric power systems: Purchase/use equipment that relies on insulating agents other than SF_6.
- Magnesium casting: Use a gas for magnesium melt protection that avoids the global-warming concerns associated with SF_6.

Representative Technologies

- Electric power systems: Existing insulating agents other than SF_6 include oil, air, or vacuum insulation; but SF_6 is the predominant choice for high-voltage applications. Despite extensive research efforts, no single gaseous compound has been isolated that serves as a substitute for SF_6 in high-voltage applications. SF_6 remains the insulating medium of choice. Gas mixtures, however, have been used successfully, including mixtures of SF_6/N_2 or SF_6/CF_4 in cold-weather applications.
- Magnesium casting:
  - <u>HFC-134a:</u> The Cooperative Research Centre for Cast Metals Manufacturing (CAST) in Australia is conducting research and development to find a suitable substitute gas for SF_6. Based on the concept that the addition of fluorine into the magnesium oxide surface film is the key mechanism for preventing oxidation of molten magnesium, CAST has developed a process that uses the hydrofluorocarbon gas 1,1,1,2-tetrafluoroethane, otherwise known as HFC-134a.

- SO$_2$: Sulfur dioxide provides effective protection of molten magnesium, but its toxicity presents a concern for use in the workplace.
- IMA Study / SINTEF: The International Magnesium Association (IMA) established an Ad Hoc Committee on SF_6 composed of representatives from IMA, several magnesium casting firms, and an automobile manufacturer. The committee selected a research proposal from SINTEF, the Foundation of Scientific and Industrial Research at the Norwegian University of Science and Technology, to evaluate alternative cover gases for protection of molten magnesium.
- Novec 612™: 3M™ has commercialized a fluorinated ketone, $C_3F_7C(O)C_2F_5$ (Novec 612™) as a substitute for SF_6.

Technology Status/Application

- Electric power systems: At least one utility is known to use SF_6/N_2 and SF_6/CF_4 gas mixtures for circuit breakers used in cold weather, at transmission and sub-transmission voltage levels (i.e., 500 kV and below).
- HFC-134a and Novec 612™ are reported to provide good molten metal protection in magnesium production and die-casting applications.

Current Research, Development, and Demonstration

RD&D Goals

- To find substitutes for SF_6 that have comparable insulating and arc quenching properties in high-voltage applications and/or protect molten magnesium – and significantly less or no global-warming potential.

RD&D Challenges

- Electric power systems: To date, no widely applicable alternatives have been found for SF_6. The primary RD&D challenge is to find an acceptable insulating medium for high-voltage applications.
- Magnesium casting:
  - Characterizing chemical and physical mechanisms that govern protection of molten magnesium through use of cover gas.
  - Selecting effective gas substitutes that not only guard against magnesium burning, but also minimize emissions of greenhouse gases or other pollutants of concern.
  - Isolating the best methods of gas distribution to overcome the potential disturbances associated with magnesium melt turbulence and temperature.

RD&D Activities

- EPA and the magnesium industry are working in a voluntary partnership to eliminate SF_6 emissions.
- Magnesium casting: SINTEF and CAST continue their work with alternative gases and HFC-134a. Based on their findings regarding the solubility of fluorine in molten magnesium, SINTEF is researching the viability of bubbling a fluorine-bearing gas through the melt or adding fluorine in a solid matrix, such as iron fluoride.
- The Electric Power Research Institute (EPRI) is investigating a solid-state current limiter that may lead to future equipment designs that do not require SF_6 insulation.

Recent Progress

- Electric power systems: Gas mixtures, as discussed above, have been used successfully in cold-weather applications.
- Magnesium producers and casting firms report promising results from early production-scale trials of alternative fluorinated cover gases.

Commercialization and Deployment Activities

- If a substitute gas is found, commercialization and deployment are not expected to represent hurdles. Gas mixtures appear to be readily available to potential users in cold regions where they are applicable.

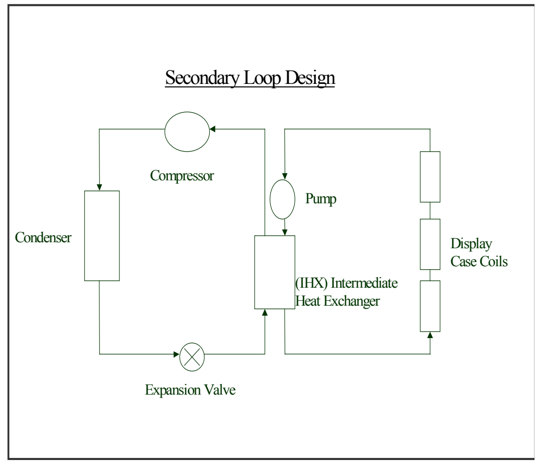
Market Context

- Electric Power Systems: Circuit breaker equipment used in high-voltage electricity transmission and distribution.
- Magnesium Industry: All magnesium production and casting firms that use SF_6 for magnesium melt protection.

4.3.6 SUPERMARKET REFRIGERATION: HYDROFLUOROCARBON EMISSIONS

Technology Description

Distributed refrigeration technology can be seamlessly integrated into a store.



Secondary-Loop Refrigeration, where an extra pump and internal heat exchanger are added to the equipment used in a conventional design.

To comply with the U.S. Clean Air Act, supermarkets are phasing out the use of ozone-depleting refrigerants. As substitutes, the industry is using hydrofluorocarbons (HFCs), which are potent greenhouse gases. To ensure that food products are kept cold, the typical supermarket design pumps these HFC refrigerants through miles of piping and thousands of joints. Historically, annual emissions of 35% to 50% of the 2,000- to 4,000-pound charge have occurred. As old stores are replaced and new ones built, new technologies can drastically limit greenhouse gas emissions.

System Concepts

- Better equipment design and store layout can lead to a reduction in the amount of refrigerant needed for a given amount of product cooling.
- Additionally, replacing the complex miles of piping with either distributed cooling systems or a single centralized refrigeration plant can reduce the percent of refrigerant emitted annually.

Representative Technologies

- *Distributed Refrigeration* is a technology that puts refrigeration equipment closer to the food display cases, eliminating the need for excessive refrigerant piping throughout the store to reach a mechanical room sited away from the food.
- *Secondary-Loop Refrigeration* segregates refrigerant-containing equipment to a separate, centralized location, and uses a benign fluid to transfer heat from the food display cases.

Technology Status and Applications

- Both concepts have existed for some time but have seen very little adoption in the highly competitive, low-margin supermarket business.
- Only a handful of secondary-loop systems have been installed in the United States, primarily for "medium-temperature" (e.g., dairy products) portions of supermarkets. Very few "low-temperature" (e.g., frozen foods) systems exist in the world.
- Both technologies centralize refrigerants to one or a few locations. This allows for economical installation of leak-detection equipment to alert system operators when HFC refrigerant emissions occur.

Current Research, Development, and Demonstration

RD&D Goals and Challenges

- Continuously improve energy-use performance of these new technologies, investigating various designs, control strategies, and operational techniques.

- Investigate ways to reduce installation and operational costs of new technologies.
- Demonstrate applicability and advantages in various locations, store sizes, and product mixes.
- Educate store designers and builders regarding new technologies and how these technologies can be integrated into new or retrofitted stores at a net savings.

RD&D Activities

- EPA has built a facility to test secondary-loop refrigeration systems. Additional funding from DOE has been provided to support the research and test related products.
- Various manufacturers and supermarkets are conducting their own proprietary research on these technologies.

Recent Progress

- Existing systems have proved relatively easy to operate and maintain. Minimal refrigerant leakage has provided an economic benefit for the storeowner as well as an environmental benefit for society.
- Under the U.S./Australia Climate Action Partnership, the possibility of building and monitoring a typical and secondary-loop store is being explored. This will allow verification of potential benefits.

Commercialization and Deployment Activities

- The most opportune time to implement these technologies is during new store construction or during major overhaul and retrofit of existing stores. There are more than 30,000 supermarkets in the United States, and this is likely to grow with a growing population. Because many stores are currently switching from ozone-depleting refrigerants, there is a high potential to introduce these new technologies quickly if technical, economical, and educational challenges are met.

Market Context

- High competition in design and construction of supermarkets creates unwillingness to explore newer, unfamiliar technologies despite potential benefits.
- Low-margin business creates "chicken-and-egg" situation where supermarkets are unwilling to install new technologies until the benefits are proven, but benefits cannot be proven until supermarkets install new technologies.

4.4 NITROUS OXIDE EMISSIONS FROM COMBUSTION AND INDUSTRIAL SOURCES

4.4.1 NITROUS OXIDE ABATEMENT TECHNOLOGIES FOR NITRIC ACID PRODUCTION

Technology Description

Nitric acid (HNO_3) is an inorganic compound used primarily to make synthetic commercial fertilizer. As a raw material, it also is used for the production of adipic acid and explosives, metal etching, and in the processing of ferrous metals. Plants making adipic acid used to be high emitters of nitrous oxide (N_2O), but now that adipic acid plants in the United States have implemented nitrous oxide abatement technologies, nitric acid production itself is the largest industrial source of N_2O emissions. The nitric acid industry currently controls NO_x emissions using both nonselective catalytic reduction (nonselective catalytic reduction) and selective catalytic reduction (selective catalytic reduction) technologies to reduce N_2O to elemental nitrogen. While nonselective catalytic reduction is more effective than selective catalytic reduction at controlling N_2O, nonselective catalytic reduction units are not generally preferred in today's plants because of high-energy costs and associated high gas temperatures. Only 20% of nitric acid plants use nonselective catalytic reduction today. Additional research is needed to develop new catalysts that reduce N_2O with greater efficiency, and to improve nonselective catalytic reduction technology to make it a preferable alternative to selective catalytic reduction and other control options.

Nitric-acid plant controls for NO_x using both nonselective catalytic reduction and selective catalytic reduction technologies. Nonselective catalytic reduction is very effective at controlling N_2O.

System Concepts

- Nonselective catalytic reduction uses a fuel and a catalyst to consume free oxygen in the tail gas and convert NO_x to elemental nitrogen (Chartier, 1999). Nonselective catalytic reduction can reduce N_2O emissions by 80%-90%. (IPCC, 2000)

Representative Technologies

- The gas from the NO_x abatement is passed through a gas expander for energy recovery. Nonselective catalytic reduction units produce stack gases in the 1,000°F to 1,100°F range that require more exotic materials for constructing the expander and have higher maintenance costs.

Technology Status/Applications

- Virtually all of the nitric acid produced in the United States is manufactured by the catalytic oxidation of ammonia (EPA, 1991). During this reaction, N_2O is formed as a byproduct and is released from reactor vents to the atmosphere. While the waste gas stream may be cleaned of other pollutants – such as nitrogen dioxide – there are currently no control measures aimed at specifically eliminating N_2O emissions.

Current Research, Development, and Demonstration

RD&D Goals

- RD&D goals are focused on the catalysts used to convert NO_x into elemental nitrogen.

RD&D Challenges

- The use of a catalyst that can reduce a higher percentage of N_2O emissions is not the focus of the current research. The technology is primarily implemented in order to reduce NO_x emissions, not as an N_2O emission-reduction technology.
- Develop catalysts that reduce N_2O to elemental nitrogen with greater efficiency.

- Promote the use of nonselective catalytic reduction over other NO_x control options such as selective catalytic reduction and extended absorption.

RD&D Activities

- Information on R&D activities to develop new catalysts for nonselective catalytic reduction technologies is unavailable. To date, RD&D expenditures have been made by the industry. Estimates of future expenditures by the industry are not available.

Recent Progress

- Currently, the nitric acid industry controls for NO_x using both nonselective catalytic reduction and selective catalytic reduction technologies. Nonselective catalytic reduction is very effective at controlling N_2O, while selective catalytic reduction can actually increase N_2O emissions. Nonselective catalytic reduction units are generally not preferred in modern plants because of high energy costs and associated high gas temperatures. Only 20% of nitric acid plants use nonselective catalytic reduction.

Commercialization and Deployment Activities

- Nonselective catalytic reduction units were widely installed in nitric acid plants built between 1971 and 1977. It is estimated that approximately 20% of nitric acid plants use nonselective catalytic reduction (Choe, et al., 1993). Information on the status of the commercial development of nonselective catalytic reduction catalysts is not currently available, however.

Market Context

- Approximately 80% of current plants do not employ nonselective catalytic reduction, but instead use selective catalytic reduction or extended absorption units, neither of which are known to reduce N_2O emissions. Research is underway into materials for catalysts that are applicable for N_2O control in nitric acid plants that do not employ nonselective catalytic reduction. Nitrous oxide emissions from nitric acid production will be influenced by the degree and type of NO_x emission control efforts that are applied in both new and existing nitric acid plants.

4.4.2 NITROUS OXIDE ABATEMENT TECHNOLOGIES FOR TRANSPORTATION

Technology Description

Basic research is needed to understand the formation and magnitude of N_2O emissions from fuel combustion and catalytic-converter operation.

Nitrous oxide (N_2O) can be produced from fuel combustion and catalytic-converter operation in vehicles, primarily due to the nitrogen in the air. Little is understood about how much N_2O is produced by vehicles and under what conditions and with what catalytic-converter technology. The main research thrust in the near term is to begin to answer these basic questions.

In addition to direct emissions of N_2O, nitrogen oxide (NO_x) emissions from mobile and stationary sources have a significant impact on atmospheric N_2O levels. More than 25 million tons of NO_x is emitted annually in the United States. Following transport and chemical interactions, approximately 7 million tons of these nitrogen emissions are deposited downwind. This compares to about 11 million tons of nitrogen deposited from fertilizer application. Since the 11 million tons is reported to account for about 70% of anthropogenic N_2O emissions, the 7 million tons from atmospheric deposition appear to be significant. In the past, greenhouse gas emissions inventories have ignored the atmospheric nitrogen deposition due to uncertainties involved. Research is needed to define the contribution of NO_x emissions to nitrogen deposition and subsequent N_2O emissions, and to identify the global warming benefits from ongoing and future NO_x emissions control programs.

System Concepts

- Better understand the formation and magnitude of N_2O emissions from fuel combustion and catalytic-converter operation.
- Evaluate the climate-forcing potential atmospheric nitrogen deposition, especially from combustion sources.
- Develop emission models to assess the potential climate benefits from changes in emissions from nitrogen oxides.

Representative Technologies

- Combustion and post-combustion NO_x control technologies used in the tropospheric ozone control program.

Technology Status/Applications

- NO_x control technologies are in place due to the ozone and acid deposition programs.

Current Research, Development, and Demonstration

RD&D Goals

- Accurately understand the amount of N_2O produced in various vehicles, how it forms, and how it can be reduced.
- Develop N_2O measurement techniques for emerging gasoline and diesel engines and their emission-control systems. Measurement technology is needed for both laboratory and field measurement.
- Develop vehicle- and engine-testing programs to generate data about N_2O emissions for a variety of vehicles and engines equipped with a range of current and advanced emission-control technologies and operated over a range of real-world operating conditions.

• Research on the relationship of N_2O emissions to technologies and approaches that reduce fuel consumption by stationary and mobile combustion sources, including programs that reduce vehicle miles traveled. • Quantify the climate-forcing impacts due to NO_x emissions, nitrogen deposition, and N_2O emissions. **RD&D Challenges** • To establish linkages of NO_x emissions to climate-change impacts due to nitrogen deposition and enhance modeling capabilities to address these linkage issues.
Recent Progress
• EPA's ozone-control program has reduced emissions of NO_x.
Commercialization and Deployment Activities
• Additional NO_x emissions controls will be implemented in the future to meet ambient air quality standards for ozone and particulate matter.

4.5 EMISSIONS OF TROPOSPHERIC OZONE PRECURSORS AND BLACK CARBON

4.5.1 ABATEMENT TECHNOLOGIES FOR EMISSIONS OF TROPOSPHERIC OZONE PRECURSORS AND BLACK CARBON

Technology Description

(Above) Reflective roofing technology is an effective way to reduce temperatures in cities, leading to GHG reductions and tropospheric ozone concentrations, (Source: Sarnafil)

(Left) Available options to reduce open biomass burning include changing the frequency and conditions of prescribed burning and reducing open waste burning. (Photo: *National Geographic,* presented by T. Bond, 2002)

The role of black carbon (soot) and tropospheric ozone in global warming is still incompletely understood and additional research is needed to characterize emission sources, atmospheric interactions, and technological responses. It is likely that activities to reduce tropospheric ozone precursors and black carbon (BC) will have large public health and local air quality benefits, in addition to their role in mitigating climate change. Abatement technologies in this area include:

- *Transportation control technologies* - Tropospheric ozone and particulate matter (PM) emissions, of which BC is a component, resulting from motor U.S. vehicles have long been targeted because of their health and environmental consequences. Thus, vehicle manufacturers have developed increasingly effective control technologies to abate ozone precursors (especially nitrogen oxides or NO_x) and emissions of PM, in response to stricter engine and emission standards. Aside from emission controls, increasing fuel efficiency also reduces ozone precursors and BC.
- *Temperature reduction in cities* - Heat islands form as cities replace natural vegetation with pavement for roads, buildings, and other structures. There are several measures available to reduce the urban heat island effect that can decrease ambient air temperatures, energy use for cooling purposes, GHG emissions, and ozone concentrations. (Related information can be found in the technology profile “Urban Heat Island Technologies” under “Buildings”).
- *Biomass burning* - Important sources of BC aerosols in the United States include combustion of not only fossil fuels but also biomass burning. Available options to reduce open biomass burning include changing the frequency and conditions of prescribed burning and reducing open waste burning.

System Concepts

- *Transportation control technologies* - For onroad and nonroad vehicles and equipment, future abatement technologies primarily involve sophisticated computer engine controls and treatment of exhaust emissions. Reduced fuel consumption and vehicle use also reduce ozone precursors and black carbon emissions.

- *Temperature reduction in cities* - Reduced temperatures reduce the need for summertime cooling energy, decrease biogenic volatile organic carbon emissions and evaporative losses from mobile and stationary sources, and reduce photochemical reaction rates, which may reduce ozone production.
- Assess the importance of *biomass burning*, including agricultural, open, and wild fires.

Representative Technologies

- *Transportation control technologies* include advanced tailpipe NO_x controls (including NO_x adsorbers), PM filters (traps) for diesel engines (including catalyzed traps capable of passive regeneration), and hybrid and fuel cell vehicles.
- Representative technologies for *temperature reduction in cities* include:
  - Strategically planted shade trees
  - Reflective roofs: There are over 200 Energy Star™ roof products, including coatings and single-ply materials, tiles, shingles and membranes. Energy savings with reflective roofs range as high as 32% during peak demand (summer average of 15%).
  - Reflective paving materials: There are several reflective pavement applications being developed, including new pavement and resurfacing applications, asphalt, concrete and other material types. Whitetopping is becoming increasingly popular.
- Alternatives to *biomass burning* include prescribed burning programs (which are directed at minimizing wildfires), and regulation or banning of open burning (such as in land clearing).

Technology Status/Applications

- *Transportation control technologies* - Heavy-duty diesel engine manufacturers are pursuing advanced NO_x controls and particulate matter filters to meet stringent 2004 and 2007 emission standards, and hybrid and fuel cell alternatives are under development.
- Technology status for *temperature reduction in cities*
  - Shade Trees - Nationally, there are numerous tree-planting programs. Some utilities have partnered with urban forestry groups to encourage residential shade tree planting to reduce energy consumption from air conditioning. Further, several communities have implemented shade tree ordinances.
  - Reflective Roofs - A few states (e.g., Georgia and Florida) have incorporated reflective roofs into their state energy codes. Some states (e.g., California) and communities have reflective roof incentive programs. Reflective roofs are given credit in several environmental rating programs including the U.S. Green Building Council's LEED (Leadership in Energy and Environment) rating system.
  - Reflective Pavements - Some communities are installing alternative pavement parking lots and alleys – mainly using porous pavement technologies. Whitetopping is also becoming increasingly popular.

Current Research, Development, and Demonstration

RD&D Goals

- *Transportation technologies* - Cost-effective NO_x and black carbon engine and vehicle controls, especially for diesel engines.
- *Temperature reduction in cities* - Understand and quantify the impacts that heat island reduction measures have on local meteorology, energy use, GHG emissions, and air quality; develop an application, based on geographic information systems, that predicts heat island outcomes from different development scenarios.
- *Basic research* is needed to better understand black carbon's role in climate change including establishing linkages between air pollution and climate change by enhancing modeling capabilities; designing integrated emissions control strategies to benefit climate, regional and local air quality simultaneously.

RD&D Challenges

- *Temperature reduction in cities* - The interaction between meteorological, land surface, and emission-specific parameters are not fully understood.
- *Biomass burning* - To design integrated emissions control strategies to benefit global climate and regional and local air quality simultaneously and improve current wildfire research to be address black carbon.

RD&D Activities

- Better understanding of the role of ozone and black carbon in climate change

• *Transportation control technologies* - Transfer of onroad diesel emission control technology to nonroad applications; development of in-use emission measurement techniques; gasoline vehicle particulate matter (inc. black carbon) characterization; develop retrofit emission control technology, and develop understanding of role of reducing fuel consumption and vehicle use on non-CO_2 GHGs. • *Transportation control technologies* - Current focus of industry and EPA research is on developing and demonstrating effective, compact, and durable advanced NO_x and particulate matter control systems. • *Temperature reduction in cities* - Tulane University and Lawrence Berkeley National Lab (LBNL) are modeling the impacts of heat island reduction measures on local meteorology in seven U.S. domains; LBNL is analyzing the urban fabric (surface composition) in several cities; and several groups in California are examining net benefits from trees.
Recent Progress
• *Transportation control technologies* - In 2000, stringent passenger car/light truck/sport utility vehicle standards were established to result in historically low levels of per-vehicle emissions of NO_x beginning in 2004. In 2001, stringent heavy truck and bus standards are resulting in creative technological approaches to difficult NO_x and particulate matter standards. • *Biomass burning* - EPA began monitoring of black carbon as part of the IMPROVE network in 1988 (110 monitoring sites). EPA also developed new source performance standards for residential wood heaters (promoting complete combustion and reducing particulate emissions). Open burning (including land clearing) in many parts of the country has been regulated or banned in order to minimize emissions and help achieve national ambient air quality standards for particulate matter and ozone.
Commercialization and Deployment Activities
• *Transportation control technologies* - All new passenger cars, light trucks, and sport utility vehicles will have highly sophisticated emission controls after 2004. Manufacturers of heavy-duty engines have significant demonstration experience with particulate filter technologies, especially on urban buses. • *Temperature reduction in cities* - Reflective roofing and paving technologies may be broadly applicable to U.S. cities, but benefits will vary. In addition, several reflective roof programs (e.g., California's Cool Savings Program) require use of Energy Star™ Roof Products.

5.0 ENHANCING CAPABILITIES TO MEASURE AND MONITOR EMISSIONS

5.1 HIERARCHICAL MM OBSERVATION SYSTEM

Technology Description

Introduction

- The primary focus of measuring and monitoring (MM) is to develop technologies for the measuring and monitoring of gross and net CO_2 and other GHG emission and sinks. MM must be a component of each mitigation technology option to assure that ***net*** emission reduction is occurring and that the integrity of sinks is verifiable. Measures of performance within each mitigation option, which are quantifiable and support evaluation of progress and possible future financial transactions, must be developed.
- Technology-specific profiles have been developed; but, in addition, there will be new sensor and controls needed to help each mitigation technology improve its performance – those are addressed in those sections.
- An effective MM capability will require a hierarchical structure that can address scales from in situ soil carbon measurements, to emissions from vehicles, to large point sources, and area sources ranging from a landfill to large spatial regions (up to countries).
- Assuring integrity of sinks is another key component of the system. As sequestration (all methods) is implemented, quantitative changes and leakage rates (<<1%?) must be verifiable or else leaks alone could result in emissions exceeding those of today.
- There is significant connection between observations and modeling related to emissions, sinks, and carbon stocks, and climate change mediated biogeochemical feedbacks that will be accomplished with the CCSP and the MM portion of the Climate Change Technology Program (CCTP). CCTP will utilize the Climate Change Science Program (CCSP) advances to the maximum extent.

System Concepts

- Sensors and associated information technology systems that provide an ability to determine carbon stocks, emissions, and sinks in a nested approach that can integrate point source information (e.g., leakage from geologic repository) with regional measurements or indicators of all GHG emissions to allow analysis at the scale-up to countries.
- Systems must be designed to be additive and comparable so that information from one "layer" is verified and used by the next layer. It is probable that some locations will be needed as validation sites to illustrate MM approaches. These sites will have intensive measurement at the ground-based scale and thus verify the ability of remotely sensed systems to accurately estimate carbon stocks and fluxes.
- Integrated MM measures will provide needed data for calculating net CO_2 and other GHG emissions per unit of economic activity.

Representative Technologies

- Inventory reporting methods and emissions factors for activities that provide for full life-cycle accounting of net CO_2 and other GHG inventories, emissions, and sinks.
- Platforms include satellites, buoys, aircraft, ground-based networks, and global arrays, which can house the typically broad spectrum of sensors.
- Innovative chemical or isotopic markers to track sources and sinks at the process level detail that would facilitate regional tracking of GHG emissions.
- Sensors include such items as continuous emission monitors, laser-based technologies (e.g., LIBS), mass spectrometers, lidar, radar, etc.
- Data technologies include networked transmission (wired and wireless), data archiving technology, and computational platforms for distribution and analysis.

Technology Status/Applications

- Emergence of new sensing technologies – e.g., chemical, laser, infrared, radar, light detecting and ranging (LIDAR), multispectral video, mass spectrometers – and computing power capable of handling large amounts of data has spawned a new generation of instruments, databases, and computer models that can be adapted to MM challenges. However, integrated systems of data collection, management, and processing at the scale needed for MM do not exist.

- NASA's AURA satellite, part of the Earth Science Enterprise mission, will host a suite of scientific instruments to measure atmospheric trace gases, including ozone, aerosols, and greenhouse gases. NASA's Aqua and Terra are already delivering some useful data on aerosols, water clouds, methane, and carbon monoxide.
- Simultaneous, high-precision measurements of O_2 and CO_2 and isotopes for estimating the role of various processes within the carbon cycle at regional scales.
- Soil carbon analysis instruments are under development, but not ready for deployment.
- Area-scale CO_2 flux measurement systems are available and under improvement.
- Continuous emission monitors (CEM) are available, but remain too expensive for full deployment and are not linked to data systems to be effective.
- Satellite- and aircraft-based sensors for estimating biomass are being improved.

Current Research, Development, and Demonstration

RD&D Goals

- Develop an integrated system that meshes observations (and estimations) from point sources (e.g., power plant or geologic storage site), diffuse sources (e.g., from commercial and agricultural systems), regional sources (e.g., city/county), and national scales so that checks and balances up and down these scales can be accomplished. The system should be able to attribute emissions/sinks to both national level activities and individual/corporate activities and provide verification for reporting activities.
- Inexpensive and easily deployed sensors for a variety of applications (stack emissions, N_2O emissions across agricultural systems, CO_2 fluxes across forested regions, CO_2 and other GHG emissions from transportation vehicles.
- Accurate "rules-of-thumb" (reporting/accounting rules) for practices that reduce emissions or increase sinks where comprehensive and accurate measurement is not feasible. Such rules must be based on sound scientific principles.
- A high-resolution system that captures process-level details of sources and sinks (e.g. O_2 or CO_2, isotopes) and a methodology to scale it up reliably.
- Data archiving and analysis system-to-integration observations and reporting information.

RD&D Challenges

- Alter current remotely based sensors (satellite and aircraft) from a focus on measuring atmospheric constituents to a focus of measuring CO_2 and other GHG stocks and net fluxes.
- Ground-based biomass and soil carbon measurement methods that are rapid, inexpensive, and accurate – and can address heterogeneity issues.
- Methods to detect leakage rates from geological storage systems that may be small and may be highly variable over space and time.
- Methods to measure ocean CO_2 sinks and leakage rates.
- Sensors that could be placed on individual emission sources (e.g., stack or vehicle exhaust) to provide data for new or modified MM technologies to aid emissions reduction by energy production systems.
- Development of specific sensors, and their application to vertical integration of net emissions across all scales.
- Formalized data and information systems that capture and distribute data, and that provide protocols for reporting results.
- Framework under which measuring and monitoring are linked in a functional manner – and also work within a regulatory system for carbon credits or incentives.
- Simultaneous measurements of many chemical/isotopic variables to capture process details.

RD&D Activities

- Scientific research on climate and the carbon cycle are resulting in new sensors and methods to estimate stocks and fluxes.
- Newly funded R&D on sequestration options is resulting in new measurements systems for net ecosystem exchange of carbon, soil carbon and biomass changes, leakage indicators from geological systems, and ocean CO_2 exchange methods.

• Geophysical methods to determine integrity of geologic storage systems are under development and can be tested as large-scale demonstrations come on-line. • By 2010-2012, current plans will deploy satellites capable of measuring greenhouse gases in columnar samples of the atmosphere. With focused development and data-handling systems, such a sampling regime could be used to estimate a region's or nation's emissions.
Recent Progress
• Ongoing demonstrations of geologic storage systems are helping to define the needs for characterizing particular geological structures and constant monitoring. • Global networks of greenhouse gas monitoring stations, in conjunction with advanced modeling techniques, have continually improved the understanding of greenhouse gas concentrations. • Laser-induced breakdown spectroscopy instrument to measure soil carbon in situ for less than 10% of the lab costs of other methods with comparable reliability. • Mid-range infrared spectroscopy to measure soil carbon and chemical composition. • Ocean buoys that can measure and transmit data from multiple depths are being used in scientific studies, but are not ready for cost-effective deployment.
Commercialization and Deployment Activities
• Limited application within various technology areas is occurring, but no vertically integrated system is being tested at this time.

5.2 MM FOR ENERGY EFFICIENCY

Technology Description

Introduction

If measuring and monitoring (MM) for energy efficiency must be able to estimate impacts from mitigation actions at the level of corporations or sectors of usage, then MM must have the ability to quantify reductions in emissions at the point of energy usage through measurement or rules-of-thumb. The primary targets are transportation, buildings (commercial and residential), and industrial processes. The MM challenges significantly overlap needs in other technology areas. For example, the challenges in point and diffuse sources MM as part of "Other GHG" applies to energy efficiency, but with a focus on CO_2. The point sources are industrial facilities, while the diffuse sources are primarily vehicles.

System Concepts

- Continuous emission monitors (CEM) for point sources with data transmission and archiving complemented by inventory-based reporting so as to be able to evaluate the success of specific actions to improve efficiency.
- For transportation, the systems could include: (1) testing at point of production and applying assumptions to actual performance, (2) on-board emission sensors with data transmission, and (3) local-scale sensors that function autonomously with data transmission so as to homogenize emissions in an area (must also have sensors to track number/type of vehicles).
- Testing of equipment for residential and commercial usage (appliances, HVAC) at point of production; possibly with future sensors to monitor actual performance with data transmission (used for some installations, not feasible for all homes).
- Testing of equipment for industrial processes (e.g., industrial boilers and furnaces) at point of production; possibly with wireless sensors and data transmission capability.

Representative Technologies

- CEM for CO_2 (linked with energy use statistics at a facility).
- Direct measurement, or indirect measurement via tracer studies, over landscapes (for vehicle emissions); infrared, lidar, etc.
- Test systems at point of production, complemented by testing actual use for some percentage of installed systems.

Technology Status/Applications

- CEM are well developed, but improvements in performance, longevity, autonomous use, and data transmission are needed.
- Local-scale systems generally not available, although concepts are being developed and tested at the research stage (e.g., isotopic indicators of CO_2 sources).
- Testing at point of production well established; methods to track actual performance autonomously not available.

Current Research, Development, and Demonstration

RD&D Goals

- Develop sensors and data transmission systems that allow quantification of emission reductions resulting from energy efficiency improvements.

RD&D Challenges

- Develop CEM that are robust, inexpensive, accurate, and operate autonomously with data transmission.
- Demonstrate tower- or satellite-based sensors to measure CO_2 and other GHG at local scales.
- Data fusion with remotely sensed imagery and Geographic Information Systems (GIS).
- Determine whether tracer/isotopic methods can identify source of CO_2 and other GHG at local-to-regional scales.
- Develop sensors for vehicles and appliances to measure energy use and emissions with data transmission.
- Develop emissions estimates from the combustion of noncommercial fuels (propane, wood, landfill gas).

RD&D Activities
• High-temperature NO_x, O_2, ammonia, and other sensors are under development. • Engine diagnostics and controls. • Fast-response mass spectrometers are being developed. • A field laboratory that uses state-of-the-art FM-AM-LIDAR for remote monitoring of truck emissions (NOX, PM) and engine performance has been established in Knoxville, Tennessee.
Recent Progress
• Examples of new R&D results related to sensors, estimation methods. • Development of robust, wireless sensors and data transmitters for use in high-temperature, caustic industrial environments (e.g., steel mills, pulp and paper industry). • Development of the International Measurement and Verification Protocol for estimating energy savings.
Commercialization and Deployment Activities
• Activities are focused on deployment of new technologies, and measures of performance are typically comparisons of energy used. Limited use of sensors and data transmission directly for MM purposes.

5.3 MM FOR GEOLOGIC CARBON SEQUESTRATION

Technology Description

Introduction

Storing CO_2 in geological reservoirs (oil/gas reservoirs, coal beds, saline formations, etc.) requires that concentrated CO_2 streams be available[1]. These will result from separation and capture at fossil-fuel power plants and advanced concepts such as fuel cell or hydrogen facilities. Methods to fully account for carbon sequestration in these systems will require analysis of energy costs and full GHG accounting for separating, capturing, and transporting CO_2 as well as during the injection to below-ground reservoirs. In addition to direct injection, there are concepts being proposed that involve storage of other carbon sources in deep reservoirs that would promote the generation of CH_4 for energy. These concepts face many of the same challenges as injection and storage of concentrated CO_2 streams. Once stored, the focus is on methods to measure and monitor (MM) for long-term storage or leakage. The challenge is to be able to detect the transport or small releases of carbon dioxide from great depths that may be highly variable in space and time.

System Concepts

- Separation and Capture: Dual focus of (1) methods based on process knowledge to fully account for energy penalties and carbon costs to obtain CO_2 streams and (2) sensors to monitor fugitive emissions around the facility.
- Transportation: Leak detection from pipelines or other transportation systems will include mass balance methods (in/out measurements), pressure transducers, remote detectors, and addition of specific gaseous tracers enabling remote leakage detection.
- Geologic Storage: Multiple approaches will be necessary and include (1) direct detection of surface leakage (probably requires area or remotely sensed approach due to heterogeneity of release pathways), (2) indicators of leakage based on natural and induced tracers, (3) seismic/ electromagnetic (EM)/electrical resistivity (ER)/pressure monitoring networks, (4) intensively monitored validation sites (with those known to be leaky) may be required to confirm monitoring methods. For enhanced oil/gas recovery systems, robust measurements need to be made on both the injected CO_2 and on the produced hydrocarbons to get an accurate carbon change balance because of measurement challenges on gases that are changing pressures/temperatures along their production pathways.

Representative Technologies

- For leak detection from capture/separation, pipelines, and surface leaks from reservoirs there are options within traditional leak-detection technologies, advanced technologies (e.g., hand-held infrared remote imaging spectrometer, portable tracer gas detectors, inexpensive time averaged activated carbon traps for tracer gases), and aircraft or satellite-based sensors for CO_2. Improved leak detection needed in produced hydrocarbon streams as well.
- Indirect indicators for subsurface performance could include (1) observable effects on soil gas compositions and ecosystems (microbial and vegetation systems), although it is likely that changes would be observable only under high leakage rates, (2) deviations from model-predicted biogeochemical conditions of the subsurface fluids using either naturally occurring tracers/indicators or tracers induced during injection that have a well-predicted behavior pattern, (3) geophysical methods (pressure transient tests, seismic, EM, ER, etc.) methods to detect pressure changes and map migration pathways, (4) altered geochemistry of candidate receptor formations, and (5) detection of added tracers in control sites at various depths and within formation fluids from depth to the near surface.

Technology Status/Applications

- Leak-detection technologies are available but are too labor-intensive for routine use at a global scale.
- Even excellent leak detection technologies currently provide spot measurements over very small parts of very large geographic sampling areas.

[1] The discussion of separation, capture, and transportation of CO_2 here also applies to the option for direct injection of CO_2 into deep ocean regions.

- Time-averaged traps that absorb and retain tracer gases that have been added to the sequestered CO_2 could be readily developed/deployed for quarterly or annual verification procedures.
- Process flow information is evolving that should result in accurate estimates of CO_2 costs associated with capture and separation.

Current Research, Development, and Demonstration

RD&D Goals

- Develop ability to assess the continuing integrity of subsurface reservoirs using integrated system of sensors, indicators, and models.
- Improve leak detection from separation and capture and pipelines systems (many opportunities to take advantage of accomplishments from other technology development efforts).
- Apply remote sensors for other purposes to fugitive emissions from reservoirs and capture facilities.
- Improve/develop/implement tracer addition and monitoring programs.
- Evaluate microbial mechanisms for monitoring and mitigating diffuse, wide-area GHG leakage from geologic formations.
- Determine "acceptable" leakage percentages since dissolution of CO_2 into shallower formation fluids through a "diffusion grating" sequestration horizon enhances sequestration capacities many fold.
- Document dissolution/mineral trapping potential that will remove CO_2 from the formation fluids.

RD&D Challenges

- Low leakage rates occurring at spatially separated locations makes full detection difficult (this applies to both pipelines and reservoirs) likely requiring time averaged detection of added tracers.
- Heterogeneity of leakage pathway and probable alteration over time makes detection and quantification difficult for reservoirs (local vs. large area measurement capability).
- Indicators (e.g., seismic, EM, tracers) need further development for quantitative application or time averaging.
- Null results are expected, but this makes it difficult to "prove" that sample frequency and locations are not missing leak emanations.

RD&D Activities

- Significant efforts are ongoing for separation and capture technology development.
- Demonstration tests for geologic storage are ongoing and planned, which should provide test beds for MM options.
- Seismic testing methods are well-developed for exploration, and can be deployed for evaluating integrity of geologic formations for long-term storage of CO_2.
- Geochemical studies in deep formation environments are investigating the evolution of potential mineral trapping of CO_2.

Recent Progress

- Seismic methods are being used at the Sleipner test to map the location of the injected CO_2 gas phase, but such methods are not capable of aiding mass balance over the long-term performance periods.
- Geophysical methods need to be developed to track supercritical CO_2 in a diffuse (fingered) configuration that will be most typical of extended injection.
- Models, geophysical methods, and tracer indicators are being developed through the GEO-SEQ project.
- Development of innovative coatings for activated carbon particles within beads that may improve passive time-averaged sampling.
- Detection of CO_2 emission from natural reservoirs has been investigated by researchers at the Colorado School of Mines, University of Utah, and the Utah Geological Survey, including attempting isotopic discrimination of biogenic CO_2 from microbial respiration.
- Fundamental research on high-resolution seismic and electromagnetic imaging and on geochemical reactivity of high pCO_2 fluids is ongoing in basic science programs.
- ORNL application of PFT tracer gases to Frio tests and NETL PFT testing at surface during injection (Frio and New Mexico).

Commercialization and Deployment Activities
• Sleipner demonstration ongoing – seismic methods in qualitative mapping of CO_2 volume and integrity of geological formations. • Sleipner demonstration ongoing – seismic methods in qualitative mapping of CO_2 volume and integrity of geological formations. • GEO-SEQ field tests at Frio site. • SNL-LANL field tests. • Australian demonstrations. • Canadian demonstration at Weyburn, Saskatchewan, in collaboration with the North Dakota gasification plant. • A system of CO_2 capture and geologic reservoirs has a vast potential for storing CO_2. Demonstrations are in place or planned and offer outstanding opportunities for early development and testing of MM methods, so that wide-scale implementation of the technology will be acceptable to the public in the future.

5.4 MM FOR TERRESTRIAL CARBON SEQUESTRATION

Technology Description

Introduction

Terrestrial ecosystems (forests, pastures, grasslands, croplands, etc.) offer significant near-term and low-cost options to sequester carbon. Of course, such lands also can contribute to emissions through normal operations (e.g., tillage practices, fertilizer use, fires, and pests). Measuring and monitoring (MM) technologies must address both aspects so that a full accounting of changes in carbon stocks and fluxes of CO_2 or other GHG can be determined.

System Concepts

- A hierarchical system will integrate carbon sequestration (CS) measurements of different system components (e.g., soils, ecosystems) and for a range of scales (e.g., plot, landscape, regional) to provide a net accounting of CO_2 (and other GHG) inventories, emissions, and sinks.
- Routine reporting and measurement systems must be complemented with intensive monitoring on multiscale experimental sites to ensure validation of the methods.
- A system for analysis of the large quantities of data must be developed, as data alone will be insufficient to assess changes in stock, emissions, and sinks.

Representative Technologies

- The USDA Forest Service's Forest Inventory and Analysis Program and the Natural Resources Conservation Services' National Resources Inventory provide the underlying data for estimating a national carbon inventory and annual changes in carbon pools for forest, pastures, and croplands.
- Airborne and space-based platforms used to remotely sense land use/cover changes and biomass (e.g., LAI, soil moisture) are in place and are undergoing use and further enhancements and validation via land-based studies.
- Eddy covariance flux towers for area-scale CO_2 flux measurements.
- Laser-induced breakdown spectroscopy for soil carbon analysis for point measurement ($<mm^2$) and neutron-scattering methods for volumetric measurement ($\sim 1\ m^3$).
- A variety of models and decision-support tools for converting observations to information that can be used to implement greenhouse gas stabilization practices are being developed.

Technology Status and Applications

- Imaging, LIDAR, and RADAR remote sensing methods are being developed and tested for 3-D imaging of forest structure. Quantification is lacking and directly coupled, land-based measurements are not able to be easily integrated with remote sensing data.
- Laboratory-based LIBS analysis is calibrated and in testing; rapid, in situ soil carbon measurement systems are under development but not ready for field implementation.
- Eddy covariance flux measurement systems are being developed, but are not ready for deployment with all landscapes and would be difficult to implement at high spatial density.
- Methods and models to process land inventory data for estimating carbon changes and attributing changes to human-caused and natural factors are being revised as more accurate data are provided by recent technologies.

Current Research, Development, and Demonstration

RD&D Goals

- Provide integrated, hierarchical system of ground-based and remote sensing for carbon pools and CO_2 and other GHG flux measurements.
- Reduce uncertainty on regional-to-country scale inventories of carbon stocks.
- Develop low-cost, portable, rapid analysis systems for in situ soil carbon measurements.
- Develop standard estimates that relate management practices to net changes in emissions/sinks over time (e.g., life cycle of wood products, changes in agricultural crop rotations, energy use in ecosystem management, etc.).

RD&D Challenges

- Emission/sink factors for management practices must be based on a more complete understanding and quantification of ecosystem carbon allocation and storage processes.

- The broad range of required scales, cover types, and ecosystems will require the development of (1) remote sensing integrated with other measurements at various levels of coverage, duration, and intensity and (2) low-cost, robust measurement systems that can effectively be used at different scales.
- For such data collection methods to be of value, advanced data distribution, analysis, and simulation tools will be needed for scale-up of site-specific changes in carbon stocks to regional and global estimates. Sites covered need to be expanded as part of extensive monitoring and intensive measurement systems.

RD&D Activities

- The AmeriFlux network is being completed. It will improve our understanding of carbon pools and fluxes in large-scale, long-term monitoring areas and intensive experimental sites.
- Terrestrial carbon process R&D and technology development through the North American Carbon Program (NACP) will result in an understanding of mechanisms of carbon sequestration, and will contribute to the development of standard estimates for applications of carbon management practices.
- Technology for in situ sensors is supported.
- Development of remote sensing platforms and ground-based validation of carbon stocks is underway and should lead to national-scale methods.

Recent Progress

- USDA FIA and NRCS program provide information to assess the structure and condition of U.S. forests, croplands, pastures, and grasslands that is then converted to state, regional, and national carbon inventories.
- Prototype soil carbon analysis systems have been developed and are undergoing preliminary field testing.
- Satellite and low-altitude remote sensing technologies have been developed that can quantify agricultural land features at spatial resolution of approximately 0.5 m^2.
- Prototype versions of Web-based tools for estimating carbon budgets for regions.
- Increased accuracy of carbon sequestration estimates related to land management and full carbon accounting.

Commercialization and Deployment Activities

- Forest inventory measurement methods are being deployed at the project scale within the United States and other countries that will allow assessment of costs, utility, and accuracy.
- Tillage and land conservative practices are ongoing and offer test-beds for ground-based and remote sensing methods, as well as verification of rules of thumb for emissions factors.
- Opportunities for software development and support; and for development of models to support reporting under the 1605(b) program.

5.5 MM FOR OCEAN CARBON SEQUESTRATION

Technology Description

Introduction

There are two approaches for carbon sequestration in the ocean – direct injection and fertilization. These require somewhat different measuring and monitoring (MM) strategies. For direct injection, the separation, capture, and transportation of CO_2 must be addressed as well.[2] Sequestering CO_2 in the deep ocean below the main thermocline (depths of >1,000–1,500 m) should result in extended residence times, and the main measure of performance will be quantities of CO_2 injected and then tracking the dispersion of the concentrated CO_2 plume. MM systems are needed to monitor spatial and temporal CO_2 concentration histories. For fertilization strategies, the primary measure of performance will be the quantity of carbon exported deeper in the water column and its longevity. Sensors for direct measure augmented by remotely sensed indicators for the surface ocean and water column will be required.

System Concepts

- Injection: MM systems are needed to provide histories of CO_2 concentration profiles near the injection sites and track the dispersion and potential release of CO_2 to the atmosphere.
- Fertilization: MM systems should address both direct measurements of CO_2 concentration as well as indirect measures of performance that might be easier to accomplish.
- Alternatively, models of ocean circulation and biogeochemistry could be used to provide projections of CO_2 leakage rates and representative small volumes of the ocean would be intensively monitored for validation of model accuracy.

Representative Technologies

- Measurement of comprehensive trace gas parameters [Total CO_2 (TCO_2), Total Alkalinity (TALK), partial pressure of CO_2 (pCO_2), and pH] that represent an amount of CO_2 concentration in seawater (measurement of any two of these four parameters could result in calculation of other pair); extensive use of floats that cover various depths and report data back directly to data handling systems.
- Indirect indicators of fertilization effectiveness may be possible (phytoplankton biomass, pH, particulates, etc) rather than CO_2 measurements; satellite-based sensors may be able to provide quantitative indicators with selective validation via physical measurements.
- CO_2 sensors that "track" the dissolved CO_2 plume from injection locations.

Technology Status/Applications

- Extensive use of floats and buoys is ongoing for studies of the carbon cycle, but these are expensive and ship-intensive.
- Determining CO_2 concentration via comprehensive measurement is ongoing, but costs and complexity are prohibitive from an MM viewpoint.

Current Research, Development, and Demonstration

RD&D Goals

- Develop integrated MM concepts that include direct measurement, model analysis, and indirect indicators that can be used across the scales needed to verify process information and ocean-wide observations.
- Data transmission and analysis systems that avoid expensive ship time.
- Quantitative satellite-based sensors for surface ocean indicators of sequestration effectiveness.
- Determine whether direct measurement of plume dispersion or model analysis with selective validation is needed for direct injection MM.

RD&D Challenges

- Development and testing of robust sensors working at the pressure of deep oceans are still needed.
- Develop the ability to track the fate of direct injected CO_2.

[2] MM strategies for separation, capture, and transport of CO2 are addressed in technology Profile 5.3 MM for Geologic Carbon Sequestration.

- Develop sensors to provide robust measurements of CO_2, and other species introduced by impurities with CO_2 in seawater under a range of temperature and pressure conditions, from the deep ocean to the surface.
- Calibrate and test the sensors using the inter-comparison with proven equipment method in the laboratory and at sea conditions.
- Reduce uncertainty in measurements.
- Develop the ability to transfer measurements via satellite systems to centralized data collecting stations.

RD&D Activities

- For more than 10 years (1990-2000) the U.S. DOE and NOAA have sponsored the ocean carbon dioxide survey during the World Ocean Circulation Experiment (WOCE), monitoring the carbon concentration in the Indian, Pacific, and Atlantic oceans from the research oceanographic ships. The global WOCE carbon data set includes ~23,000 oceanographic stations.
- Low-cost discrete measurement sensors are under development. These sensors will be used in conjunction with the conductivity, temperature, depth (CTD), and oxygen sensors to measure the ocean profile on oceanographic stations.
- Development of floats with CO_2 sensors (SOLO) is underway through the NOPP program.
- Remote sensors are being developed to measure indicators of CO_2 parameters.

Recent Progress

- MBARI has demonstrated the ability to inject and monitor via video camera and other sensors at depths; the challenge is to develop these into routine sensor systems.
- Experimental facilities for testing sensors in simulated seawater at representative pressure and temperature are available at ORNL.

Commercialization and Deployment Activities

- Total CO_2 is measured worldwide by use of single-operator multiparameter metabolic analyzers SOMMAs) coupled with coulometers; Total Alkalinity and pH are measured by closed-cell automated potentiometric titration system developed at University of Miami; discrete pCO_2 is measured by an automated equilibrator-IR analyzer system, developed at LDEO.

5.6 MM FOR OTHER GHG

Technology Description

Introduction

Other GHG (e.g., N_2O, CH_4, PFCs, HFCs, SF_6) are emitted from both point sources (industrial plants) and diffuse sources (open pit coal mines, landfills, rice paddies, and wastewater treatment lagoons) and offer unique challenges due to spatial and temporal variations. Measuring and monitoring(MM) technologies for both sources must include direct measurement of emissions as well as accurate reporting that is based on inventory accounting procedures or rules-of-thumb for activities or processes. Reporting methods are available and being improved.

System Concepts

- Continuous Emission Monitoring (CEM) for point sources with data transmission and archiving complemented by improved inventory-based reporting, and remotely sensed measurements.
- For diffuse sources, the system will include (1) rules-of-thumb for emissions based on known processes (e.g., agricultural practices related to N_2O emissions), (2) area-scale sensors that function autonomously with data transmission, and (3) remote sensing methods for local-to-regional scale estimation.

Representative Technologies

- CEM for a wide variety of other GHG.
- Direct measurement over landscapes.
- Indirect measurement via tracer studies.

Technology Status/Applications

- Diffuse emissions; Current technology (labor intensive) can estimate area-averaged atmospheric concentrations from diffuse emissions. New approaches are needed to quantify source and sink rates for other GHG. A more simple, reliable, and low-cost (meaning, presumably, unattended) method of measuring area-source emissions would be very helpful in producing both more accurate inventories and improving prospects for identifying low-cost reduction opportunities.
- Point sources: CEMs and inventory-based accounting and reporting provide elementary capability for estimating point sources of GHG emissions.

Current Research, Development, and Demonstration

RD&D Goals

- Point sources: Inexpensive CEM, instruments to measure from stand-off distances, satellite-based sensors capable of point-source estimation, and improved understanding of process chemistry so that accounting-based estimates are more accurate.
- Diffuse sources: New analytical tools for autonomous measurement, improved scientific understanding of processes to develop accurate rules-of-thumb, and remote sensors to quantify other GHG at multiple scales and in the vertical atmospheric profile.

RD&D Challenges

- Modeling activities that increase the accuracy of spatial estimates of N_2O and CH_4 from land management activities (e.g., nitrogen fertilizer, manure management, rice production, etc.).
- CEM systems for industrial emissions that are robust and inexpensive that are linked to data collection, distribution, and analysis systems.

RD&D Activities

- Limited scientific studies to measure or estimate emissions in systems such as landfills or agricultural practices are ongoing.

Recent Progress

- One approach involves tracer technique with Fourier transform measurement of sulfur hexafluoride tracer gas placed with emission sources. As a proxy, the tracer observations infer annual emissions, and while this procedure works, there are presently cost and logistical limitations.
- Airborne platforms effectively monitor aerial concentrations of GHGs, and have some capability with identifying emissions sources; new detection and measurement systems are being evaluated.

Commercialization and Deployment Activities
• Point source CEM methods and area-averaged concentration of GHGs can be obtained in limited applications; improved spatial resolution of measurements is needed before approaches are accepted by commerce and industry. • Methods do not exist for remote sensing of diffuse GHG emissions.

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