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Mr. Chairman, Ranking Member Domenici, and Members of the Committee. Thank you for the opportunity to speak before you today about the technologies we need to meet increasing global energy demand, and to do so without adding unduly to atmospheric greenhouse gases. As you have heard from Dr. Neil Hirst, and as described in the International Energy Agency's report *Energy Technology Perspectives 2008*, the challenge we have before us is enormous.

Incremental improvements in our current technologies will not be enough to meet this challenge. We will need transformational breakthroughs in basic science to provide the foundation for truly disruptive technologies that will fundamentally change the rules of the game. This applies to renewables, nuclear, and CO_2 capture and storage as well as to promising technologies like fusion that are farther off.

The good news today is that we may be on the threshold of scientific and technological breakthroughs in the 21st century every bit as profound as those which transformed human life forever in the 19th. The scientific world today is changing and advancing with almost dizzying speed. Every year our capability to direct and control matter down to the molecular, atomic, and quantum levels is growing. This increasing ability to control the fundamental, nanoscale building blocks of both biological and non-biological matter holds out the promise of eventually forever transforming the way we generate, store, transmit, and use energy.

One of the chief missions of the DOE Office of Science has been to nurture and accelerate the development of this new fundamental science and these cutting-edge capabilities—capabilities that may transform our energy economy and ultimately provide answers to the great challenges we face in both energy and the environment.

Over the course of this decade, our Office of Basic Energy Sciences in the DOE Office of Science has held a dozen major "Basic Research Needs" workshops to assess basic research needs for energy technologies. These workshops have brought together scientific and technical experts from universities, national laboratories, industry, and government, from both here and abroad, to identify scientific roadblocks and determine research priorities. Each workshop has issued a major report. Together these reports define a bold and comprehensive research agenda.

Time and again we see the same themes: new materials design, development, and fabrication, especially materials that perform well under extreme conditions; control of photon, electron, spin, phonon, and ion transport in materials; science at the nanoscale and femtosecond; designer catalysts; structure-function relationships; bio-materials and bio-interfaces, and so on.

These are challenging and difficult scientific problems. That is why we refer to the problems we tackle in the Basic Energy Sciences program as "Grand Challenges." Late last year our Basic Energy Sciences Advisory Committee issued a report titled *Directing Matter and Energy: Five Challenges for Science and the Imagination*. The report summarized the work of the Basic Research Needs workshops by setting forth five grand challenges, as follows.

- Controlling materials processes at the level of quantum behavior of electrons
- Atom- and energy-efficient synthesis of new forms of matter with tailored properties
- Emergent properties from complex correlations of atomic and electronic constituents
- Man-made nanoscale objects with capabilities rivaling those of living things
- Controlling matter very far from equilibrium

These grand challenges span the Office of Science portfolio and define the tasks before us today and in the years ahead. I'd like to talk in a little more detail about our grand challenges in the field of energy—not just the barriers we face, but the opportunities before us. These opportunities provide more than hope for our energy future; they provide sustenance for us to imagine such things as:

- Solar photovoltaics exceeding thermodynamic efficiency limits
- Direct conversion of sunlight to chemical fuels
- A sustainable, carbon-neutral biofuels economy that meets over 30 percent of U.S. transportation fuel needs without competing with food, feed, or export demands
- A closed nuclear fuel cycle and abundant fossil-free power with zero greenhouse gas emissions
- Safe and environmentally benign underground storage of CO_2 for millenia
- Bringing the power of the sun and the stars to Earth with fusion energy

While as Under Secretary for Science I am responsible for advising on the entire R&D portfolio, my remarks today in response to your questions are focused on the Department's basic research portfolio aimed at transforming our energy future.

Solar Energy. Let's begin with solar energy. More energy from sunlight strikes the Earth in one hour than all the energy consumed by human activity on the planet in one year. This is abundant, carbon-free energy. Yet solar power today provides less than one-tenth of one percent of the world's primary energy. There are big challenges here, but also big opportunities. Silicon-based single crystal solar cells have reached efficiencies of 18 percent. Triple-junction cells with Fresnel lens concentrator technology are approaching efficiencies of 40 percent.

Imagine if we could develop solar photovoltaics that exceed thermodynamic efficiency limits.

Imagine, even more boldly, if we could borrow nature's design for capturing sunlight—photosynthesis—and directly convert sunlight into chemical fuels.

There are three ways we can use solar energy—by converting it to electricity, fuels, or heat. We are particularly interested in the first two: electricity and fuels. In both cases, there are three steps: capture, conversion, and storage. The challenge is reducing the costs and increasing the capacity for conversion of sunlight into electricity and fuels which can be stored and transported.

The Office of Science is pursing basic research in solar utilization to try to reach these goals. We are investigating new concepts for capturing energy from sunlight while avoiding thermalization, or heating, of carriers, such as multiple-exciton generation from a single photon. We are exploring "plastic" solar cells from molecular, polymeric, or nanoparticle-based structures that can provide flexible, inexpensive, conformal electricity systems. And we are trying to better understand defect formation in photovoltaic materials and self-repair mechanisms in photosynthesis, with the aim of developing defect tolerance and active self-repair in solar energy conversion devices, which would extend their lives.

We are also delving into artificial photosynthesis. We are working on the design and development of light-harvesting, photoconversion, and catalytic modules—bio-inspired molecular assemblies—capable of self-ordering and self-assembling into integrated functional units that can lead to an efficient artificial photosynthetic system for solar fuels. The photosynthetic reaction centers of plants are remarkably efficient, but we still have a lot to learn about their detailed reaction mechanisms. We are also just beginning to discover the number and variety of light-harvesting molecules in Nature. For instance, Craig Venter's analysis of seawater samples taken from the Sargasso Sea identified 782 new rhodopsin-like photoreceptors, where only 70 were known before. (Rhodopsin is the photoreceptor that captures light in the mammalian eye.) There is great potential in this area for direct production of fuels from sunlight.

Electrical Energy Storage. Next, we turn to the related and vital area of electrical energy storage. To make an intermittent energy source such as solar effective for baseload electrical supply, major breakthroughs are required in electrical energy *storage*. This is a much-overlooked requirement for a range of renewable energy sources, including wind energy.

Electrical energy storage devices with substantially higher energy and power densities and faster charge times would also make all-electric and plug-in hybrid vehicles much more market attractive.

Imagine solar and wind providing over 30 percent of electricity consumed in the United States, and imagine roads where the number of all-electric/plug-in hybrid vehicles exceeds those running on gasoline.

Electrical energy storage devices such as batteries store energy in chemical reactants capable of generating charge. Storage devices like electrochemical capacitors store energy directly as charge. Fundamental gaps exist in understanding the atomic-and molecular-level processes that govern operation, performance limitations, and failure of these devices. Knowledge gained from basic research in the chemical and materials sciences is needed to surmount the significant challenges in creating radically improved electrical energy storage devices—whether improvements in weight, lifetime, and charge time and capacity for transportation use, or improvements that let us better store and use large but transient energy sources like solar and wind.

In pursuit of this knowledge, the Office of Science is supporting research in areas such as nanostructured electrodes with tailored architectures. For example, fundamental studies of the electronic conductivity of lithium iron phosphate ($LiFePO_4$) led to the discovery of doping-induced conductivity increases of eight orders of magnitude. This discovery led to the DOE

Office of Energy Efficiency and Renewable Energy's funding development of the high power-density Lithium-ion batteries that power electric vehicles such as the Chevy Volt. The Office of Science is also looking at conversion reactions for batteries that yield more than one electron per redox center. New research on conversion reactions is looking at advanced materials that yield up to six electrons per redox center, allowing a large increase in power density. We are also investing in research on ultracapacitors, which complement battery power by allowing rapid charge and discharge cycles.

Bioenergy. A third area where we believe fundamental scientific breakthroughs can change the energy equation is biofuels. The development of biofuels—especially biofuels made from plant fiber, or lignocellulose, such as cellulosic ethanol and other fuels—represents a major scientific opportunity that can strengthen U.S. energy security while protecting the global environment.

Imagine a sustainable, carbon-neutral biofuels economy capable of meeting a third of U.S. transportation fuel needs without competing with fuel, feed, and export demands.

The capability to more efficiently tap into the energy contained in plant fiber or cellulose would give us the means to produce biofuels on a scale sufficient to create a nationwide biofuels economy. Unfortunately, our current means of converting cellulose, or plant fiber, to fuel is neither efficient nor cost effective. This is a tough problem. Plant fiber has evolved over the millennia to be extremely resistant to breakdown by biological or natural forces. The plant cell walls contain a substance called lignin that is tightly woven with the cellulose, forming a kind of "flexible concrete" which gives the plant its incredible strength. This "recalcitrance" of plant fiber forms the major cost barrier to making biofuels from plant fiber economically viable.

Nature, however, has evolved solutions to this problem. Termites, for example, are frighteningly efficient at converting cellulose and hemicellulose to fuel. They eat wood at an alarming rate, and convert the cellulose into energy. Using a systems biology approach to develop an understanding of the principles underlying the structure and functional design of living systems, the basic research supported by the Office of Science is focused on developing the capabilities to model, predict, and engineer optimized enzymes, microorganisms, and plants for bioenergy and environmental applications. A series of workshops led by the DOE Office of Biological and Environmental Research identified the basic research needs for such an approach.

The emerging tools of systems biology are being used to help overcome current obstacles to bioprocessing cellulosic feedstocks to ethanol and other biofuels—research tools such as metagenomics, synthetic biology, high-throughput screening, advanced imaging, and high-end computational modeling. In 2007, we launched three new DOE Bioenergy Research Centers, each funded at $25 million per year for five years, to pursue these research directions—the BioEnergy Science Center, led by Oak Ridge National Laboratory; the Great Lakes Bioenergy Research Center, led by the University of Wisconsin-Madison in partnership with Michigan State University; and the Joint BioEnergy Institute, led by Lawrence Berkeley National Laboratory. We believe that these Centers can crack Nature's code for cost-effective biofuel conversion.

The DOE Bioenergy Research Centers are focusing mainly on the use of enzymes and microbes to break down the lignocellulose or plant fiber into energy-rich sugars and synthesize these sugars into fuels. Ethanol is one focus, though the Joint BioEnergy Institute led by Lawrence

Berkeley National Laboratory is also re-engineering microbes to produce hydrocarbon fuels--green gasoline, diesel, and even jet fuel. Of course, mankind has known how to make ethanol by fermentation for some time. Lignocellulose presents special challenges. First, the degradation process—the process of breaking through recalcitrance—typically produces chemicals that inhibit or endanger the microbes used for fermentation. Second, typically you get two types of sugar monomers, one type having 6 carbon atoms and the other type having 5 carbon atoms. The 5-carbon sugars are more difficult to ferment.

But once we've figured out how to degrade the lignocellulose and recover sugar monomers from it, there's another route to making fuel: chemical catalysis. The Great Lakes Bioenergy Research Center is devoting some resources to this alternative path. The major funder of this catalytic work within the Office of Science is our Office of Basic Energy Sciences, which has stewardship within the federal government for catalysis.

Catalysis offers several advantages over fermentation. First, researchers have shown that catalytic processes can be used to turn sugar into hydrocarbon fuels, fuels more like gasoline. Ethanol has certain disadvantages relative to gasoline. Ethanol has only about 70 percent of the energy content per gallon as gasoline. Ethanol is also water-soluble, which introduces problems of corrosion when shipped by pipeline or during storage. Also, today's vehicle engines need to be adapted for use with high concentration ethanol blends, such as E85; flex fuel vehicles can also carry a cost premium over ordinary gas-powered vehicles.

Catalysis may be able to yield biofuels that are essentially indistinguishable from gasoline, conventional diesel, even jet fuel. We may also be able to produce such hydrocarbon fuels via fermentation, by re-engineering microbes to produce them, and our DOE Bioenergy Research Centers are working on this. If we could produce gasoline from plant fiber—so-called "green gasoline" —we could move to a greener fuel supply without any major infrastructure changes. Our new Energy Frontier Research Centers initiative, which I'll talk about in a moment, will provide new funding opportunities for this important work in catalytic production of biofuels.

Nuclear Energy. Today, nuclear energy provides about 20 percent of the nation's electricity, with no greenhouse gas emissions or pollution. Nuclear energy could provide much more carbon-free, pollution-free energy. A key challenge to industry growth, however, is the need to solve the problem of spent nuclear fuel. Current "once through" nuclear reactor policy leaves spent fuel rods with long-term heat loads and radioactive decay, and a significant fission fuel content.

Imagine if we could close the fuel cycle; imagine abundant fossil-free electric power with zero greenhouse gas emissions.

Advances in basic science leading to new recycling technologies could in fact provide a major reduction in spent fuel—recycling the spent fuel for further use in fission reactors and reducing storage requirements by up to 90 percent. Performance of materials and chemical processes under extreme conditions is a limiting factor in all areas of advanced nuclear energy systems. The challenge is to understand and control chemical and physical phenomena in complex systems from femtoseconds to millennia, at temperatures to 1,000 degrees Celsius, and for radiation doses leading to hundreds of displacements per atom.

In 2006 and 2007, the Office of Science held three workshops designed to identify the basic science needed for the development of advanced nuclear energy systems and to close the fuel cycle. In addition to the Basic Research Needs workshops, two additional workshops were held in the area of nuclear physics and advanced scientific computing. Research areas identified in those workshops include: materials and chemistry under extreme conditions; actinide chemistry; separations science; nuclear theory; developing and scaling next-generation multiscale and multiphysics codes; and computational modeling and simulation of reactor and recycling systems.

Hydrogen. Most observers agree that there will be no "silver bullet" to solve our energy dilemmas. As we attempt to meet the energy and environmental needs of the 21st Century, we will increasingly rely on a portfolio of different energy sources. Hydrogen as fuel is a somewhat longer-term possibility, but it is a very attractive one.

Hydrogen has the highest energy content per unit of weight of any known fuel. Fuel cells powered by hydrogen are more than twice as efficient as internal combustion engines and produce only water. When hydrogen is burned in an engine, emissions are significantly lower than those from other alternative fuel technologies. Hydrogen can be produced from abundant domestic resources including natural gas, coal with sequestration, biomass, and even water, using nuclear energy or renewable energy sources such as solar wind, and geothermal.

Imagine an emissions-free energy future.

Combined with other technologies such as carbon capture and storage, renewable energy, and fusion energy, hydrogen fuel cells could make an emissions-free energy future possible. But this is an area that clearly requires some very fundamental research, in addition to applied research. Of particular importance is the need to understand the atomic and molecular processes that occur at the interface of hydrogen with materials in order to develop new materials suitable for use in a hydrogen economy. New materials are needed for membranes, catalysts, and fuel cell assemblies that perform at much higher levels, at much lower cost, and with much longer lifetimes. The breakthroughs needed to sustain a hydrogen economy will require revolutionary, not evolutionary, advances. Discovery of new materials, new chemical processes, and new synthesis techniques that leapfrog technical barriers is required. This kind of progress can be achieved only with highly innovative, basic research.

The Department through the Office of Science supports such research in five technical focus areas: novel materials for hydrogen storage; membranes for separation, purification, and ion transport; design of catalysts at the nanoscale; solar hydrogen production; and bio-inspired materials and processes. Funding within the Office of Basic Energy Sciences has enabled major advances in our fundamental understanding of hydrogen-matter interactions. Recent key accomplishments include: discovering atomic scale mechanisms in the reversible hydrogen storage within complex metal hydrides; developing novel micro- and nano-patterning syntheses for a new generation of fuel cell membranes with superior power output; theoretically predicting and experimentally validating new architectures and compositions of catalyst alloys for efficient hydrogen production from fossil fuels or biomass; synthesizing mixed metal oxide photoelectrodes for solar hydrogen production; and providing new insights into the development of oxygen-tolerant enzymes for bio-inspired hydrogen production. Such fundamental science accomplishments have significantly advanced our understanding of the behavior of hydrogen at

the atomic level. They have also contributed significantly to shortening the knowledge gap between present-day hydrogen technology and commercial viability.

Carbon Capture and Sequestration. Coal provides almost 56 percent of baseload electricity produced in the U.S. and will likely continue to be a significant energy source globally over the coming decades. Carbon dioxide emissions from coal-fired power plants can be reduced by improving conversion efficiency and by co-firing coal with biomass, but the largest emission reduction potential will likely come from employing CO_2 capture and storage (CCS).

Imagine safe and environmentally benign underground sequestration of CO_2 for millenia.

While DOE's Office of Fossil Energy, in conjunction with many academic and industry partners, has worked to ensure that many components of CCS have been validated at an industrial scale and will soon conduct large scale field tests to determine the potential for the long-term safe storage of CO_2, full scale deployment of CCS requires an intensive science-based approach to understanding the long-term behavior of subsurface geological systems where CO_2 can be safely and securely stored for centuries to millennia. The scientific foundations must be laid for both firm regulation and public acceptance. This means we must be able to make the critical measurements of geological properties needed to design and build multiple, effective, stable, geological carbon sequestration sites; we must also improve our ability to predict subsurface properties from limited invasive sampling. Improved high-resolution geophysical monitoring and verification approaches are needed to observe subsurface processes in real time and to track processes at operating sequestration sites for validation of safety and security.

We must also develop a better understanding of the geochemical stability of deep potential storage sites, since CO_2 injection will introduce new reactive chemical components, and storage creates compositionally complex systems, potentially reactive chemical environments, and gradients in pressure and temperature. And we will need the computational modeling tools that can predict CO_2 plume movement and storage integrity for varied geological storage locations over large distances and long time scales.

Ultimately, we need to predict with confidence the transport and fate of CO_2. To do that, we need to learn how to better describe the fundamental atomic, molecular, and biological processes and to translate those microscopic descriptions to properties of materials and fluids. Sustained investment now in fundamental research in such areas as dynamic imaging of flow and transport of CO_2, fluid-induced rock deformation, understanding the complexities and dynamics of mineral-water interfaces, and biogeochemistry in extreme environments will enable the development of these capabilities.

Fusion. Finally, one of the most promising future energy solutions lies in fusion. Fusion is the energy that powers the sun and the stars. Fusion energy on earth will use deuterium from water and lithium to create tritium, fusing deuterium and tritium into helium and a fast neutron (14 MeV). Deuterium and lithium are abundant and cheap, the helium will escape from the earth's gravity, and the energy of the neutron can be captured to generate electricity or produce hydrogen. Fusion has the potential to provide clean, carbon-free energy for the world's growing electricity needs on an almost limitless scale. The key challenge is sustaining and containing the 100 million degree-plus fusion reaction on earth. Scientists have made progress containing fusion reactions using powerful magnetic fields for confinement.

Imagine a future of unlimited, emissions-free energy for humanity. Imagine a future where humanity ceases to struggle with the challenge of providing abundant energy without damaging our earthly environment.

The basic science needs to enable this technology include: fundamental understanding of plasma science; materials for the extreme thermochemical environments and high neutron flux conditions of a fusion reactor; and predictive capability of plasma confinement and stability for optimum experimental fusion power plant design. In November 2006, the United States signed an agreement with six international partners to build and operate an experimental fusion reactor, ITER, that will demonstrate the technical and scientific feasibility of a sustained fusion burning plasma. US scientists are working side by side with their counterparts from China, the European Union, India, Japan, the Republic of Korea and the Russian Federation in the ITER effort.

Energy Frontier Research Centers. If we are to realize this clean, abundant, and affordable energy future envisioned here today, we must engage the Nation's intellectual and creative talent to tackle the scientific grand challenges of transformational energy research. One way the Office of Science is seeking to do this is through Energy Frontier Research Centers, which we are asking Congress to authorize and fund in the Department's FY 2009 budget request. The funding opportunity announcement for the Centers was posted on our website on April 4, 2008. These Centers are intended to conduct innovative basic research to accelerate the scientific breakthroughs needed to create advanced energy technologies for the 21st Century. Assuming Congressional approval of Energy Frontier Research Centers, $100 million will be set aside for these Centers each year, with each Center receiving $2 to $5 million annually for five years. Universities, national laboratories, industry, non-profits, and partnerships among these groups are eligible to apply. The goal is to bring together our Nation's best minds to tackle formidable energy challenges in groups large enough to make a difference.

Conclusion. I want to thank you, Mr. Chairman, for providing this opportunity to discuss the fundamental research the Department of Energy is pursing to accelerate the scientific breakthroughs necessary to achieve not only for the United States but for all of our global neighbors the clean, secure, economic energy future we envision.

This concludes my testimony. I would be pleased to answer any questions you might have.